Philip Tow · Ian Cooper
Ian Partridge · Colin Birch *Editors*

Rainfed Farming Systems

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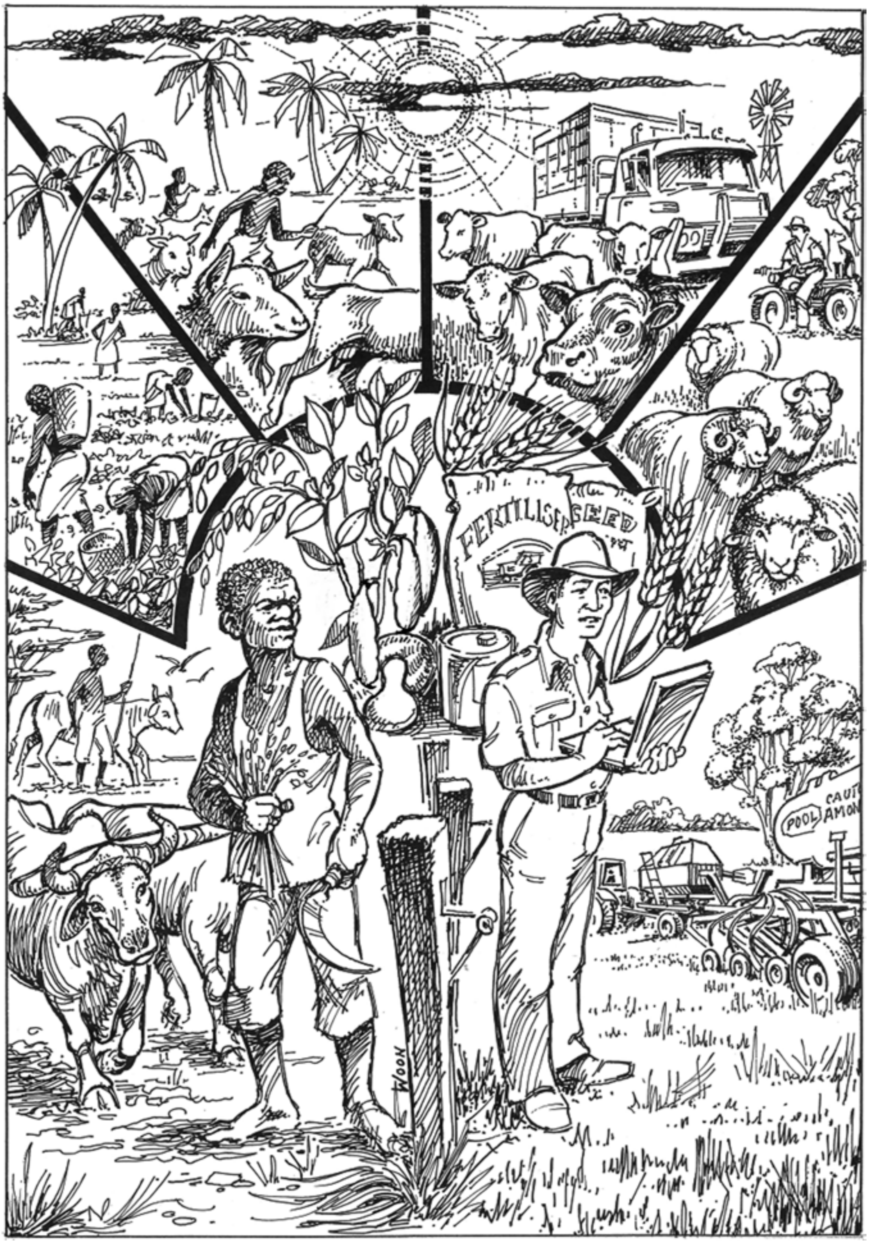
ISBN 978-1-4020-9131-5 e-ISBN 978-1-4020-9132-2
DOI 10.1007/978-1-4020-9132-2
Springer Dordrecht Heidelberg London New York

Library of Congress Control Number: 2011930860

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)


FERTILISER
SEED
POOL

Foreword

Few books have attempted global surveys of farming systems. Hans Ruthenberg's *Farming Systems in the Tropics* (3rd Edition, 1983) is a classic that has long been out of print but is still widely cited. John Dixon and colleagues' *Farming Systems and Poverty: Improving Farmers' Livelihoods in a Changing World* (2001) a more recent effort, takes a broader view of farming systems, but is also out of print. This book *Rainfed Farming Systems* is the most ambitious effort to date and fills major gaps in our knowledge; it covers both commercial farming in the developed world and small-scale, often subsistence-oriented, farmers in developing countries.

Rainfed Farming Systems is also most timely given that rainfed agriculture will be under pressure to help supply the 70% increase in food production required by 2050 as water available for irrigated agriculture is increasingly limited.

My own involvement in rainfed farming systems dates from growing up on a cereal–sheep farm in the upper north of South Australia where my family continues to farm. There I learned that the two greatest challenges facing rainfed farmers are making the best of available moisture and dealing with high levels of climatic risk.

In the 1970s and 1980s, I worked with the International Maize and Wheat Improvement Center (CIMMYT) where, in the wake of the Green Revolution in irrigated areas, we turned to the challenges of rainfed farming. We employed a farming systems approach that necessarily involved looking at the system rather than at single commodities, bringing together the perspectives of natural scientists and social scientists. Most importantly, we worked hand-in-hand with farmers and their advisory services to gain a better understanding of the circumstances under which new technologies would be used. We also learned the importance of putting farmers at centre stage when defining and testing new technologies in their fields.

All of these elements are well covered in *Rainfed Farming Systems*, which goes well beyond our rather rudimentary approaches of only two decades ago. The farming systems perspective has continued to evolve and this is seen in the following chapters where sustainability, resilience and equity are all now central dimensions of successful farming systems. The multi-disciplinary perspective represented here is impressive, with strong disciplinary chapters covering soils, weeds, pests and diseases, tillage, genetic–management–environmental interactions and crop–livestock interactions as well as economic, social and cultural aspects.

The book highlights the critical importance of strong partnerships between scientists and farmers with each learning from the other. An especially valuable contribution is in the number of chapters authored or co-authored by farmers themselves in a series of farm case studies in Part V.

In spite of the natural, social and economic challenges of rainfed farming across the world, the unfolding story here is that much progress is being made. Rainfed farming systems have continued to evolve and adapt in a rapidly changing world. The chapters show that change has been evolutionary, generally involving complex interactions within farming systems. In some cases, productivity gains in rainfed systems have been higher than in irrigated areas; however, crop yields continue to be too low, and nowhere more so than in Sub-Saharan Africa where our understanding of local farming systems is still far from perfect. Even in seemingly successful systems, new problems continue to arise, requiring the search for solutions which, as always, have to be evaluated within a systems perspective.

The huge effort by the editors and authors of *Rainfed Farming Systems* to provide a comprehensive systems framework and bring together a rich and diverse set of experiences will be a valuable resource for future generations of scientists, students, advisers, policy makers, and farmers.

Derek Byerlee

Member, Science Council,
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Preface

Rainfed Farming Systems provides a comprehensive collection of principles and applications, covering most aspects of rainfed farming system structure, operation, management and improvement. These aspects are expressed as relationships among the many components of farming systems and between components and the external factors that influence them. They are also expressed in terms of such characteristics as productivity, profitability, efficiency, flexibility, resilience and sustainability. Rainfed farming systems are defined in this book as those that normally experience suboptimal rainfall and significant water deficits in at least part of the growing season, thus limiting agricultural production. For this reason and to keep a workable scope to the book it does not deal with tropical agricultural systems, except for a brief discussion of systems in the semi-arid tropics. Temperate rainfed (but largely rainfall adequate) farming systems such as in Europe and New Zealand are also omitted.

This book provides an understanding of rainfed farming systems that will lead the reader to work more effectively with them in research, development, consulting and extension, policy making and field practice. This will be done in the context of many challenges for agriculture: climatic variability and long term climatic change; degradation of most agricultural soils; spread of diseases, pests and weeds; rapid innovation in technology in some countries but inadequate technology and infrastructure in others; and the interaction of market and political forces at both local and global levels. *Rainfed Farming Systems* will cover the principles required to deal with these challenges, but it will also be particularly concerned with the broader issues faced by farmers, of fitting all the components together into a workable system that is productive and profitable, in the context of local climate and soil, of economic opportunities and constraints, of family and community expectations and of government policies. It is also generally recognised that this must be achieved while maintaining or even improving the resource base of soil, water, desirable genetic features of farm plants and animals. Frequently other assets such as wildlife and natural vegetation must be conserved as well. Systems that combine these attributes are often described as 'sustainable'.

For these purposes, the book is presented in five inter-related, system-oriented parts.

Part I deals with individual, but systems-related disciplines of agriculture, it deals with the universally important topics of climate; soil (physical and chemical aspects, soil biology and soil carbon); water supply and use; pest management, economic and social aspects, crop-livestock relationships, and system design.

Part II aims to provide an integrated understanding of some important rainfed farming systems around the world, from parts of China, south Asia and west Asia, northern and southern Africa, Canada, the USA, South America and Australia. Chapters seek to provide a broad understanding of the systems they depict, and may include case examples to illustrate their themes, principles and applications.

Part III delves into some aspects of the structure, operation and management of rainfed farming systems to show how these systems can be improved.

Part IV deals with the combination of research, development and education or extension, and shows how the 'systems approach' of past decades is moving towards a 'participatory systems approach' involving all concerned, from farmers, to researchers, advisers and policy makers. One chapter describes subsistence agriculture in Tanzania where science may be less important than community culture and tradition, and improvement in such farming systems is slow. In contrast, progress in soil management under conservation farming, is impressive in several countries.

Part V contains farm case studies which show how farmers have responded effectively to a range of challenges and external changes over time, and kept their systems productive, profitable and environmentally sustainable.

Chapter 50 allows the editors to sum up their conclusions from the wide range of important information and understanding provided by the authors.

In developing this book, the editors worked with authors from a wide range of developed and developing countries and from national and international organizations. They aimed to achieve the broadest possible coverage of rainfed farming systems, and above all to be informative and stimulating. The editors wish to acknowledge the valuable contributions made by authors towards achieving the goals of the book, with accuracy, comprehensiveness and depth. These contributions give us confidence that the book will be interesting, relevant and useful to agricultural professionals, practitioners and students of rainfed farming systems throughout the world, and to the community as a general reference book.

Philip Tow, Ian Cooper, Ian Partridge, and Colin Birch
Editors

Acknowledgments

The Editors wish to acknowledge the work of the authors in providing a valuable understanding of the science, technology and practice of Rainfed Farming Systems around the world. The critical comment of others on drafts of chapters of this book is also appreciated. We are most grateful for the support of our employers, and of our families and friends. We also acknowledge the pictorial contrast, provided by artist Sid Woon, of agriculture dependent largely on labour and that dependent much more on science and technology.

Contents

Part I
Principles and Their Application

The 14 chapters of Part I deal analytically with individual disciplines of agriculture. Systems-orientation is provided through use of appropriate examples and applications. Part I seeks to make clear the major principles and concepts for the operation and management of farming systems. It therefore provides a basis for the other, more holistic Parts (II–V) of the book.

Part I assumes a basic knowledge of agricultural disciplines. Specialised terms are defined in a Glossary, to which the reader is referred in all chapters of the book.

Chapter 1 provides definitions, principles and concepts related to farming systems structure and operation and to the important, central topics of efficiency of use of water, nutrients and energy, including ecological concepts of energy (emergy) evaluation.

Chapter 2 provides a classification of rainfed farming systems based broadly on Climate as a key determinant and then on the levels of Productivity and Farming Intensity, as determined by a range of other factors, which apply to all farming systems.

Other chapters in Part I deal with the universally important agricultural topics of climate, soil (physical and chemical aspects, soil biology and soil carbon), water, weeds, diseases, insect pests, impact of technology, economic and social aspects, crop-livestock relationships, and farming system design.

Chapter 1
Principles of a Systems Approach to Agriculture

Some Definitions and Concepts

Philip Tow, Ian Cooper, Ian Partridge, Colin Birch, and Larry Harrington

Abstract A systems approach is needed to understand and manage a 'farm'. This chapter examines the definition and concepts of farm systems, their structure, operation and management, the relationships among internal and external factors, response to changing circumstances, and modifications to deal with change. Study of a system requires definition of goals and objectives, boundaries and the structure and function of its components. Feedback mechanisms and interactions are important features of farm system structure and operation. Farm systems can often be better understood through analysis and the study of their sub-systems; and circle or problem-cause diagrams can assist this. Farmers design their systems to make best use of the prevailing climate and soil but a wide range of technological, commercial, social, political and personal factors determine farmers' goals and management. Important characteristics of systems include: productivity, profitability, efficiency, stability, sustainability, equity, flexibility, adaptability and resilience. Efficiency of resource use should be optimised, bearing in mind Liebscher's Law of the Optimum. Efficient use of energy and water are necessary for profitable production.

Keywords System • Systems approach • Farming system • Farm system • Subsystem • Open system • Goals • Boundary • Feedback • Interaction • Productivity • Profitability • Efficiency • Stability • Sustainability • Equity • Flexibility • Adaptability • Resilience

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_1,

1.1 Introduction and Definitions

Farmers in both developed and developing economies continually seek and apply solutions to particular problems and challenges confronting them. These problems include climatic variability and climate change; soil degradation; pests, diseases and weeds; increasing costs and market instability or access. In rainfed farming, rainfall uncertainty and the risk of soil moisture deficits are continual challenges.

Such matters can rarely be considered in isolation since farmers have to coordinate farm activities and enterprises into a workable whole or ‘system’ to achieve their **goals**. These goals must also be considered together since some may have higher priority, others may be of equal priority, interdependent or conflicting. Thus a farmer’s goals may include a combination of such factors as: increasing food production, maximising profit and achieving stability of income under a variable climate while also improving the soil, conserving fauna and flora and achieving a chosen family/community lifestyle.

Natural systems which are free of significant human impact exhibit many internal relationships. Together these produce a coordinated whole where different plant and animal species compete or complement and eventually balance each other. Unlike farm systems, they are not subject to human management nor produce significant outputs. However, both are reliant on flows of energy as discussed further in the supplement to this chapter.

Managing the whole requires an understanding of how the various parts of the farm ‘system’ can operate together in the context of local climate, soil, available technology, economic opportunities and constraints, family and community expectations and government policies. This ‘workable whole’ may be termed a ‘sustainable system’ if it operates at the required level of productivity and profitability and continues to do so over extended time, while allowing for some modification of the ‘system’ to meet changing circumstances and without degradation of the resource base. Achieving this requires a **Systems Approach**.

Such matters form the theme of this book. It deals with the definition of farm systems, their structure, operation and management, the relationships among internal and external factors, response to changing circumstances, and modifications to deal with change. In this chapter, we shall introduce the systems approach and define many of the concepts used in the book.

Initially we will define a farm system simply as a number of parts that are related by their influence on each other. Figure 1.1 shows a simple example of a farm system with four sub-systems, each comprising a number of components. Any operational unit in agriculture may be defined as a system if it shows an overall response to an influence applied to any part of it. What is done in one part of the system will eventually have consequences that influence the system as a whole. Examples include:

- Restricting the types of crops which can be grown in one field in order to control weeds or diseases will influence the crops and management decisions on other fields and also the overall productivity and profit.

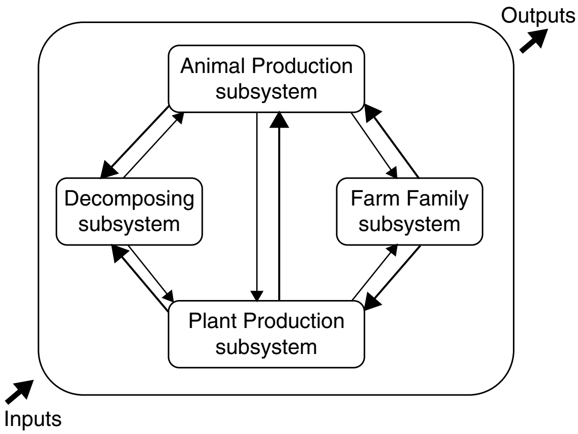

Fig. 1.1 A generalised farm system

- Preferential allocation of resources to a particular enterprise, unit or location on the farm will have consequences in resource allocation and management for all enterprises and locations in the short and longer term.
- Re-sowing pasture on one field will initially place increased grazing pressure on the other pasture fields but decrease it once the improvement is complete.
- In southern Africa, there is in many maize-based systems, competition for early season labour. Early-sown fields need weeding about the time that farmers also wish to sow additional fields. If the labour is used for weeding, less area is sown. If the labour is used for planting, yields in early-sown fields are reduced due to weed competition.

A farm may be regarded as a system if it satisfies the criteria just discussed. It may also be regarded as an **agroecosystem** because it is a collection of organisms (plant, animal and microbial) that inter-relate with each other and with their physical environment and have been modified by humans to produce agricultural products. (see also Chap. 21 – Case Study). When we are dealing with the design of an agricultural system which has been clearly defined and probably analysed and compared with others, we shall talk about a **'farming system'**. When referring specifically to an individual farm, we can also use the term **'farm system'**.

All parts of a farm may not necessarily be considered part of the same system. Thus a piggery or a seed-cleaning plant may be part of a predominantly crop-production farm, but not part of an overall farm system unless there are material flows and feedbacks between these enterprises and the crop production area. For example, livestock housed in a farm feedlot or piggery and fed from farm produce would be considered as being part of a farm system if their manure is returned to the soil that produced the feed or if the finance and labour allocated to the livestock influenced allocation to the cropping areas. In mixed cereal–sheep farming, as in southern Australia, wool production can be considered part of the same farm system as crop production because the sheep and crop inter-relate through their use of the same land. Sheep graze the legume-based pasture and the crop benefits from the legume nitrogen remaining in the soil after the pasture phase. Sheep also benefit from grazing the cereal residues.

To study systems, we must be able to define the **goals** or **objectives** of the system managers. These may be both short-term and long-term, and have financial, technological and personal features. Financial goals may have a high priority, but goals such as maintaining the resource base of soil, water, livestock genetics and natural vegetation will also be important. In developing countries, farm family goals and objectives are often sequential—the first priority is to achieve food grain self-reliance, the second is to seek sources of cash income. The influence of the farm family's goals on the system is further explored in Chap. 12

In order to operate a farm system well, we must also be able to describe its structure, analyse its operation or function and evaluate its performance. The first step is to define its **boundary** which is determined by the purpose of the system; its position is critical for appropriate analysis (Kelly and Bywater 2005). Olsson and Sjöstedt (2004) argue that defining what should be included in the system and what should be left out is the crucial issue in applying a systems approach.

Spedding (1988) also stressed the importance of defining the boundaries of farm systems, as well as the feedback mechanisms which operate within the boundary (See the definition of system near the end of Sect. 1.1). He defines **feedback** as the carrying back of the effects of a process to their source so as to modify those effects (Fig. 1.2). To understand this, consider a flock of sheep grazing an area of pasture (*the source*) within the *boundary* of a fence. A feedback mechanism operates here through the *effect* of the sheep on the pasture by the grazing *process* (eating, trampling, and recycling nutrients). This effect is on the growth, botanical composition and quality of the pasture, which then affect the grazing process, the intake of nutrients and the productivity of the sheep and again the pasture. A feedback may have a positive or negative effect.

In a rainfed situation, and considering available soil moisture as the *source,* for crop growth, provision of ample nitrogen early in the growing season may cause rapid crop growth (*process*) and utilisation of moisture *(effect).* If soil moisture is not replenished by further rain, the feed back effect (to the source) will be depletion of available moisture, with moisture stress and retardation of crop growth at an earlier stage than if nitrogen and available moisture were better balanced.

Feedback effects may occur over a longer time: for example, animals with a high reproductive rate (*source*) will experience high demands for lactation, with resultant high grazing pressure (*process*) and reduced pasture availability (*effect*). This could produce a feedback of lower pasture availability for the animals, resulting in a loss of body condition and hence a lower reproductive rate in the following year (Anderson and White 1991).

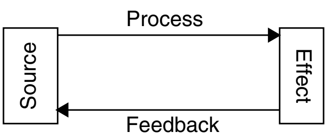

Fig. 1.2 The feedback cycle

Another feedback of long-term significance is related to either soil carbon accumulation (as when there is no tillage and crop and pasture residues are left to accumulate) or carbon depletion (as when soil is cultivated annually and plant residues are removed). Carbon accumulation improves soil structure, water-holding capacity, soil fauna and flora populations, and possibly plant nutrient availability (See Chaps. 6 and 14). These are important components of what may be termed ‘soil health’ (the *source*), which benefits plant production. The lowering of soil carbon (*effect*) by the *processes* of cultivation and residue removal may degrade these attributes of soil health and ultimately reduce plant production.

Having defined the boundaries of a system, we can then specify its **components, structure and function. Components** of a farm system may be located on, above or below the ground and may be plants, animals, micro-organisms, soil components (biological, nutrients, moisture, air), water supply, machines, fences and sheds and other ‘capital’ items. Components may be classed as **resources** if they contribute directly to system productivity. There may be multitudes of components in an ecosystem so, in practice, we should aim to manage those that are likely to have a significant effect on system performance. Farm system **structure** is how the system is organised and is closely related to the **function** of the system. It includes the components and their patterns of organisation as enterprises and rotations. The **operation** of the system includes production and management and the flow of materials, energy, information, labour, machinery, and capital into, out of and within the system, and the annual *calendar of activities*. Farmers usually set **priorities** for their operations, both short-term (even daily) and long-term.

We have to distinguish between component parts of the system and **external factors** or **influences** that act on the system from outside. External factors include climatic features such as solar radiation, rainfall and temperature. These are not originally within the farm system boundary as there is no feedback to them from the farm. Some external factors such as new pests enter the farm system uninvited. Others are introduced purposefully to the system, often at some cost, because they are considered useful for the operation of the system; these include seeds, fertilisers, pesticides, fuel and other materials and are usually termed **inputs**. The combination of system components and external influences can be referred to as **elements** of the system. The elements may be used to characterise or **define a farm system**, to pin-point essential features of management and to enable comparison with other systems (See Chap. 2).

External influences also include such factors as market conditions, legal frameworks, government policies, institutional structures and other social influences, education, availability of various types of technology (such as information, training or equipment), availability of finance, and the appearance of new pests, diseases and weeds. These are part of wider systems that the farmer must deal with. In some societies, organisations which are part of such wider systems include in their operations a *quadruple bottom line* of financial gain, environmental improvement, society welfare or viability, and protection of cultural heritage. More recently, a fifth bottom line has been proposed, food security—a necessity for subsistence farmers or encouraged by governments. These concepts will be developed in Chap. 12.

However, this does not remove the need to understand the physical and biological farm system to ensure its productivity and sustainability.

The **farmer/farm family** may be regarded as an external influence that has an input of labour, finance and management or as an integral part of the system in which feedback mechanisms operate between the farmer/farm family and the biological/physical components in the field. Either of these choices is acceptable, depending on the purpose of the system study or analysis. For some purposes, it is useful to regard the farmer as part of a wider system, interacting both with the farm system and various other family, economic, cultural, social, political, environmental and technological issues. Particular goals of the farmer and farm family will also affect the way the system is operated, and these may include features such as family wellbeing and environmental values. Advice from farm consultants and researchers could also be considered an input. Members of farm families may support the farm by off-farm work or contracting, thus providing an 'input' of capital.

There may be an interactive relationship between researchers, advisers/consultants and farmers. Farmers, researchers and advisers may form a group to initiate, plan and execute research and participate in its application in the management of the farm (See Chaps. 36 and 37). As there is two-directional or multi-directional feedback of information, time and resources for experimentation resulting from these relationships, the organisation could be regarded in part as a component of the farm systems.

The outcomes of supplying inputs and of operating the farm system are the **products**. In subsistence agriculture, the farm family largely consumes these. Commercial agriculture has sometimes tended towards the subsistence type in periods of great economic difficulty (due to drought or economic depression). However, on the whole, the aim is to sell products outside the system. Such products can be termed **outputs** of the system. They represent a loss to the system of mineral elements that may have to be replaced by inputs from external sources. This is in contrast to natural ecosystems where nutrients are usually **recycled** within the system. An agricultural system is often described as an **open system**. In some systems, crop and pasture residues and animals manures have been regarded either as wastes or products that are removed for use elsewhere (see Chaps. 2, 15, 16, 22 and 38). In other systems residues and manures are retained to recycle some of the carbon and nutrients they contain, as well as to improve other aspects of soil health (see Chaps. 26, 33, 34 39 and 40).

Interactions are important in farm systems. **Interaction** occurs when the effect of one factor varies with the level or strength of another factor. A commonly encountered interaction is that between two types of plant nutrients (usually applied as mineral fertilisers), e.g. a phosphorus (P) x nitrogen (N) interaction. Figure 1.3 shows the interaction by means of two response lines with different rates of P application.

A further example would be the way the relative yielding ability of crop varieties (genotypes) varies with some seasonal variable such as rainfall; one variety may be more favoured than others in a high-rainfall year, but perform relatively poorly in a low-rainfall year. This is further complicated by the interaction with time of planting. For example, the choice of the most appropriate variety may depend on the ability

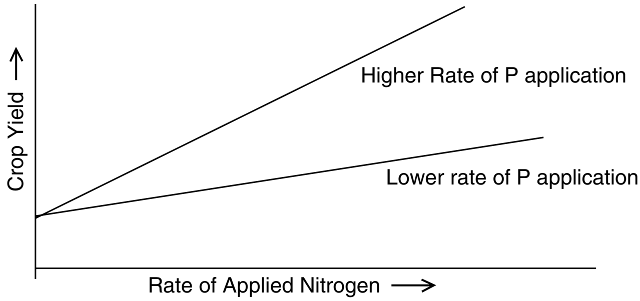

Fig. 1.3 Response of crop to nitrogen at two levels of phosphorus application

of the farmer to plant a crop at a particular time. The best results from early planting will come from varieties which grow and develop over a longer rainfall season whereas, with late plantings, an early-flowering variety may be better. This is an interaction of maturity type and time of planting. Selection of variety is also influenced by the expected amount of rainfall in the growing season so that a variety x rainfall x planting date interaction is important. Even more complicated interactions may occur when choice of variety or crop species is influenced by other factors such as soil type and frost incidence at different locations on the farm, or the susceptibility of varieties to diseases and pests.

Interactions become particularly important when they relate to the operation and management of farm systems. Both farmers and researchers need to be aware that the outcome of applying an input or management factor may vary not only with the level of that factor but also with the level of a second factor, or more. All relevant factors must be at appropriate levels to gain desired results. An example of this is where the response to one nutrient increases when other nutrient deficiencies are corrected (as in Fig. 1.3), provided rainfall is adequate for a full response.

Keeping in mind the definitions of previous pages, the following modification of a definition of a system by Spedding (1988) is a useful guide adopted in this book:

> A system is a group of interacting components, capable of reacting as a whole to external stimuli applied to one or more components and having a specified boundary based on the inclusion of all significant feedbacks.

Underlying this definition is the understanding that what happens to one part or component of the system will have ramifications (large or small) for other parts, even if the effects are delayed. Thus defining the boundaries and significant components of the system is important in its operation and management.

Because of the various feedbacks and interactions in a farm system, it is not always possible to study the system as a whole. It is sometimes necessary to reduce it to its components or at least its **sub-systems** and study them separately. We could study the effects of different tillage methods on crop establishment and production in a small plot of ground. Aspects of animal nutrition could be studied with animals in a pen. Weed control methods may be compared in small plots, and so on.

In this way, we should learn something about each aspect of production, but very little about how various factors operate when they are all ‘thrown in’ together, inter-relate and participate in feedback loops. To study a farm system, it is necessary at some stage to see it all in operation as a whole, to see how the various factors act on each other. Some factors may be more important than others, and their relative importance can only be seen when they are acting together. In this book, we shall study farming systems as a whole as far as possible, while also analysing them and studying important aspects separately where that helps in the understanding of principles.

1.2 Understanding Farm Systems Through Analysis and the Study of Sub-Systems

Analysing a system helps towards our understanding of how the parts relate to the whole, and to its major or **central output(s)**. This is useful if it helps in specifying significant inputs and outputs and the relationships between factors which determine the outputs. Defining a **sub-system** helps in studying the effect of part of the system on the central output. This is often necessary because of the complexity of the whole system. One simple but useful tool for achieving both aims is the ‘circular diagram’ of Spedding (1988).

The method starts analytically with placing in the centre of the diagram an **output of central interest**, e.g. crop production, livestock production or income. The major factors thought to influence this output are then grouped in a ring about this centre, with appropriate arrows pointing inwards. However, there may also be effects of these factors on each other, in the same ring, and arrows travelling around the circle indicate these. All factors on this ring are in turn controlled or influenced by ‘secondary factors’ which can be arranged in a second, outer ring, with arrows used as before. A decision needs to be made, based on available knowledge, as to what are **major determinants** of the central output. These are included while others may be left out. A third ring or even more may be added, providing a further expansion of the **analysis** and, it may be expected, a better grasp of the whole system for its management. Information in any one ring provides an analytical understanding of the factors connected to it in the next inner ring. Construction of the diagram and its use over time may reveal deficiencies in knowledge of relationships that will need to be investigated.

The use of circular diagrams is illustrated in Figs. 1.4 and 1.5. The first provides an analysis of production from an annual pasture legume used in a crop–pasture rotation in the Mediterranean-type environment of South Australia. The second is for a simplified cereal–pasture–livestock system in a similar climatic environment in the Kingdom of Jordan. The latter system has three major outputs, with major influencing factors and components in outer rings. Influences also operate across the three major groups, as shown by connecting arrows. For maximum value to management, the inputs, outputs and relationships should be quantified in various ways. However, even with minimal quantification, construction of the diagram allows us to express our understanding of system structure and important relationships.

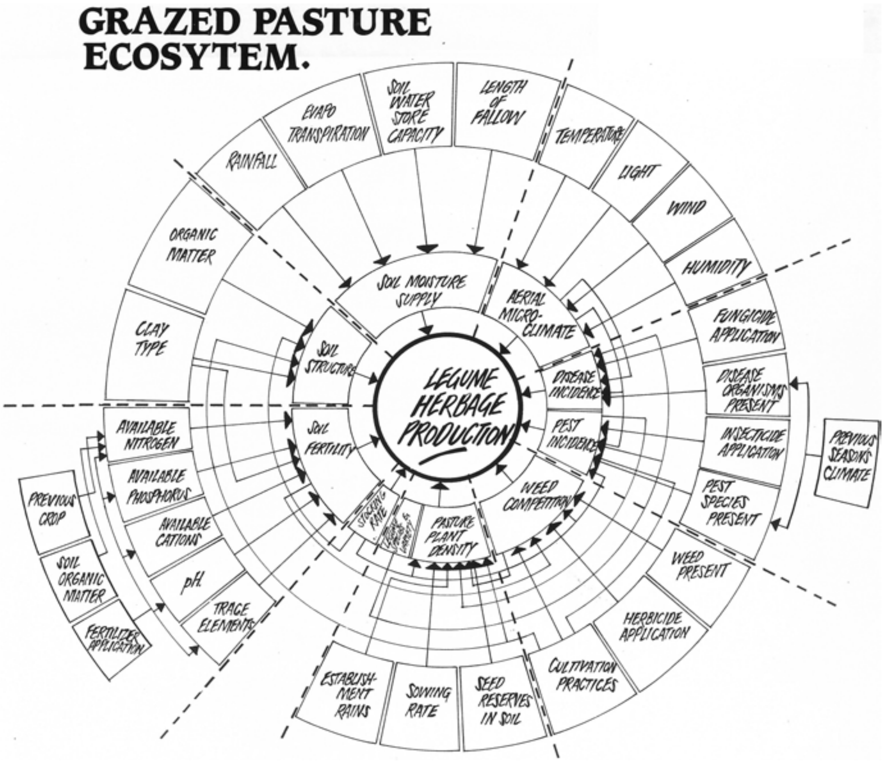

Fig. 1.4 Factors affecting the production of annual legume herbage (Tow unpublished)

The diagram also provides a means of defining sub-systems for special study, and of breaking down the complexity of the whole system. A **sub-system** can be specifically described as being concerned with the effects on the central output of changes in one component of the system. The sub-system then consists of the centre, a component in one of the rings and all of the factors that are linked between the two. Spedding suggests thinking of parts of a sub-system as if wires link them so that the sub-system can be lifted out of the whole for study on its own. In this way, only those factors in the system that influence the way in which the selected component affects the centre will be included.

In the Legume Herbage Production diagram (Fig. 1.4), it is seen that the 'stocking rate' affects herbage production directly and also through its effects on soil fertility, pasture plant density, weed competition and pest incidence. The 'cultivation practices' factor affects herbage production directly and also through its effects on weed population, pasture plant density, soil structure and pest incidence (when cultivation maintains the soil surface in a form unattractive to certain insects). In contrast, the 'soil moisture' sub-system is depicted as being simple, with no connections to Legume Herbage Production via other factors. This indicates that the study of this sub-system

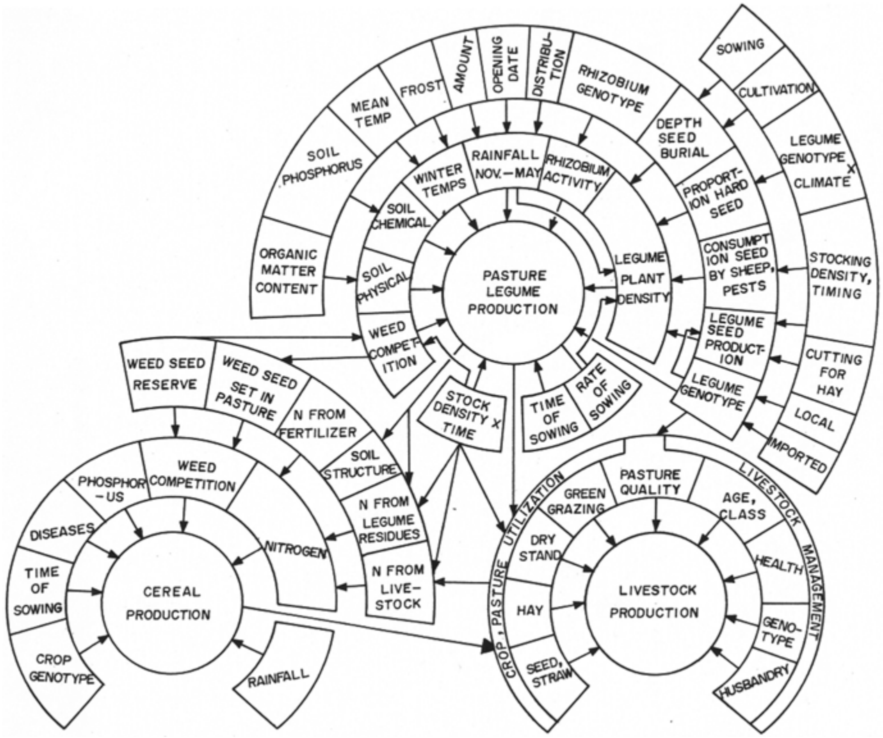

Fig. 1.5 A simplified whole cereal–pasture–livestock system (Tow and McArthur 1988)

would involve measurement of only soil moisture and herbage production. It could also indicate that the diagram needs to be re-considered, for example, if there is an interaction between water supply and weed competition.

The circular diagram will be useful if it involves the system manager or scientist in searching for information, examining it critically and systematically, and then using it to help modify the farm system to better achieve goals.

Another tool for analysing systems is the **Problem-Cause or Cause-Effect** diagram (Fig. 1.6 Tripp 1991). It helps to determine and display the likely causes of problems and to identify intervention points for solving these through technology or policy change. A similar tool has been described by Pearson and Ison (1997) showing how various problems are linked.

1.3 Systems Approaches

Farm situations may lead to a variety of 'systems' approaches. Where there is a declared objective that is agreed as desirable, a **hard-systems** methodology (HSM) is often called for. The analyst works back from the objective and endeavours to

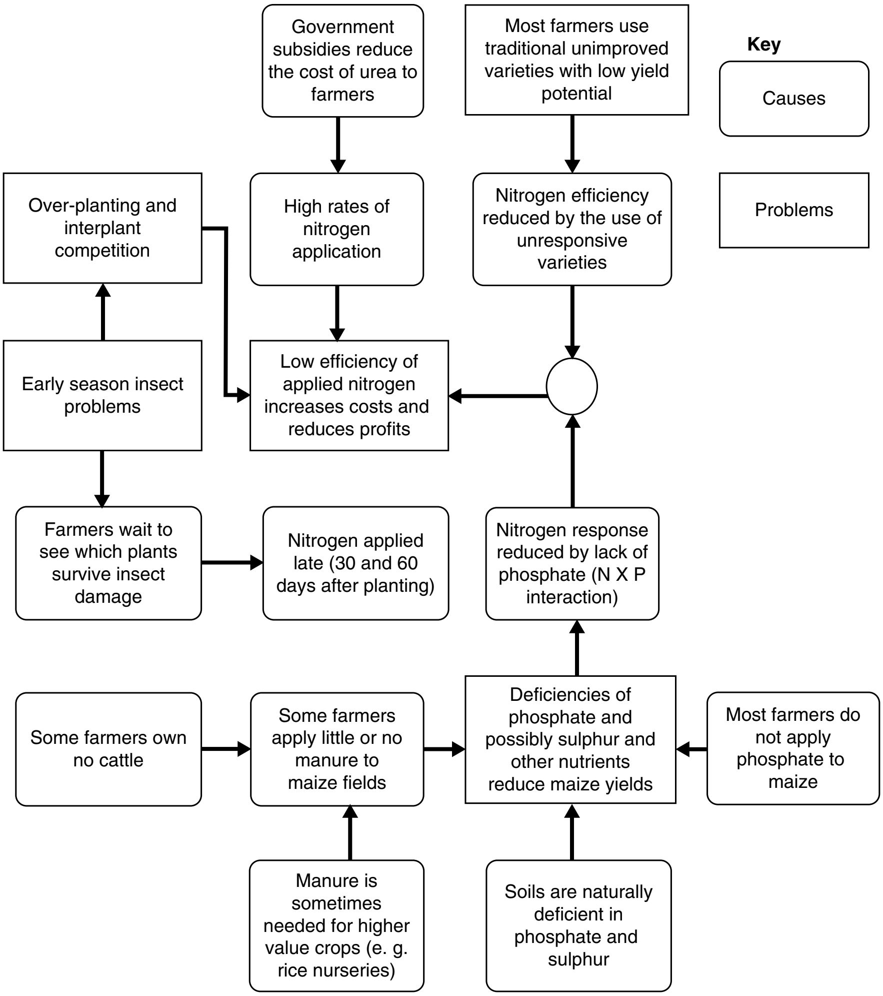

Fig. 1.6 Example of Problem Cause Diagram 'Hypotheses on the problems and causes associated with soil fertility management in maize in Indonesia' (Tripp 1991)

create a system or solution that will achieve it, A unique or optimal solution is desired and this is suitable for problems that are well-defined, well-structured and quantifiable.

Many situations are not well defined and there may be different views on the problem. These call for a **soft-systems** methodology (SSM). This is a structured way of approaching poorly structured problems; it starts with a situation where there is a sense of unease. It involves finding out about the situation and taking action within it by doing some careful, formally organised systems thinking about it. (Kelly and Bywater 2005).

Some authors (Schiere et al. 2004) introduce uncertainty into the analysis and move to what they term **complex system methodology** (CSM). A characterisation of a complex system from a CSM point of view would be:

> A complex system has innumerable emergent properties[1], boundaries that are hard or even impossible to define, and relations and characteristics that are open to an infinite number of different interpretations.

The approach taken depends on the system being studied. Soft or complex system approaches provide more flexibility than the hard-systems approach. The process of resolving a complex problem may be of equal or even greater value than the solution itself. For example, gaining an understanding of staff or family feelings about the issue may be important.

1.4 Purpose, Structure and Characteristics of Farm Systems

1.4.1 Purpose

Natural systems contain many organisms that may operate together in a dynamic balance for the efficient and sustainable use of natural resources. These organisms complement each other, for example in their ability to use different climatic or micro-climatic conditions, to benefit from the residues and wastes of other organisms, to assist each other symbiotically and to develop habitats which favours particular flora and fauna. Natural systems have a quality of permanency while, at the same time, they have the capacity to adjust to environmental change and internal disturbance.

Farm systems are developed to achieve farmer goals within the potentials and limits of climate, soil, technology, social structure, economics and markets. Apart from productivity and profitability they also need to contain qualities akin to the permanence and adaptability to change of natural systems as discussed later in this section. Some of the features of rainfed farming systems include:

- Crop and crop-pasture rotations and management practices can be developed to assist in control of diseases, pests and weeds (See Chaps. 8–10).
- Components may complement each other (perhaps with positive interactions and feedbacks) for more efficient year-round use of resources such as finance, time, labour, machinery and markets.
- Components may operate together for mutual benefit (**symbiosis**), as with the legume–rhizobium bacteria symbiosis (See Chap. 6).
- Components may have synergistic (complementary) relationships. For example, there are **synergies** of livestock with crops and pastures when the livestock grow

[1] Properties that arise out of a multiplicity of relatively simple interactions.

by consuming stubble, fallen grain and pasture, while crops benefit when pasture legumes add N to the soil and when livestock eat weeds and recycle nutrients in dung and urine (See Chap. 11).

More efficient response to the environment is possible along with overall improved productivity, flexibility and sustainability. These terms will be discussed in more detail later in this chapter.

Other advantages of a particular system could be efficient, year-round use of resources such as capital, machinery, buildings, time and labour, responding to influences such as market opportunities and the particular skills of farmers. From the biological point of view, systems may be developed to improve productivity by helping to control plant or animal diseases or weeds, to convert crop residues or weeds to animal products and manure, or to supply nitrogen by means of legumes.

1.4.2 Designing the System

The most obvious strategy in system design is the adoption of enterprises that are suited to the environment. Crops can be divided broadly into tropical, sub–tropical, Mediterranean and temperate types according to their temperature requirements. Without irrigation, the crops that can be grown are usually restricted to those adapted to the temperature conditions during the rainfall season, as well as to the length and other characteristics of the rainfall season itself. The system designed around these crops may require preparations and operations that facilitate optimal utilisation of fairly short periods of favourable temperature as in temperate areas, or of favourable soil moisture as in areas with Mediterranean climates and the semi-arid tropics as in northern Australia, eastern Africa and parts of India (See also Chap. 13 concerning design of farming systems).

When soil conditions vary widely within a farm (e.g. from sand to heavy clay), separate systems involving different soil management procedures, crop and pasture species, livestock use and rotations may be required for each. Partial integration may be achieved through the movement of livestock over all soil types.

In all systems, a particular set of conditions including structure, operation and management is required in order to achieve and maintain the desired productivity, economic and lifestyle objectives. These conditions are modified or **evolve** over time in order to meet new challenges and problems. Flexibility in a system is thus also important where adaptations are needed to suit changing circumstances. Examples of such evolution are described in Chap. 2, in Part II and in several other chapters in later Parts of this book.

Having discussed the overall purpose of developing a system, we now examine characteristics that apply in greater or lesser degree to all farming systems. Conway (1985, 1991) has suggested four important characteristics of systems: productivity, stability, sustainability and (in relation to the whole community) equity. Others should also be added for farming systems, for example profitability, flexibility, efficiency and resilience.

1.4.3 Productivity and Profitability

Productivity may be defined as the amount of product for a given set of resources. In rainfed farming the achievable level of productivity is determined ultimately by the amount and distribution of rainfall. While farmers cannot change rainfall, they can manage their response to it (see later in this chapter, Chaps. 3 and 4) They also have some control over the other resources. For instance, soil conditions, which are declining in many parts of the world, can be improved through managing organic matter, nutrient deficiencies, soil structure and erosion (see Chaps. 5, 6, 14, 33, 34, 39 and 40). Other factors important in determining productivity include the genotypes of the crops, pastures and livestock (well **adapted** to the local environment); protection against weeds, pests and diseases (see Chaps. 8–10); available labour and/or farm machinery; and the level of management expertise (as discussed throughout this book).

Increased productivity does not necessarily lead to increased **profitability**; profit is determined by the difference between the value of outputs and the cost of inputs to the producer. Further, value of products is also determined by their **quality**. For example, premiums may be paid for wheat suitable for particular purpose such as pasta production. High **feeding value** of grazed pasture (simplified as *nutritive value x voluntary intake*) is of paramount importance in achieving profitable livestock production.

There are also economic and sociological constraints and factors related to government policies, such as farm subsidies. Furthermore, there may be social costs (externalities) that make increased productivity detrimental to society as a whole (See Chaps. 12 and 30).

1.4.4 Stability

In farming, **stability** generally refers to a situation of minimal fluctuation from year to year. While it may be defined simply as ‘consistency of production’, from the farmer’s point of view we should add ‘consistency of income’. In terms of production, if the variation in yield over years has a normal distribution, the *Coefficient of Variation* (CV) (Standard Deviation/Mean) is a useful measure. A large CV represents a wide distribution of yield relative to the mean—low stability—and vice versa. Income stability can also be defined as the frequency over many years of those outcomes that lead to unacceptably low income.

Sources of instability in production and profitability include:

- climate variability—amount and distribution of rainfall; drought; spasmodic occurrence of hail; late season frost; rain at harvest.
- incidence of diseases and pests, with new ones appearing from time to time.
- fluctuation in prices received for outputs and paid for inputs, which affects profitability.

These sources of variation occur in spite of the stabilising influences of improved cultivars and farming practices.

Some degree of instability can be tolerated, especially if its causes and magnitude can be predicted and something can be done to lessen the impact. Examples of the latter include:

- Use of climate forecasts that predict low seasonal rainfall, to avoid wasteful expenditure on fertiliser
- Use of forward contracts to avoid price instability.

However, a more serious situation occurs when a large downturn in productivity, as caused by drought, coincides with or is followed by a serious economic downturn, especially if the combined downturn lasts a few years.

Minimising income fluctuation is generally regarded as a desirable goal. Some governments assist by providing subsidies and other types of financial assistance, research support and advisory services. Farmers attempt to achieve stability through **diversification** of crops and enterprises on the farm, supplementary irrigation where water is available, off-farm work or investments, and use of 'futures' in marketing.[2] Some of these methods may require special knowledge and expertise in management with risks that may outweigh the potential benefits.

Diversification may help make more efficient use of time, labour and machinery through the year. In south Asia, farmers may use staggered crop planting dates and crop mixtures to prepare for unknown rainfall distribution and amount. In southern Africa, livestock sales are used to stabilise income when drought leads to crop failure. In Australia, many farmers aim to accumulate funds in off-farm investments to buffer against downturns in income. Farmers may also achieve greater stability by **specialisation** into enterprises which require special skill, where high quality can be achieved or where value can be added to the original product. Examples of such specialisation within a rainfed farming system are seed production, high-quality hay production for sale and production of crops such as herbs, medicinal plants or native flowers for special markets. Examples of specialised livestock enterprises include poultry, deer, goats and alpacas.

1.4.5 Sustainability

Doubts have been raised about the capacity of agriculture to continue to meet production demands indefinitely. Challenges include:

- The need for higher levels of food production for an increasing world population and increased competition for the limited arable land by urbanisation.

[2] See Glossary and Chap. 12.

- Environmental pollution from the use of agricultural chemicals, e.g. toxic residues of pesticides in soil, waterways and foodstuffs, contamination of waterways with soluble fertilisers.
- Development of resistance of insects to pesticides, diseases to fungicides and bactericides, and weeds to herbicides.
- Increasing cost of energy, leading to increasing cost of agricultural inputs.
- Increasing problems of soil erosion, acidity, salinity, structural breakdown and other forms of soil degradation, with costly amelioration usually necessitating government support.
- A rapidly unfolding water crisis. In rainfed agriculture, this may be experienced as lower seasonal rainfall, increasing frequency of drought and less water for supplementary irrigation.

A key question is whether these challenges can be met while conserving the resource base (soil, water, genetic resources) and satisfying the many and varied requirements of farm families and the wider community—this requires a sustainable system. *In agricultural business terms, and at the level of the individual farm, sustainability refers to operating a farm profitably over the long term without loss of or damage to the resource base.* The farm is unlikely to remain profitable over the long term if the resource base is not maintained or improved.

There are many definitions of sustainability. Resource managers refer to sustainability as the maximum harvesting of forests or fisheries consistent with the maintenance of a constantly renewable stock. A hunter–gatherer system also operates on the same principle since removal of produce for human use is likely to occur at a rate which will allow replacement by plant and animal reproduction. The same concept applies to the optimal use of a groundwater aquifer. In such examples, sustainability is the steady state at which what is being removed is continually replaced.

In agriculture, this definition also seems to apply to such processes as removal of soil nutrients by crops and their replacement by fertiliser, or germination of seed reserves in the soil of annual pasture legumes to produce a pasture and their replacement when the legume produces seed at the end of the season. However, sustaining agricultural resources and production is complex because of the many feedback mechanisms and interactions generated through production processes.

The term **'resource base'** refers particularly to the soil, which should be protected from erosion, salination, acidification, structural breakdown, compaction and fertility decline. In a broader sense, however, the resource base can include native vegetation used for shelter, beautification, bird life or grazing; surface or underground water supplies and water table control; pasture seed reserves and high-quality livestock genetic resources.

Even if productivity can be sustained without damage to the resource base, input costs may become so high that profitability cannot be sustained. New, relatively low-cost or high-return enterprises may have to be found to maintain overall profitability, for example farm tourism or commercialisation of native flora. The farmer needs to be able to foresee trends towards unsustainability and to make adjustments early while containing costs. A number of production-based or environmentally-based **indicators** have been produced and need to be monitored as part of management (See Chap. 27).

In the range of farming systems described in Chap. 2, the managers of low-input systems may need to increase inputs to achieve sustainability. In contrast, high-input system managers may need to reduce inputs (especially chemical inputs) so as to reduce (a) costs and (b) the risk of toxic chemical residues in the atmosphere, plants, soil or ground water. This approach implies the need to use ecological means to control pests, diseases and weeds; some examples will be given in this book (Chaps. 6, 8–10).

The term ‘sustainable agriculture’ has been defined in a bewildering number of ways, as summarised by Reeve (1990) and Malkina-Pykh and Pykh (2003). Reeve exposes a vast array of presuppositions, biases and untested solutions. In general, the concept involves improving rather than degrading resources, be they environmental, financial, human or social, and handing on resources to the next generation in good condition. Since agriculture operates in a constantly changing environment, it is a goal to be continually worked towards rather than an end point.

Malkina-Pykh and Pykh (2003) quote from a number of earlier authors and agree that sustainable agriculture involves satisfying the requirements of (1) farmers/farm families for income and a satisfying way of life; (2) the environment (soil, water, landscape); and (3) society (farm families and society being interdependent in a number of ways). Sustainable agriculture is also dependent on “helpful government policies to promote environmental health, economic profitability and social and economic equity” (See also Chaps. 2 and 13).

These authors argue therefore that a ‘**systems perspective’** is essential to understanding sustainability. Achieving this will sometimes involve the farm ecosystem, sometimes the wider system which includes society and government and even the global system which includes world markets, climate change, information and communication. They explain that a systems perspective provides an understanding of relationships, both among system components and between these and external influences. It can provide a clear view of the **consequences** of the various interactions and feedbacks (See also Chap. 21). Yet they conclude that “the work required to ensure agricultural sustainability, although influenced to some extent by outside forces, is mainly field or farm specific”. They suggest the need for **whole farm planning** which goes beyond economics of the farm business to matters of ecological sustainability and quality of life. Again, this requires a systems perspective—spatially and temporally.

Experience shows that continual adjustments need to be made to the design or ‘makeup’ and operation of systems in order to adapt to changes imposed on or adopted by the farmer. It is suggested that a farming system which could be called sustainable would not need to remain fixed or static, but rather would adapt readily to changing circumstances so as to continue providing for the requirements of farmers, environment and society. It would maintain the properties of high productivity, profitability and stability of income, already discussed, as well as equity, flexibility, efficiency and resilience—yet to be discussed.

Every country has examples of farming systems which have changed or evolved over time in response to changing circumstances. South Australian rainfed farming systems constitute an example of changes from the time of initial agricultural development in the mid-nineteenth century to the present day. Cereal farming (wheat and barley for grain and oats for hay) was the main rainfed farming system in South Australia in the early decades after European settlement. A cereal–fallow rotation was generally adopted. Livestock were also included—horses for traction, cows for milk and cream production, sheep, pigs and poultry for wool, meat and eggs. This cereal system broke down in the low-rainfall areas in the north of the state in the 1880s because climatic patterns were poorly understood and the temporary run of good seasons ceased. This was in spite of the fact that a boundary had been skilfully mapped by Surveyor-General Goyder (Meinig 1962) on the basis of the distribution of semi-arid and arid native vegetation types.

The cereal–fallow system again almost broke down in the late nineteenth century because of soil phosphorus deficiencies until superphosphate was introduced. Further adjustments to the cereal-fallow system were needed as soil fertility and structure declined and severe soil erosion occurred, in the 1920s and 1930s. After World War II, the remedy adopted to increase profitability and stability was the 'Ley Farming System', in which cereals were grown in rotation with pastures of mainly annual legumes grazed by sheep (in place of cereal–fallow), and with pulses such as peas (See also Puckridge and French 1983 and Chap. 26, Tow 1991).

'**Sustainable agriculture'** is achieved through a set of desirable goals or objectives for agricultural systems. It involves (1) managing the land for a healthy ecological balance, (2) a sensitivity to land capabilities, (3) using technologies and practices which have minimal adverse impact on the system while maintaining production and economic viability. A sustainable Farming System will have qualities of equity, flexibility, adaptability, resilience and efficiency to enable it to maintain productivity, economic viability and the resource base, in the face of changing circumstances.

1.4.6 Equity

Equity involves all the stakeholders in the system being treated equally and justly. Equity issues are often driven by access to resources of land and water. Equity issues also arise from externalities—inappropriate cultivation can lead to wind or water erosion affecting neighbouring farms and communities, and spraying crops may result in drift of herbicides.

When a new variety, chemical or practice is developed, those farmers who are quick to adopt it and benefit from improved productivity can take advantage of initially lower competition and higher prices. This may be regarded as a fair result of free enterprise and the superior skill and management of the successful farmers; thus it would not be regarded as inequitable. However, a government agency providing assistance for a new practice that was suited for adoption on only some farms would be inequitable. Another example could be the systematic bias in plant varietal development towards the circumstances of a small group of favoured producers. Conversely, varietal development by a commercial company could favour a large group of farmers from whom there would be a large demand for seed, leaving a smaller group with different requirements unserviced. Crop and pasture cultivars that grow well under a wide range of climatic and soil conditions are highly appreciated by all agriculturists.

1.4.7 Flexibility and Adaptability

In market-oriented agriculture, farmers see the need for flexibility to be able to change their crop species or livestock class or rotation sequence in order to take advantage of market prices. This can only be done within the constraints of available resources (climate, soil, machinery, physical structures, available seed supplies, technical services, labour and finance).

The farmer must also be flexible in attitude and capability, this being enhanced by education as well as experience. Improved profitability leads to improved financial flexibility. Mutual support within farmer groups can also be productive. The way climate risk and its management affect the capacity for flexibility is discussed in Chap. 3. Here we must consider the particular characteristic of 'Adaptability' in a system that makes flexibility possible.

According to Marten (1988), an adaptable system is one that "can respond to opportunities for improving production"—presumably without permanent detriment to the ecological function. He suggests using a '*Corrective Feedback Loop*' to return an agroecosystem to 'satisfactory limits' after temporary changes have been made. The method largely involves monitoring key indicators or determinants of performance, and applying corrective action where necessary.

His example is a decline in soil fertility due to reduced organic matter and increasing erosion. The corrective action is to add greater amounts of organic matter, sufficient of which must be left on the surface to prevent erosion. This is what is claimed to be achieved by **Conservation Agriculture** and **no-till farming**, when crop stubble is left on the surface and gradually mixes with the soil. For the feedback loop to function effectively, four components are proposed:

- A point of reference with regard to the condition or functioning of an agroecosystem (for example, an acceptable range of soil fertility or crop yields).
- Measures of how the agroecosystem is functioning—such as periodic assessment of soil fertility, incidence of diseases controlled by management and yield data.
- A comparison of the assessment with the reference point.
- Measures for corrective action must be compatible with the overall aims and functioning of the system.

Many **crop-monitoring** groups comprising farmers and advisers have been formed and have been provided with aids and guides to assessing crop health and system sustainability (See Chap. 27). Individual farmers also monitor their crops and soils using precision agriculture equipment (see Chaps. 4 and 34).

1.4.8 Resilience

Resilience is a property that is similar to adaptability as defined by Marten (1988). The term is also used in rangeland and pasture ecology to refer to a capacity to adapt to external change by a change in botanical composition that is still within the requirements of the manager. It may also refer to the ability of valuable plants to recover following harsh treatment such as heavy grazing or drought (See also Chap. 3).

In rainfed farming systems, resilience may be used to describe the ability of components of the system to recover from drought or soil degradation. It may also refer to the ability of the whole system to be changed temporarily to fit in with changing conditions (e.g. an economic downturn), and later to revert to the original structure when conditions suit. A good example of this is the ability of farmers in southern Australia to change from a mixed crop–livestock system structure to continuous cropping as economic conditions dictate, and then to return to mixed farming again when livestock become more profitable (See Chap. 26). Requisites for resilience in this case include the availability of well-adapted crop and pasture cultivars, availability of fencing (permanent or temporary), structures for watering and care of livestock, appropriate knowledge and experience and suitable marketing arrangements.

The stability of soil biota communities is important for their continued functional capability when exposed to different external stresses (see also Chap. 6). Stability depends on both **resistance**—ability to withstand disturbance and **resilience**—the ability to recover after the disturbance (Fig. 1.7, where resistance refers to the level of decline in ecosystem function and resilience indicates the amount of recovery).

Knowledge of a soil's resilience assists in the development of systems or practices that promote the recovery of degraded soils. Measurement of resilience involves quantifying short-term changes in specific biological properties (such as measures of the activity, diversity and population levels of soil biota) following an exposure to disturbance or stresses, such as chemical applications and wet-dry or freeze-thaw cycles. For example in southern Australian rainfed soils, biological resilience (expressed as changes in microbial activity) was found to be lower in fallow–crop rotations than under continuous cropping (Fig. 1.8). Soil biota under fallow–crop rotations generally experience boom-bust cycles for C availability. The depletion of carbon-rich microsites affects the distribution, diversity and metabolic status of microbial communities and reduces the overall biological resilience. Legume crops in these environments provide lower inputs of C compared to those provided by wheat crops. In addition, higher N content in the legume residues results in faster degradation and depletion of C-rich microsites.

In lower fertility soils, it is critical that a regular addition of carbon sources occurs to maintain the functional capability of the biota.

1.4.9 Efficiency

A major difference between agricultural systems and natural systems is that, in the former, many of the useful products of biological transformations within the system

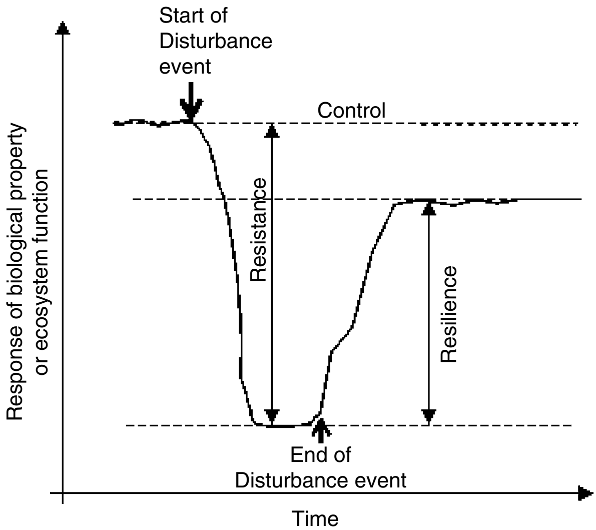

Fig. 1.7 Stability of soil biotic communities – resistance and resilience (based on Herrick 2000 and Griffith et al., 2004)

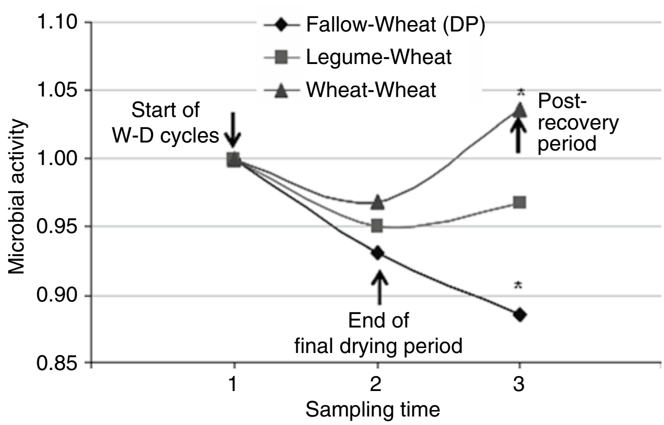

Fig. 1.8 Microbial activity resilience responses to wet-dry cycles – after 6 years of three farming system practices (rotations and associated tillage practices) at Kerribee, NSW, Australia. Values normalised using data from samples that were not exposed to stress events (Gupta, V.V.S.R., CSIRO, unpublished)

are removed. This directed production and removal necessitates continued input of materials and energy over and above natural rainfall and solar radiation. These inputs include labour, machinery, fuel, seed, fertilisers, pesticides and medicines for livestock. Almost all resources for farming are limited by availability or cost, and so must be used efficiently.

The difference in value between inputs and outputs (*profitability*) is usually the final point of interest, often expressed as a percentage of value of the assets employed. However, it is also important to determine the ratio of inputs to outputs (*efficiency*) and to correct serious inefficiencies. In practice, it is usually impossible for all enterprises or units on the farm to be highly efficient (and profitable) at all times, or even at one time. In broad terms, the aim is to maximise efficiency of utilisation of resources as a whole, but this may be limited by the constraints and risks within which the manager must work. Thus it is not usually considered that immediate financial efficiency must be maximised because that may impose undesirable demands on the farmer's time and energy and the resources of soil, livestock or pastures. It may also increase risk. In the long term, the farmer who conserves valuable resources adequately may prove to be the most viable financially.

In dealing with efficiency, we should determine:

- The efficiency with which each resource is used.
- The effect of change in one component of the system on the overall efficiency of the whole system.
- Appropriate output/input ratios, for example yield per unit of land, labour, fertiliser, solar radiation, support energy, cash input or rainfall.

The better the functioning of the system is understood, the better the manager can determine how to improve efficiency or determine how efficiency would be altered by modifications to system structure or management. One type of factor to consider is the situation where the efficiency of use of one resource is dependent on the level of supply of another resource, i.e. there is a positive interaction. Further, the most limiting resources are likely to be used most efficiently when others are in plentiful supply. This principle was promoted by Liebscher in the nineteen century as the **Law of the Optimum** (a modification of **Leibig's Law of the Minimum**).[3]

It has been investigated and confirmed by de Wit (1992) with respect to agricultural yield. Liebscher's Law states that "a production factor which is in minimum supply contributes more to production, the closer other production factors are to the optimum". Accordingly, as de Wit stated, no production resource is used less efficiently and most production resources are used more efficiently with increasing yield level due to further optimising of growing conditions.

The example in Fig. 1.9 (presented by de Wit 1992) shows that (1) the response to nitrogen occurred in all types of weather (bad, medium and good), (2) the response to nitrogen increased with improving weather, and (3) the increased production with better weather occurred even at the lower levels of nitrogen availability.

De Wit (1992) presented other examples to illustrate Liebscher's Law. For example, he showed that both the uptake of one nutrient (N or P) and the resultant yield are increased by bringing the level of the second nutrient nearer to optimum.

In situations where certain production resources are in plentiful supply either naturally or by design, there is the possibility that some of these plentiful resources will be surplus and there is thus opportunity for loss and wastage, e.g. sunlight and soil nutrients in dry areas, water in wet areas, herbage supply for livestock in peak growth periods. **Here 'efficiency' refers to using the maximum possible proportion of a given resource for productive purposes and allowing little of it to be lost or wasted**.

[3] See Glossary.

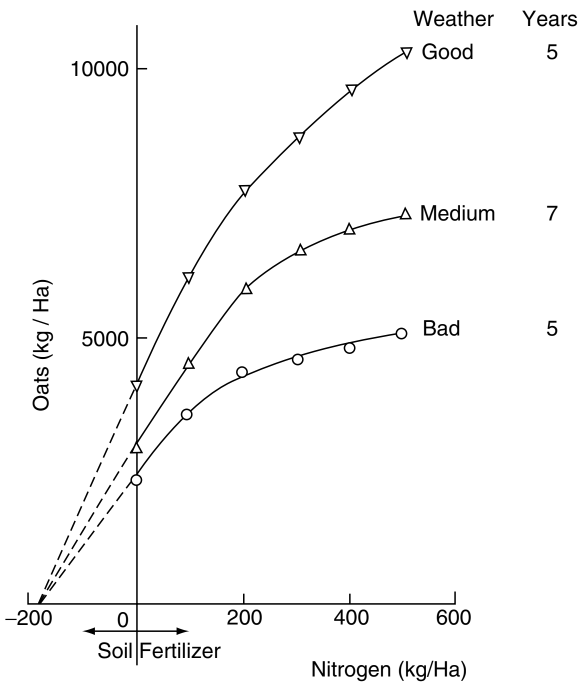

Fig. 1.9 Average nitrogen response curves of wheat for years with relatively good, medium and bad weather for 1925–1940 (Nielsen 1963)

Low efficiency of utilisation of an abundant resource will occur unless the availability of other resources is raised. In rainfed agriculture, efficient utilisation of rainfall is almost always of primary importance, but requires good management to achieve it consistently. For example, rainfall near the start of the growing season can be wasted by poor organisation and delays in land preparation and sowing. Soil compaction or lack of surface protection may result in incomplete infiltration of rainfall and consequent runoff and loss.

An example of this type of 'efficiency' comes from Burkina Faso in the West African Sahel (Roose et al. 1999; Kaboré and Reij 2004). As a result of serious degradation of the land, with a bare, crusted and impermeable soil surface, rainfall runoff was high, and sorghum and millet grain yields as low as 200 kg/ha, in spite of annual rainfall being 400–700 mm. Farmers have developed a labour-intensive but otherwise effective and inexpensive method (the Zaï practice) of both capturing rainfall and building soil fertility, to increase grain yields. Through the dry season, they dig thousands of small planting pits over the fields, to which they add dung and other farm residues. Termites attracted to the organic matter dig galleries below the floor of the pits, which absorb rainfall and runoff quickly and store it deeply. Termite use of organic matter also releases plant nutrients into the pit. Sorghum or millet is sown into the pits where it grows well with the available water and nutrients In some instances, small amounts of N and P nutrients have been added to raise grain yields to about 1,600 kg/ha. The result is food security, with some surplus grain for sale, and even the raising of well water levels. Thus efficiency of rainfall utilisation is raised by perhaps 800%, with many benefits. Thousands of farmers have now used Zaï to reclaim barren, degraded land (See also Chap. 2).

In rainfed agriculture, N and P are often important limiting factors and both must be near their optimum availability in order to maximise yield. The difficulty with this is that below-average rainfall often limits the response to these nutrients. Application of nitrogen, calculated to ensure adequate supply in a year of 'normal' or average rainfall may be uneconomic or even have a negative effect on yield if little rain falls. Some nutrients, such as available phosphorus, that are left unused in a dry year may be conserved for use in a following season, although efficiency of use may be poor. Nitrogen in the organic form can be accumulated as legume residues. This nitrogen tends to be mineralised in proportion to the amount and duration of moisture supply and therefore tends to be conserved in a dry year. Fertiliser nitrogen is less liable to be conserved in the soil in mineral form for future use (See Chaps. 4–6 and 14).

In rainfed farming systems, greater efficiencies of fertiliser and rainfall use are being sought by using seasonal climate forecasts and crop growth monitoring to optimise the time and rate of nitrogen fertiliser application. However, these concepts are yet to be perfected because of the probabilistic, rather than categorical, nature of seasonal climate forecasting (Ash et al. 2007).

1.4.9.1 Efficiency of Utilisation of Energy

In situations where farm labour has become increasingly scarce and expensive, the trend has been to replace the energy of labour by support energy in the form of machines and tractors and their fuel, and by farm implements with increasingly large work capacities. This is understandable when it is realised that, in the 1950–1970 period, oil cost some $1.50 per barrel, which was equivalent to having a person working for 4,000 h for $1.00 (Leach 1976). Thus by using oil to drive agricultural machinery, the efficiency of utilisation of labour has been vastly increased while the efficiency of utilisation of total energy for agricultural production (the amount of product output energy per unit of input energy) has markedly declined. When, in the 1970s, predictions were made that oil would become increasingly scarce and expensive, much research was conducted into energy use and efficiency in agriculture.

Leach has provided estimates of labour energy outputs (MJ per man-hour). The values vary from about five for hunter-gatherers (very similar to the estimate for home gardening) to 11–30 for subsistence farmers, 40–50 for 'semi-industrial' crops in the tropics to 3,000–4,000 MJ per man hour for highly mechanised, 'full-industrial' cereal crops in the UK and USA. However, even in modern, mechanised farming systems, introduction of livestock greatly reduces energy output per man hour and values are less than 200 in totally livestock enterprises. This is because the conversion of input energy to product is much lower for livestock than for crops.

Leach (1976) also provided a comparison of Energy Efficiency Ratios (Er) of edible energy output to energy input. Energy inputs exclude solar energy. The ratios vary from about 25 for pre-industria1 farmers to 1–4 for 'full-industrial' crop production and 0.1–0.4 for modern animal production (the production of human food by feeding grain to livestock is highly energy inefficient). Gifford (1976) studied the energetics of cereal–sheep mixed farms in South Australia. The Efficiency Ratio for digestible energy outputs varied from a mean of 2.1 in a low-rainfall region to 4.1 in a medium-rainfall region. These values contrasted with much lower Er values for more intensive farm systems in Europe, the UK and USA.

Bayliss-Smith (1982) has analysed the energy budgets for a number of other farming systems around the world. He obtained energy ratio values of about 14 for each of three widely different systems:

- A pre-industrial New Guinea system based on crops (root crops, sugar cane, bananas, vegetables) and pigs (acting as a means of conserving the energy from perishable crops and a source of protein) and some hunting/gathering.
- A pre-industrial (1820 s) farm in Wiltshire England based on cereals, ley and permanent pasture and root crops. Horses provided power and manure. Sheep kept on arable land at night transferred nutrients there from down-lands and meadows grazed during the day
- A semi-industrial (1950s) farm in India based on sugar cane (irrigated and fertilised) and subsistence cereals. Bullocks provided power and low nutrient manure.

For comparison, energy budgets were calculated for a modern fully industrial system in Wiltshire and a part-industrialised irrigated system in India in 1975. The energy ratio for a present day, mixed cereal–livestock Wiltshire farm was calculated as 2:1, only one-seventh as efficient as a farm in the same region a century and a half earlier. In the 1975 Indian system, both rice and sugar cane were cash crops, yielding well because of high inputs and high genetic potential. However, bullocks still provided power. The energy ratio was 9.7 (still fairly high, but the farmer had to buy all his food). (Note: current estimates indicate that a farmer in a developed country such as the USA or Australia feeds more than 100 people).

The energy efficiencies of modern conventional and organic farming systems have also been compared (Pimentel et al. 1983), using corn, wheat, potatoes and apples as examples. In the organic system, nutrients were assumed to be supplied by livestock manure, sewage sludge or legumes, and by rock phosphate and glauconite (source of potassium). The substitute technology for herbicide weed control was additional mechanical cultivation and mowing.

The only effective non-chemical control methods for insect pests and diseases were crop rotations and regulated planting time, but only a few problems could be overcome by these means. Of the four crops selected for the analysis, the authors claimed that corn and wheat could be produced with minimal pest problems, whereas both apples and potatoes suffer severe losses from insects and plant pathogens if pesticides are not employed. The same types of tillage and harvesting operations were used in both systems. However, the organic system used more cultivations for weed control and more labour was also required to apply livestock manure or sewage sludge. The energy and labour efficiencies are shown in Table 1.1. Organic corn and wheat production were more energy efficient but less labour efficient than conventional production. Organic apple and potato production were less efficient in terms of both energy and labour, due to ineffectiveness of insect and plant pathogen control measures.

Table 1.1 Comparison of conventional and organic farming systems for the energy and labour efficiencies for four crops (Pimentel et al. 1983)

	Energy ratio (Output: Input)		Labour productivity (kg/h labour)	
Crop	Conventional	Organic	Conventional	Organic
Corn	4.47	7.35–7.6	834	534–583
Wheat	2.38	3.22–3.49	422	217–314
Potatoes	1.28	1.12–1.20	943	295–367
Apples	0.89	0.06	236	12

Note: Values for organic farming vary according to whether N is supplied by manure, sewage sludge or prior crops of alfalfa or soybeans

An alternative, more comprehensive view of measuring and accounting for energy used in production is the concept of emergy. This concept is discussed by the authors of Chap. 21 in a supplement to this Chap. 1.

1.4.9.2 Water Use Efficiency

For the water-limited farming systems dealt with in this book, the efficient use of rainfall is of paramount importance for overall production efficiency. This involves both the efficient capturing of precipitation for use by the crops and the efficient utilisation of the captured water by the plants themselves (see Chap. 4).

Water use by crops and pastures is accompanied by other water movements and changes to soil water content, as set out in the **Water Balance Equation**, $W_2 - W_1 = P - R - D - (Es + T)$, where the change in soil water content from Time 1 to Time 2 (W_2–W_1) equals the precipitation (P which may be rain, snow or dew) less runoff (R), drainage below potential root zone (D) and water lost through **Evapotranspiration** (Es + T, where Es = soil evaporation, loss of water by evaporation from the soil, T = transpiration, water travelling through the plant and out through the leaves).

In brief, the water received by precipitation may be lost in part by runoff and deep drainage, is lost also by evaporation from the soil surface and is used in plant transpiration. Over time, such as a crop growing season, there is usually a resultant change in the soil moisture content. It is important to note that only Transpiration has value in plant production.

An example of a landscape where all components of the equation are operating is shown in Fig. 1.10 (Turner 2004).

All the above ways in which precipitation is distributed can be managed in farm systems, with the aim of achieving efficiency of its utilisation by the crop or pasture, i.e. Water Use Efficiency (WUE). The components of WUE and the ways in which they are related to farming systems are further discussed below.

Transpiration Efficiency

The general definition of Transpiration Efficiency (TE) is Dry Matter production per unit of water transpired. It is an important aspect of WUE which can be

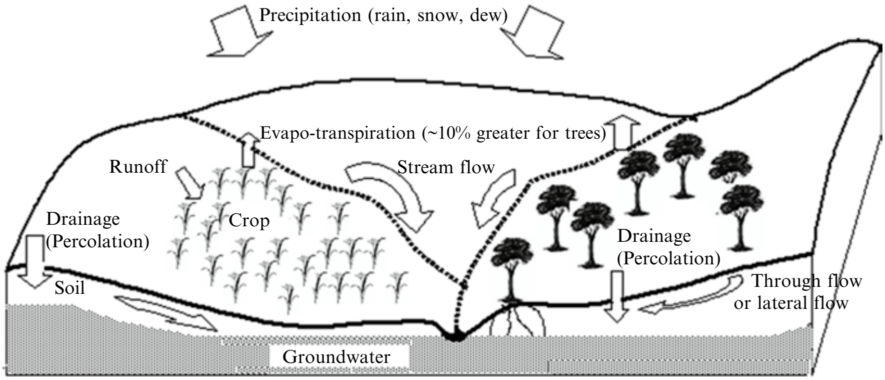

Fig. 1.10 The hydrologic cycle showing surface and subsurface flows. Trees have more evapo-transpiration, less runoff, less drainage and lower groundwater levels

manipulated by plant breeding and management. For this to be done, TE needs to be measured or estimated in appropriate ways, from the level of the leaf to the crop in the field: (i) at the leaf level by measuring gas exchange (CO_2 and water vapour, units g CO_2/g H_2O); (ii) in containers where water use is measured (by weighing) and whole plants are harvested for DM yield (units of kg DM/kgH_2O); and (iii) in the field by calculating from measured or estimated above-ground DM production, rainfall, soil moisture and soil evaporation (units of kg DM/ha/mm transpired).

For instantaneous leaf TE, a figure of 0.03 g CO_2/g H_2O has been quoted (Turner 1986). At this level of measurement, several environmental and plant factors are known to influence TE of leaves including: (a) differences between the saturation vapour pressure of the sub-stomatal cavity and the vapour pressure of air outside; (b) the resistance of stomata to the passage of CO_2 and water vapour; and (c) differences in the mechanisms of metabolism of Carbon by C_3, C_4 and CAM[4] plants.

Cooper et al (1987a, b) simplified the relationships associated with (a) and (b) to provide a simple formula: N/T=k/(es−ea), where N=crop carbon fixation, T=transpiration, k=a crop-specific constant and (es–ea) is the daily mean saturation deficit of the air. The most probable way to increase TE as defined here is to maximise carbon fixation when the humidity is high, i.e. es–ea is small, which is most of the time in humid climates and during the cooler months in a drier Mediterranean-type climate. This in turn has implications for

(continued)

[4] Crassulacean acid metabolism.

(continued)

modifying genetic traits and agronomic aspects of system management, for example, to maximise crop growth while TE is highest (Cooper et al. 1987a, b; Turner and Asseng 2005). Genetic differences in TE have led to breeding of wheat cultivars with high TE. However, such traits have to be matched with specific environments (Turner and Asseng 2005). Turner (1986) quotes a range of TE values of 2.5–6.5 mg DM/g H_2O for wheat cultivars.

The outcome of these differences and others can be detected in the production of whole plants per unit of transpired water if both shoots and roots can be measured. For example, Tow (1967) measured water use and total DM production for tropical plant species grown at 25ºC in nutrient solution in containers sealed against evaporation. Nutrients and water were non-limiting; light intensity was constant but sub-optimal. The results illustrated the difference in TE between the C_4 tropical grass (4.9 mg DM/g H_20) and the C_3 tropical legume (2.7 mg DM/g H_20) grown under the same conditions.

Experimental techniques have been devised to determine Es and T separately in the field (Cooper et al. 1983). Es is reduced by shading of the soil surface by the crop canopy; shading increases with crop growth or denser planting. Seasonal Es values ranging from 60 to 160 mm were found with different levels of shading under a wheat crop (Herwaarden and Passioura, 2001).

To maximise TE, it is important to decrease the **ratio Es/T** by reducing Es (Cooper et al. 1987a, b; Turner and Asseng 2005). This goal is being increasingly achieved in Conservation Agriculture by covering the soil with crop residues.

Without measurements to separate Es from T in the field, other means to estimate these values have been devised, notably by French and Schultz (1984a, b). In the absence of deep drainage and surface runoff, in a Mediterranean-type climate, they assumed a simplified Water Balance Equation:

$$\text{seasonal crop water use} = \text{soil moisture at sowing} + \textbf{growing season rainfall}^{5} \\ - \text{soil moisture at harvest.}$$

Then they devised a practical means of separating soil evaporation from transpiration, in order to estimate not only WUE but also Potential Crop Yield. They plotted grain yield against seasonal water use for a large number of experiments over 12 years (1964–1975) in South Australia (Fig. 1.11). The line through the highest points over the range of seasonal rainfalls was an estimate of **Potential Grain Yield**. The point of interception of that line on the X axis (zero yield) was an estimate of the seasonal evaporation (Es) of water from the soil surface—about 110 mm. The slope of the line was an estimate of TE—20 kg grain/ha/mm transpired water, a value which agrees with the results of many other researchers (see Chap. 37). This method provides average values for Es and potential yield. French and Schultz (1984a)

[5] The rainfall growing season in this environment is the period April-October.

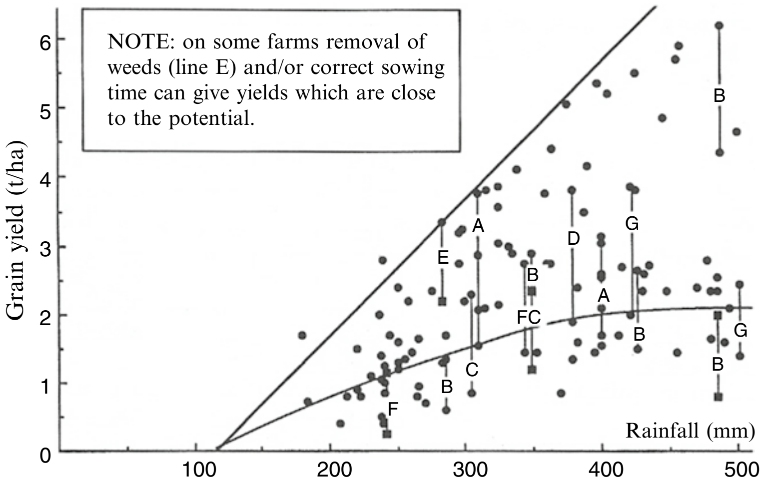

Fig. 1.11 The relation between grain yield of wheat and the derived April-October rainfall for selected experimental sites and farmers' fields in SA. The sloping line indicates the potential yield. The curved line shows the mean district yields in SA. These are only about half the potential at 250 mm and one-third the potential at 400 mm. The responses to different treatments are shown by lettered vertical lines linking points. Yield increases were obtained by the application of nitrogen (points linked by a *B line*), phosphorus (*C line*), copper (*D line*) and control of CCN (*F line*). Yield reductions occurred because of delayed time of sowing (*A line*), effects of weeds (*E line*) and waterlogging (*G line*) (French 1991)

and French 1991 also found that values for Es varied with soil type. Thus it could be as high as 170 mm on hard-setting soils where rainfall tended to lie on the soil surface, as low as 60 mm on sandy, well-drained soils and as low as 30 mm in situations where rainfall is very low and production is dependent largely on stored soil moisture. French (1991) also showed that estimated average Es and TE varied with crop type, being 130 mm and 15 kg/ha/mm respectively for grain legumes, and 70 mm and 45 kg/ha/mm respectively for annual legume pasture DM.

French and Schultz (1984a) also recognised that WUE and Potential Yield decrease with increasing Potential Evapo-transpiration. They used a formula of de Wit (1958), Y = m W/P, where Y = Potential DM yield (kg/ha); m is a constant for particular crops and soil conditions, including the proportion of moisture lost by evaporation from the soil; W = Total seasonal water use (mm) and P = mean daily growing season (from sowing to maturity) Class A Pan Evaporation (mm/day). The authors estimated values of m for various experimental crop and soil evaporation situations. For grain yield,

$$m = 65\left(1 - \left(\text{loss by evaporation } (\text{mm}) / \text{ total water use } (\text{mm})\right)\right)$$

In southern Australia, the loss by Es is 33% of water use and m = 42.

In spite of the many approximations in calculations, the concept of Production Potential has proved to be a useful benchmark for farmers of southern Australia (and elsewhere), even more so than TE or, more generally, Water Use Efficiency (WUE). This has been recognised by research agronomists (for example Anderson and Sawkins 1997; Passioura 2004) as well as consultants and advisers. When farmers estimate Potential Yields and ask why their crop yields are well below potential (as in Fig. 1.11), they are motivated to locate and remedy limiting factors such as disease, nutrient deficiencies or poor management. This concept of limiting factors, promoted by Blackman (1919), and so important in operating farming systems, is useful in increasing Water Use Efficiency. As limiting factors are corrected, crop yield increases to a greater extent than crop water use. Thus water use efficiency increases as yields approach the potential (See also Chaps. 4, 27, 28 and 44).

Precipitation Use Efficiency

In situations where plant root growth and Es cannot be measured or estimated, the best measure of WUE is the production of total shoot or grain production per unit of rainfall. This is usually termed Rainfall Use Efficiency, but is better termed **Precipitation Use Efficiency (PUE)** to include snowfall and dew. It is defined as the mass (kg) of dry matter (DM) or grain produced/unit area/mm rainfall received and used. Runoff and deep drainage may be included as components of the rainfall received, subtracted from it if they can be estimated, or regarded as negligible in strongly water-limited environments. Stored soil moisture before and after the crop should be taken into account. Reducing run-off and deep drainage makes more water available for plant growth.

PUE is used on a field scale to compare productivity of various plant or management or farm systems. For example, Tow (1993) in a pasture species experiment used estimates of rainfall use efficiency (kg DM/ha/mm rain) to illustrate differences in production potential and environmental adaptation of three types of pastures in a subhumid, subtropical environment. In this case, some estimates were made of run-off and drainage. Even so, such measurements cannot be a complete estimate of PUE because the proportion of DM in roots could vary among crops and environmental situations.

Useful information has also been obtained by comparing treatments for the **Evapo-transpiration Ratio, ER** (kg water used/kg DM produced), for plants grown both in the field and in containers. ER is the inverse of rainfall-use efficiency if runoff and drainage are negligible. It is also the inverse of TE if that can be measured separately from soil evaporation. For example, the ER of field-grown lucerne has been shown to vary widely according to the summer irrigation regime expressed as a proportion of pan evaporation (Snaydon 1972); this showed the plant's sensitivity to certain summer environmental conditions in determining productivity and water use efficiency. Similarly, the ER of three pasture types (lucerne, a tropical grass and a mixture of the two) in the field varied with environmental conditions and nitrogen levels as well as species (Tow 1993).

In more recent years, water balance and yield forecasts have been made by means of computer models (such as Yield Prophet, Chap. 37) using modern knowledge of plant and soil water relations and climatic analysis (Brennan et al. 2007). Yet estimates of PUE can still be useful on a broad scale. Increases in wheat yield in parts of southern Australia over the last two decades, while rainfall has decreased, represent a significant increase in PUE (Turner and Asseng 2005,) through the combined interaction of genotype x environment x farmers' management (See also Chap. 28). PUE can be more useful than yield alone for assessing farm systems.

Farm Water Use Efficiency (kg product/ha/mm rain) has been used to compare water use efficiency in two simple farm systems using rotations of fallow–wheat and wheat–wheat (Cornish and Pratley 1991). Wheat yield/ha was higher in the former because it had the advantage of water accumulated during fallow, but rainfall use efficiency was higher in the wheat–wheat rotation because less water was lost by soil evaporation (in the fallow) and thus more water passed through the plants. Considered over the whole rotation, cropping in successive years was more productive—and more profitable, though more risky than fallow–crop. The concept of **Fallow Efficiency** considers the proportion of water entering fallow soil that is eventually captured by the following crop, which varies with climate and soil conditions, including texture, depth and surface cover (Chap. 4, Cornish and Pratley 1991).

'**Water Productivity**' is a broad concept that can be useful in rainfed agriculture although it has greater usefulness in irrigated agriculture (Molden et al. 2003). It takes into account the whole flow of water in the water cycle to trace the overall efficiency of its utilisation. This concept can be used at any scale—plant, field, farm or catchment. Its measurement may be more useful than concepts of drought resistance and drought tolerance in following and remedying problems of water deficiency (Passioura 2004).

Water Productivity is expressed as an efficiency ratio that has a physical or economic term on the numerator and a water term as the denominator. It is defined as agricultural output per unit of water depleted. **Water depletion** means that water is rendered unavailable for further use in the present hydrological cycle. In rainfed agriculture, this occurs by transpiration, evaporation, runoff and deep drainage, but it may also occur when water stored in a subsoil becomes unavailable to plants because of the presence of toxic levels of certain minerals, such as boron, manganese or sodium (Chap. 4). On the other hand, water left unused (**undepleted**) in the subsoil by one crop (e.g. field peas) may be used (depleted) by another crop with deeper roots, in the following season. Thus use of the concept of Water Productivity can encourage a useful analysis of water use. Molden et al. (2003) regard Water Depletion as a key concept for water accounting, which is particularly important in irrigated agriculture.

Estimates of WUE are useful in evaluating environmental adaptation of genetic material, agronomic requirements and other management practices, for the whole or part of farm systems.

1.4.9.3 Economic Efficiency

Economists view efficiency in a number of ways. **Productive efficiency** relates the ratio of output value to cost and attempts to minimise costs for a given level of output or maximise output for a given level of costs. When considering the farm as a system, the manager's aim is to maximise returns by one of these means.

Alternatively, economists use **allocative efficiency** which relates to how scarce resources are allocated among goods and services produced by an economy in such a way as to maximise the net benefits obtained from their use. The optimum situation is where it is not possible to change the allocation of resources to make someone better off without making someone else worse off—the Pareto criterion of efficiency.[6] If somebody could be made better off without making any other individual worse off, then clearly net benefit is not maximised, and therefore the resources have not been allocated in the most efficient manner. This is likely to be of interest only if we are looking at a system that is bigger than the individual farm.

Management of a farm business is the process of conducting activities efficiently and effectively often through other people (see also Chap. 12). Efficiency is measured by the relationship between inputs and outputs and refers to efforts to minimise resource costs. **Effectiveness** refers to the degree of success in goal attainment.

1.5 Conclusion

A systems approach is needed to develop and operate sustainable farms and to adapt to changing circumstances. This approach requires an understanding of system structure and relationships including goals, interactions, feedback mechanisms, consequences of change in one part for other parts, and complementarity of enterprises and operations.

In all farming systems, productivity, profitability and efficiency of operation are of great importance. While efficiency of the whole system is of greatest significance, there is often value in quantifying the efficiency of utilisation of individual inputs such as finance, nitrogen, energy and water. The latter is of especial importance in Rainfed Farming Systems and is emphasised in this chapter and the book as a whole.

While it is important to understand a farm system in biological, chemical and environmental terms, it is equally important to understand it in terms of personal (farmer/farm family), social, economic, educational, and political relationships. This is how farmers experience their farm systems, and it brings reality while also increasing the complexity of study.

Other concepts dealt with are stability, flexibility, adaptability and resilience. These are shown to be important features of sustainable farming systems.

The remaining chapters of this book will investigate the multitude of principles and influences on farming systems and give examples of the development and operation of systems around the world and their adaptation to changing conditions.

Acknowledgements A number of people have assisted us in the development of this chapter. In particular we acknowledge Dr. V.V.S.R. Gupta for his help with Sect. 1.4.8.

[6] See also Glossary.

Supplement to Chapter 1

Emergy: A New Approach to Environmental Accounting

Gloria Rótolo, Charles Francis, and Sergio Ulgiati

S1.1 Overall Emergy Concepts

Emergy is defined as the whole available energy (based on a common unit, usually solar energy) that is used directly and indirectly to obtain a product or service (Odum 1996). It is the **energy 'memory'** of the product, and accounts for all the available energy supplied by nature and society that is invested in producing a certain output. It therefore provides a combined ecological-economic evaluation. To understand the concept of emergy or energy memory, it is necessary to appreciate its systems foundation and the background of its '**supply-side approach**', which refers to the idea of accounting for all the flows that have contributed to a product or service along the chain of its development.

The emergy concept is built on two main pillars. One of them is Systems Ecology (Odum 1983), deeply rooted in General Systems Theory (Von Bertalanffy 1968). It conceives any ecosystem as a global entity, made with interconnected components, and only understandable as a whole. Today, almost all ecosystems in the world have been directly or indirectly modified by human interventions. Therefore, within these ecosystems, nature and society are interacting and co-evolving through time. Systems Ecology is the study of the ecosystem 'as a whole', encompassing the overall performance of the system, and also the details of its design, since the overall behavior of the system—i.e. what characterises it—is produced from the interactions of separate parts and mechanisms (Odum 1983).

The second pillar on which the emergy concept relies is the biophysical laws that govern the systems. According to Odum (1996), each socio-economic system acts

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and evolves within, and together with, the natural system where it is immersed, over a hierarchy of scales of time and space. This simply means, first of all, that all socio-economic systems—including agricultural systems—are subject to the principles of irreversible thermodynamics[7] that determine their self-organisation[8] patterns, from the small-scale of chemistry and biology up to a global scale, through the identification of energy flows used over the whole metabolic chain of systems. In particular, those designs that maximise power output from the resource available prevail, as suggested by Lotka's Maximum Power Principle (Lotka 1922a; b). Successful systems develop structures that maximise useful resource consumption and production, by feeding back matter and information. In order to take quality of flows into account, Odum (1983, 1996) restated Lotka's principle via the emergy concept as a Maximum Empower Principle. The revised statement is:

> Systems that develop the most useful work with inflowing emergy sources, by reinforcing productive processes and overcoming limitations through system organisation, will prevail in competition with others.

or, in other words,

> In self-organisation patterns, systems develop those parts, processes, and relationships that maximise useful empower (throughput flow of emergy).

It is important that the term 'useful', i.e. something that produces a positive consequence, is used in these two statements. For example, drilling oil from wells and then burning it off may use oil faster (in the short run) than refining and using it to run machines. However, it will not compete, in the long run, with a system that uses oil to develop and run machines that increase drilling capacity and ultimately the rate at which oil can be supplied.

Within a maximum empower and natural selection framework, maximum efficiency as defined in classical thermodynamics textbooks is no longer the driving prerequisite. First of all, complex systems adapt to environmental conditions by *optimising*, and not necessarily maximising, their efficiency, so that global maximum power output can be achieved and maintained. Maximising global production is the goal, which is reached by 'choosing' the most appropriate efficiency for each of the co-products. As a consequence, resource throughput is also maximised consistently

[7] In physics, thermodynamics is the study of the conversion of energy into work, also depending on variables such as temperature and pressure. Thermodynamic reversible processes are those that are in an equilibrium state because they develop very slowly by infinitesimal changes and can in principle be reversed without loss or dissipation of energy. In an irreversible process, finite changes are made; therefore the system is not at equilibrium throughout the process. From a thermodynamics perspective, all complex natural processes are irreversible. If a thermodynamic system (any system of sufficient complexity) is brought from one thermodynamic state to another, a certain amount of 'transformation energy' will be used in building the structure. Meanwhile there will be heat energy loss or dissipation, which will not be recoverable if the process is reversed.

[8] Self-organisation is the process by which systems use (degrade or upgrade) energy and matter flows to develop structure and organization (Odum 1996).

with availability of resources. In this way, systems tune their thermodynamic performance according to the surrounding environment.[9]

In general, when resources are abundant, the advantage goes to the system which is able to draw on them faster than others, regardless of their efficiency. When resources decline, efficiency must grow, in order to generate the maximum possible product within the existing constraints based on smaller throughput. Although an efficiency increase is generally achieved at the expense of process speed (Odum and Pinkerton 1955).[10] Societies tend to deplete most of the known and accessible resource storages, on both the source side (reservoirs of nonrenewable resources such as oil, minerals, fertile soil) and sink side (clean air and water, ecosystem integrity). Resources become increasingly scarce, due to increased use per person and increased population. Therefore, according to the Maximum Empower Principle, fast consumption is no longer a winning strategy for survival and must be replaced by increased global efficiency (doing more with resources available).

Within the new framework of Emergy Analysis and Maximum Empower Principle, it is possible not only to integrally analyse these complex nature-socio-economic contexts as a whole system—by accounting for the energy flow throughout it—but also to consider feedback mechanisms among the system's components that derive from self-organisation processes. Depending on the way these feedback flows work within the system, the self-organisation process will allow the survival of the system as it is, or its evolution to other forms depending on which of the components are more reinforced. For example, the excess use of agrochemicals on crops might provoke the appearance of resistant species that have been evolving under the threshold level for damage by the chemical, and that now become major pests.

Howard T. Odum and his colleagues, working on the evaluation of ecosystems at different scales, found it feasible to integrate the natural and socio-economic systems by introducing the idea of energy quality within a system driven by multiple flows of energies. **Energy quality** refers to its form and concentration.

[9] Photosynthesis, a low energy-efficiency process (0.1%), is an example of such a behavior. Solar energy is abundant and constant, but other resources (water and nutrients) are not generally so. By optimising its efficiency via a complex, (still not completely clear), biochemical mechanism, the photosynthetic process adapts its performance to the amount of available resources. A higher energy efficiency would not fit the availability and appropriate use of needed resources other than solar radiation (e.g. water, nutrients). The optimum efficiency 'chosen' by green plants maximises their biomass over time within the existing constraints. Moreover, the larger system of the biosphere allocates fractions of solar energy to patterns other than the photosynthetic one (wind, water, oceanic currents) thus maximising and maintaining the global productivity much more than by maximising one individual pattern (e.g. rain).

[10] The interplay of available resources, efficiency and power is an important factor affecting a process. For example, the eighteenth century industrial revolution in England was driven by large amounts of coal used at less than 1% efficiency (early steam engines). The winning factor in market competition was not just energy, but power (generating products and expanding faster than competitors). When availability of coal was constrained by several other factors (e.g. demand, price, competition, social factors) efficiency increase became more important, in order to make more products out of available resources.

Energy of one form is not equivalent to energies of another form in their ability to do work. These different forms contribute differently to biophysical processes (Ulgiati et al. 2007; Brown and Ulgiati 2004a and b). For example, solar and fuel energies are important for the functioning of agricultural systems. However, their contributions to the system are very different, that is, they are different in form and concentration, or in their quality. In photosynthesis solar energy cannot be replaced by fuel energy; they have different roles in the system. Thus, when adding up different forms of available[11] energy that have contributed to a process or service, they must first be converted to a common form of energy (Odum 1996). Solar available energy is utilised as a common unit in the evaluation of the integrated system since it could be considered as a reference input for almost every system. This common form of energy when used in relation to obtaining a service or product is called emergy (measured in solar equivalent joules, abbreviated seJ).

Emergy evaluations are sometimes referred to as **Emergy Synthesis** (Brown and Ulgiati 2004a and b) since they are designed to build understanding by grasping the wholeness of the system from the top down instead of breaking it apart and building understanding from the pieces upward (Brown et al. 2000). Emergy actually is the available energy (i.e. the potential work) consumed in transformations. **Unit emergy values** or **emergy intensities** may be defined as the emergy input per unit of output (energy, mass, time or money). Thus **transformity** is the emergy required to make something per unit energy output (seJ/J). **Specific emergy** is the emergy per unit mass (seJ/g), and **emergy per unit money** refers to the emergy supporting one unit of economic product (seJ/unit currency) (Table 21.2 column 4 and Table 21.4). These are practical measures of system efficiency. Further explanation of emergy intensities can be found in Brown and Ulgiati 2004.

In an emergy study, **system boundaries** are established, and diagrams drawn using the energy systems language (Fig. S1.1, Figs. 21.3, 21.4 and 21.5).

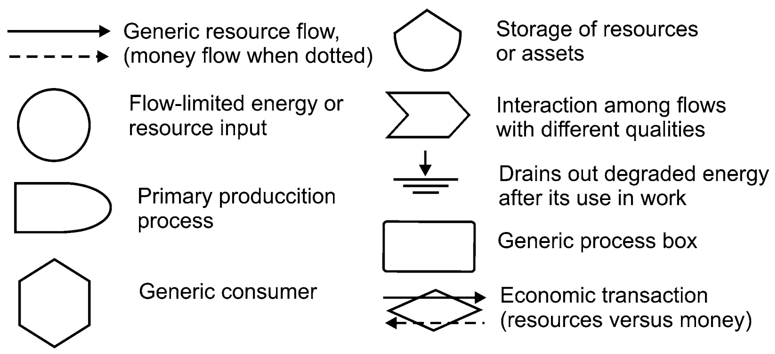

Fig. S1.1 Selected energy language symbols (Adapted from Odum 1996)

[11] The term ‘available’ is intended to be used in thermodynamic sense, i.e. energy that can be converted into work or drives a transformation process. It can be considered synonymous with free energy or Gibbs free energy. Odum also referred to it as ‘**exergy**’ (Odum 1996, p. 13, Table 1.1).

These diagrams are necessary to visualise and help quantify the components and flows as well as the renewable and non-renewable natural resources, purchased inputs, labor and services and all their interactions that are involved in the evaluation. Therefore, diagrams allow us not only to have an overall view of the resources and components that contribute to the product, of their interactions and their potential to 'organise' the input information, but also to help avoid double counting of flows coming from the same source. Once the diagram is drawn, the value of each input flow is accounted for and organised in tables (e.g. Table 21.2). Tables allow us to quantify the information by listing the resources, purchased inputs, labor and services flows and their corresponding raw and emergy values that contribute to the **system dynamics** as well as to its final product or service (Table 21.2).

If the table is for flows, it represents flows per unit time (usually per year). If the table is for reserve storages, it includes those storages with a turnover time longer than 1 year. Dynamic models for storage variation may also be constructed and run.

The final step is to calculate **emergy indices** that relate the emergy flows of the economy to those of the environment. This enables prediction of economic viability, carrying capacity, and system performance (see Chap. 21) that can be used to inform policy decisions.

The emergy value of a particular component represents all the energy transformations that have occurred throughout its chain of development. Therefore, the different places occupied by each symbol denote a hierarchical organisation. The higher the organisational level of a component in the system, the higher the 'supply-side' energy quality and the smaller the amount of available energy of the carrier. For example, grazing steers have a higher energy quality than pasture because more energy transformations were needed over the whole metabolic chain (roughly: solar radiation → rain → pasture → protein). The relatively small available energy of their body is the final 'carrier' of the much larger available energy provided by the sun to the photosynthetic process that generated the pasture. As a consequence, total protein output represents the convergence of the biosphere work and services that supported the growth of the steers. Due to the large work needed to generate the protein (large finished steers), production would have been discontinued by natural selection—if such a hierarchical quality of steers were not 'recognised' on the larger scale and rewarded economically by society.

For a more complete explanation of the theory and methodology of the emergy concept and emergy analysis, see Odum (1983, 1996) and Brown and Ulgiati (2004a). Haw and Bakshi (2004) enrich the concepts of emergy analysis, discussing specific applications, while Herendeen (2004) and Brown and Herendeen (1996) analyse differences and similarities between embodied energy, energy, and emergy analysis methods.

S1.2 Emergy as a Valuation Method

Usually money is used to value most of the outputs produced by the interacting nature-society system. The usual concept behind market value, what people are willing to pay for a product, focuses on the so-called receiver-side value, i.e. a concept of value based on the usefulness perceived by the receiver of the product. It is a different concept from that used in emergy analysis, a 'donor value' or supply-side value, according to which something has a value depending on what was invested to make it within an environmental or socio-economic chain of metabolic processes. The measure of value through emergy evaluations is independent of the market oscillating dynamics where prices can go up or down according to abundance or scarcity or just advertising efforts. Market values are not helpful for direct valuation of contributions from the environment since usually they respond inversely, that is prices are lower when product on offer is larger, although usefulness is also large because of the amount available to many users (Odum 1996, p 260). For example, in the market concept, when water is scarce, it is assigned a higher money value than when it is abundant. However, it is when water is abundant that it contributes more real wealth to the economic system and the standard of living of the people.

S1.3 Conclusions on Emergy Analysis

The emergy concept and methodology can only be utilised within a whole systems context. It is a comprehensive measure of the work of nature and society, converted to common units (Ulgiati et al. 2007). An emergy study accounts for all energy and matter input flows that contribute to a process, integrating or amalgamating the major inputs from the human economy with those coming 'free' from the environment, (Brown and Ulgiati 2004a and b).

Although the emergy method is not yet widely used for the study of economic systems, it is a comprehensive and highly useful method for analysing whole systems. More complex than neoclassical economic evaluation, more comprehensive than conventional energy analysis, the emergy approach takes into account both the environmental and the societal contributions to a given product by considering the whole system in which that product is produced. This is a more realistic and long-term assessment of the cost to society as well as to the environment. It provides a holistic basis on which to make management decisions as well as policies capable of supporting long-term sustainability. Further examples of the applications of this concept are provided in Chap. 21 of this book.

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Chapter 2
Types of Rainfed Farming Systems Around the World

Larry Harrington and Phil Tow

Abstract This world encompasses an enormous diversity of environments, and farming systems have evolved to fit into many of them. Rainfed farming systems are found in areas as diverse as the Sahelian zone of west and central Africa; eastern and southern Africa; west and central Asia; Afghanistan and Pakistan; central India; western China; semi-arid Australia; northern Mexico; and the prairies and central plains of USA and Canada. This chapter discusses ways of classifying rainfed farming systems for comparative, predictive and management purposes, and to assist in change from one type of system to another. Here, four categories of rainfed farming systems are distinguished: high-latitude rainfed systems with cold winters; mid-latitude rainfed systems with mild winters; subtropical and tropical rainfed highland farm systems; and semi-arid tropical and subtropical farming systems. Within these categories, systems are subdivided into two archetypes, based on low or high levels of productivity and farming intensity. Factors that influence the intensity and productivity of rainfed farming systems include the ratio of precipitation to potential evapotranspiration, water availability, drought risk, temperature regimes, soil quality, external input use, marketing margins, market access, tenure security, policy environment, and the purpose of crop–livestock integration. There are many interrelationships among these factors. For example, drought risk and water availability are affected by water harvesting practices, risk management practices, soil characteristics, and rainfall patterns and other climate variables. Soil characteristics are influenced by organic and inorganic fertiliser management and enterprise selection (including crop selection and crop–livestock integration). These are affected by input and product prices which in their turn are influenced by marketing margins and market access. Finally, all systems are affected by the quality of market infrastructure, and policies and institutional arrangements.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_2,

Keywords Farm system classification • P/PET • Climate • Water availability • Drought • Soil quality • Marketing margins • Market access • Tenure • Policy environment • Crop–livestock integration • Farm system productivity • Farm system intensity

2.1 Introduction

This world contains an enormous diversity of environments, associated with endless variability in rainfall, temperature, topography, land and water quality, and other factors. Farming systems have evolved to function within these environments. This process of evolution continues today, with farm families continually adjusting the structure and management of their farm systems to take best advantage of changing circumstances.

A full depiction of farming system diversity would embrace everything from intensive dairy farming in northern Europe to extensive nomadic herding in Central Asia; from GPS-guided, precision farming on the central plains of North America to slash-and-burn cropping on Central American hillsides; from peri-urban vegetable production for local markets in India to subsistence sorghum and millet production in West Africa; and from enormous cattle ranches in Brazil to tiny irrigated rice paddies in Java.

This book, however, focuses on farming systems involving crops and livestock in areas where rainfall limits crop production for a substantial part of the year – the rainfed farming systems.

Even within the category of rainfed farming systems, considerable variability remains. The aim of this chapter is to discuss ways of classifying rainfed farming systems for *comparative*, *predictive* and *management* purposes.

First, *four main categories* of rainfed farming systems are presented. These categories, which are based largely on climatic factors, are an adaptation of a taxonomy developed recently by FAO (Dixon et al. 2001). Systems in these four categories are then subdivided into those with relatively high and those with relatively low levels of *intensity*, and *productivity*, where 'intensity' is related to the quantity and quality of effort or energy going through the system, and 'productivity' is interpreted as land and labor productivity and *input use efficiency.*[1] There is discussion of biophysical and socioeconomic factors that influence rainfed farm system intensity and productivity, and the interrelationships among these factors. Finally, some examples are given of high and low productivity/intensity systems for each of the four main categories.

[1] Output per unit input.

2.2 Four Main Categories of Rainfed Farming Systems

There have been many attempts at categorising farm systems for different purposes using different criteria.

Grigg (1974), working at the global level, identified the following kinds of farming systems: shifting agriculture; wet-rice cultivation in Asia; pastoral nomadism; Mediterranean agriculture; mixed farming in Western Europe and North America; dairying; plantations; ranching; and large-scale grain production. This categorisation overlooks the likelihood that a rainfed farm system may combine elements of several of the listed systems.

Duckham and Masefield (1970) developed a taxonomy based on two principle factors: intensity (intensive; semi-intensive; extensive; very-extensive) and principal land use (perennial tree or shrub crops; tillage or annual crops; grazing or grassland; and alternating between tillage and either grassland, bush or fallow). Systems were further divided into those located in temperate or tropical climates. Their taxonomy disregards the extent to which livestock are typically integrated into rainfed systems.

Dixon and Gibbon (2001), in discussing farming systems in developing countries in a recent FAO publication, preferred a much larger array of categories. They discussed several dozen farm systems from around the world, each one defined with reference to the region or continent where it predominates. Aggregating these systems into broader categories, they ended up with the following final set: coastal artisanal fishing; urban-based, smallholder irrigated schemes; wetland rice-based; rainfed humid; dualistic (large/small); rainfed highland; and rainfed dry/cold. The latter two are clearly rainfed systems as discussed in this present book. Dixon and Gibbon further define and describe these two systems as follows:

> The 10 smallholder rainfed highland farming systems in steep and highland areas contain an agricultural population of more than 500 million. In most cases, these are diversified crop–livestock systems, which were traditionally oriented to subsistence production … these days these are characterised by intense population pressure on resources … and heavy grazing pressure … given the lack of road access and other infrastructure, the level of integration with the market is low. (p. 311)

> The 19 smallholder rainfed dry/cold farming systems cover an enormous area—around 3.5 billion hectares—but support a relatively modest agricultural population of around 500 million. These lower potential systems are generally based on mixed crop–livestock or pastoral activities, merging eventually into sparse and often dispersed systems with very low current productivity or potential because of environmental constraints to production. Market development in these extremely low potential areas is limited … (p. 311)

While recognising the importance of crop–livestock integration in many rainfed systems, this taxonomy excludes developed countries, and discounts opportunities for commercial production in developing countries. It does, however, provide a sound basis for further development of a classification.

For the purposes of this book, we put forward the following four main categories of rainfed farming systems.

1. High-latitude rainfed systems with cold winters
2. Mid-latitude rainfed systems with mild winters
3. Subtropical and tropical highland rainfed systems
4. Semi-arid tropical and subtropical rainfed systems.

Systems '3' and '4' build on two of the eight FAO categories described above, while systems '1' and '2' are temperate systems not discussed in the FAO taxonomy.

Each of these can be further divided into two sub-categories, corresponding to the 'low' or 'high' intensity and productivity archetypes discussed in the next section. These sub-categories represent the opposite ends of a continuous range, movement along which is not uncommon. The intensity and productivity of a farm system in a specific category (for example, 'semi-arid tropical or subtropical rainfed systems') can increase or decrease over time in response to changes in farmers' practices, market conditions, government policies, and other external circumstances.

2.3 Two Archetypes

Within rainfed farming systems, there is considerable variability in intensity and productivity where 'intensity' is related to the quantity and quality of effort or energy going through the system, and 'productivity' is interpreted as land and labor productivity and input use efficiency. Two archetypical systems can be envisioned that represent the opposite ends of this variability. Table 2.1 lists some of the many factors often associated with low or high rainfed system intensity and productivity.

As listed, these factors may be interpreted as being interdependent. For example, higher marketing margins[2] are associated with lower rainfed farm system intensity and productivity – 'other things being equal'. But other things often are not equal, and there are numerous interrelationships among these factors; one factor may modify the effects of others. For example, organic and inorganic fertiliser use and enterprise selection both influence soil fertility. But fertiliser use and enterprise selection are affected by marketing margins, market access and input and product prices. These in turn are affected by the quality of market infrastructure, and policies and institutional arrangements that influence the extent to which rainfed farmers have access to input and product markets.

The following sections will show how biophysical and socioeconomic factors, and their relationships, can affect the intensity and productivity of farming systems, cause variations in their structure and operation, and allow movement along the low-to-high productivity/intensity continuum.

[2]See glossary or Sect. 2.5.1 for explanation.

Table 2.1 Factors often associated with low or high farming system intensity and productivity

Factor	Relatively low farming system intensity and productivity	Relatively high farming system intensity and productivity
Ratio of precipitation to potential evapotranspiration	Lower	Higher
Water availability and productivity	Lower	Higher
Drought risk	Higher	Lower
Marketing margins	Higher	Lower
Purpose of cropping	Family subsistence	Cash sale
Market access	Worse	Better
External input use	Relatively low	Relatively high
Policy environment	Unfavorable	Favorable
Reasons for organic farming	Inputs not available or affordable	Capture premium market prices
Tenure status	Less secure	More secure
Soil quality, e.g. capacity to store moisture	Worse	Better
Soil amendments	Manure, compost – or none	Inorganic and/or organic fertilisers
Purpose of livestock	Store of value/ risk management	Income diversity

2.4 Effect of Biophysical Factors on System Intensity and Productivity

2.4.1 Climate and Available Moisture

Rainfed farming systems are located in 'dryland' areas where the presence of a well-defined dry period limits crop production for a substantial part of the year and also where water stress within the cropping season is not uncommon. In these areas, the mean annual ratio of precipitation (P) to potential evapotranspiration (PET) is usually substantially less than one. (PET is the amount of evaporation/transpiration that will occur if there is no deficiency of water in the soil. It is estimated through catchment water balances, or hydrometeorological equations such as the Penman equation which is based on daily mean temperature, wind speed, relative humidity, and solar radiation, or energy balances.)

Sometimes, dryland sub-categories (e.g. arid, semi-arid, dry sub-humid, sub-humid) are distinguished on the basis of defined P/PET limits. 'Arid' areas, for example, are sometimes defined as having P/PET ratios greater than or equal to

0.05 and less than 0.20, while ‘semi-arid’ areas are those having P/PET ratios greater than or equal to 0.20 and less than 0.50.[3]

Rainfed agroecosystem intensity and productivity, and the range of crop species and cultivars that can be grown, are likely to be affected by the distribution and cross-seasonal variability of rainfall as well as by mean annual total precipitation.

> Other things being equal, an environment with a higher P/PET ratio is more likely to support more intensive and productive agroecosystems. In addition, rainfed farming systems are likely to be more intensive and productive where the dry period is relatively short, precipitation events are relatively well-distributed within the rainy season, and the onset and finish of the rainy season are relatively predictable.

Global climate maps suggest that rainfed farming systems are found in such diverse areas as northern Mexico; eastern and southern Africa; west and central Asia; the Sahelian zone of west and central Africa; central India; Afghanistan and Pakistan; western China; sub-humid/semi-arid Australia; and the prairies and central plains of USA and Canada (Fig. 2.1).

Modern GIS tools allow a precise, immediate and ‘on-demand’ delineation of climatic zones. These tools employ existing public-domain databases to generate custom climate maps based on a user-defined range of parameters for elevation, minimum and maximum temperatures, and P/PET ratios for a defined length of time (Hartkamp et al. 2001). With these tools, it becomes possible to identify the climatic zones most suitable for specific farming systems.

In one instance, Hodson et al. (1998) used specialised GIS tools to analyse the similarity of the climates of two major wheat production areas in Bolivia – the highland intermountain valleys and the lowland plains – to those of other regions. For highland environments, zones of climate similarity were found only in scattered regions of Bolivia and Peru. For lowland sites, however, combined results of analyses of the favorable season plus the coolest or driest quarters of the year (when wheat is actually grown in lowland Bolivia) resulted in the identification of numerous environments that were similar to those of the target sites in Bolivia. These zones of climate similarity covered adjacent areas of Bolivia, two regions in Brazil, and areas in Mexico, Central America and Africa. Site similarity analysis of this sort can foster an improved understanding of relations among crop production environments, allowing prediction of how crops in similarity zones are likely to respond when new varieties or crop management practices are introduced.

2.4.2 Drought Risk

Rainfed farming systems are inherently risky. Main sources of risk for these systems are the possibility of (1) annual rainfall levels far below average, or (2) prolonged dry

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[3] These particular definitions are provided by the Convention on Biological Diversity document – ‘Assessment of the status and trends and options for conservation and sustainable use of terrestrial biological diversity: dryland, Mediterranean, arid, semi-arid, grassland and savannah ecosystems’ (UNEP/CBD/SBSTTA/4/7, 19 February, 1999, Montreal, Canada).

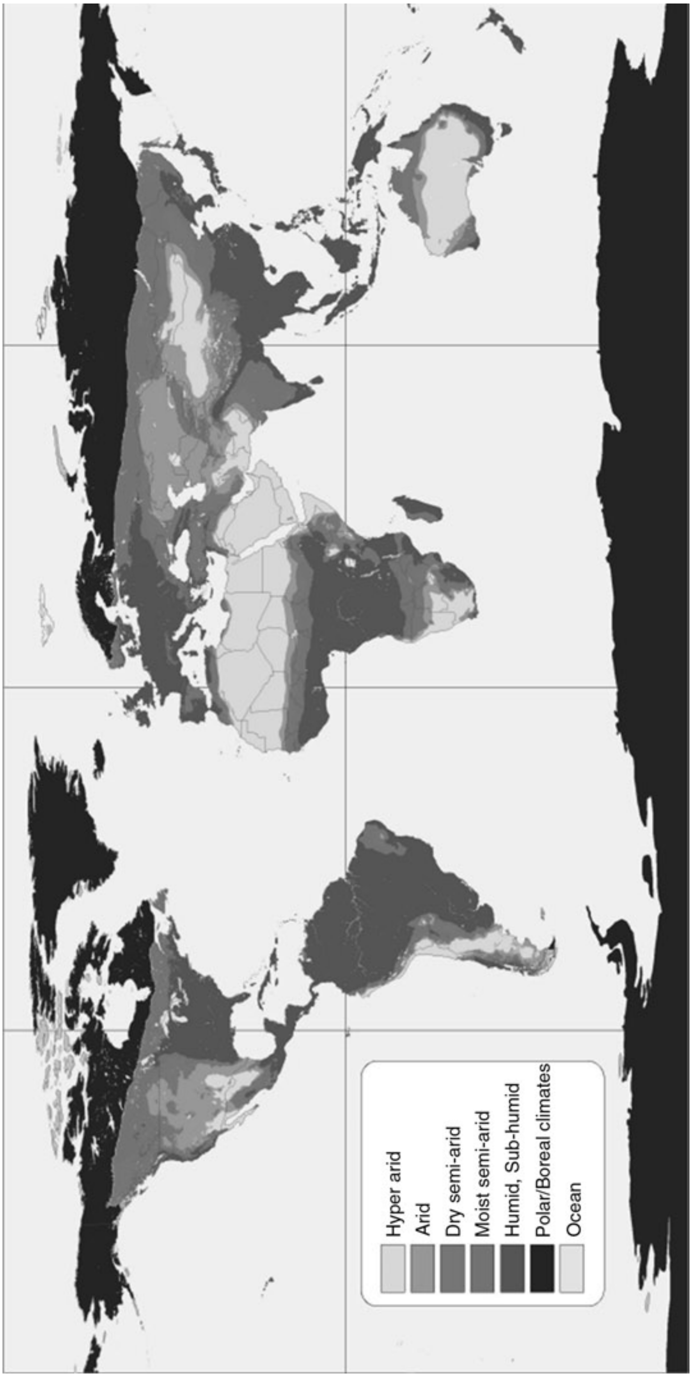

Fig. 2.1 Global map of rainfed farming environments (adapted from FAO-IIASA 2006)

periods during otherwise normal cropping seasons. Drought within a particular cropping season can take on many forms: delayed onset of the rainy season; an early finish to the rainy season; a marked mid-season dry period; or other patterns where precipitation is concentrated in a relatively small number of rainfall events. Because of rainfall variability, long-term drought (one or more years) is possible and this can be regarded by governments as reason for special assistance, thereby moderating the farmers' risk. There is some possibility of drought even in areas where rainfall *on average* is suitable for farm systems of choice.

When designing or modifying farm systems, farmers typically incorporate risk management strategies and coping mechanisms for dealing with drought. For example, subsistence farmers may plant an assortment of different species, e.g. sorghum and millet as well as rice and maize. In seasons of abundant rain, the preferred crops of rice and maize will yield well but if the rice or maize crops fail, the farm family can still subsist on the more reliable production of the sorghum and millet.

Farmers may also use crop varieties with a range of maturities. Early-maturing varieties often provide some yield even when later-maturing ones fail. Crop improvement programs targeting rainfed environments often include early maturity as an important trait. More recently, plant breeders have discovered additional ways to improve drought tolerance in such crops as maize (Banziger et al. 1999).

Another strategy is 'staggered planting'. Farmers in southern Africa may sow maize on three or four different planting dates so that at least one crop will escape the effects of mid-season drought.[4] Farmers in Kenya seek to avoid the effect of drought by establishing their crops in several ways, involving combinations of ploughing and planting, both before and after the onset of rains.[5]

Other risk management strategies involve livestock. If drought occurs and crops are destroyed, farm families may survive by selling some of their cattle or other animals. Over recent decades, farmers in southern Australia have been replacing a crop–livestock system (featuring sheep) with continuous cropping. However, as rain seems to have become less reliable (and meat and wool prices have risen) many are returning to the 'crops plus sheep' system.

> Other things being equal, farming systems are more intensive and productive when there is less risk of drought for a given average annual level of rainfall, and when farmers have access to effective risk management and coping mechanisms.

2.4.3 Water Availability

The availability of water for agricultural production does not depend wholly on rainfall amounts and patterns and potential evapotranspiration. It also depends on

[4] Sequential planting also spreads labor requirements for sowing and weeding. Staggered planting as a risk management strategy in southern Africa is discussed further in Shumba et al. (1989).

[5] Numerous examples of risk avoidance behavior by African farmers are given by Rowland and Whiteman in Rowland (ed.) (1993).

the capacity of soils to store water; the effect of topography on surface run-off and sub-surface water movement; and the extent to which farmers implement water-harvesting practices. In many relatively dry environments – as far apart as Canada and Pakistan – farmers may fallow their fields for a year or more to accumulate soil moisture. Other practices aimed at improving rainwater use efficiency include 'conservation agriculture'; the use of tied ridges, systems based on zaï (planting pits) or demi-lune (half-moon shaped planting basins); the construction of ensembles of small reservoirs or other water collection structures for supplemental irrigation; and (perhaps unique to Canada) the shaping of crop stubble in ways that maximise the capture of winter snow, thereby increasing soil water available for plant growth.

Other things being equal, rainfed farming systems that use effective water-harvesting systems tend to be more intensive and productive.

The following subsections discuss some ways of improving water availability and use.

2.4.3.1 Conservation Agriculture

Conservation agriculture is defined as minimal soil disturbance combined with the retention of crop residues on the soil surface, and the adoption of sensible, profitable rotations. It is used to improve soil moisture by reducing run-off, increasing water capture, reducing evaporation and reducing the risk of soil erosion. In Jalisco State in Mexico, for example, the retention of even small amounts of maize residues helped conserve soil water (Scopel 1997). Similar results have been found in the loess plateau of northern China where "conservation tillage has increased fallow water storage by 35%, and provided a 17% yield increase. In conservation tillage wheat production, fallow water storage has increased by 24% and yield by 13% (compared with traditional ploughing systems in both cases)" (Gao and Tullberg 2000). Conservation agriculture is further discussed in Sect. 2.7.3.

2.4.3.2 Planting Pits

Another approach to water harvesting is the '*zaï*' system found in parts of Burkina Faso and neighboring countries in West Africa. This system is used in the rehabilitation and cultivation of heavily degraded, thick-crusted, cement-like '*zipele*' fields. Two or more rows of stones of 6–10 cm diameter are embedded in the earth some tens of metres apart and across the contour; these are to slow the swift movement of water across the landscape. The farmers then prepare planting pits or 'zaï' 10–15 cm deep and 20 cm in diameter, with the excavated soil left on the downhill side of the pit. Lines of zaï are staggered so that each is dug below the gap between the two pits immediately above. At planting time, compost (crop residues, manure, and household material) is placed in the pit and covered with a small amount of earth with the seed placed just down-slope of the compost. Without stone rows, both seed and compost would be washed away by rapidly moving run-off water from the first rains. Because no further land preparation is needed at planting time, it is possible to achieve timely sowing. Weeds are rarely an issue as few can grow on the undisturbed surface of zipele lands (Zougmore 2003). See also Chap. 1 Sect. 1.5.7.

2.4.3.3 Water Control Structures

Another approach to water harvesting features the building of water control structures such as check dams and small reservoirs. One example is the long-standing and fairly elaborate '*watersheds-based approach*' to rural development found in semi-arid areas of central India, especially in the state of Andhra Pradesh. Communities are encouraged to build a wide array of water and soil conservation structures designed to reduce run-off, decrease soil erosion, and increase soil moisture and groundwater availability. At the same time, improved germplasm for farmers' preferred crops is introduced and the development of irrigation facilities may be facilitated. The impacts of investments in watersheds development in India are said to be dramatic (Joshi et al. 2004).

Water capture for supplemental irrigation can be an important strategy for upgrading rainfed farming systems; it allows dry spells to be bridged and the effects of drought to be minimised. There is considerable spatial variation, however, in the extent to which this is a practicable strategy. In Afghanistan, there are spectacular examples of water control structures that convey snow melt through underground tunnels to 'oases' where crops are grown. In Pakistan, similar structures harvest rainwater and convey it through channels to bunded fields. After rain events, the soil profile is filled with water in amounts that are adequate for the cultivation of high-value crops as well as food grains (See also Chap. 4).

2.4.4 Soil Quality

The availability of water for agricultural production also depends on soil quality, especially the capacity of the soil to store moisture.

The concept of '*soil quality*' has been defined as "the capacity of a specific kind of soil … to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation" (SSSA 1995). Soils of 'good quality' have favorable conditions for seed germination and root growth, a balanced supply of nutrients and water for plants, biological conditions that enable nutrient storage and recycling, and the absence of adverse physical and chemical conditions such as salinity, acidity, toxicity and soil-borne pathogens (Raman 2006) (See also Chaps. 5, 6 and 9).

A soil's capacity to store moisture depends on its texture, bulk density, depth, structure, level of organic matter, and the presence or absence of physical constraints such as surface crusting or a shallow hard pan. Good-quality soils are able take full advantage of available precipitation for productive purposes–that is, they demonstrate high *water productivity* (output per unit of water depleted). Fertile soils will produce more than infertile soils given similar amounts and patterns of precipitation. Soils with severe physical constraints may produce nothing at all, even when precipitation itself is not lacking.

One example of a soil with serious constraints is that of the granitic sands of southern Africa. These are characterized by 20–30 cm of very light-textured, infertile soil, with low levels of organic matter, lying on top of impermeable bedrock. When it rains, available moisture is quickly lost through surface evaporation and lateral flows on the soil–bedrock interface while the soils themselves can store little moisture. Related are the previously mentioned 'zipele' soils characterised by a thick, impermeable surface crust. If this crust is left unmodified, virtually no moisture can penetrate – even during heavy rainfall – and virtually nothing can grow.

At the other extreme are the black cracking clay vertisols such as those found in central India and parts of subtropical eastern Australia, or deep heavy-textured soils with adequate organic material as found in many temperate areas. These soils can store large quantities of moisture.

> Other things being equal, farming systems are more productive and intensive, and less risky, when soils have the capacity to store substantial amounts of water and in other ways are of high quality.

2.5 The Effect of Social and Economic Factors on System Intensity and Productivity

2.5.1 Marketing Margins and the Purpose of Crop Production

When discussing rainfed farming systems, a distinction is commonly made between '*subsistence*' and '*commercial*' systems. The former is sometimes defined as a "form of farming in which nearly all the crops or livestock raised are used to maintain the farmer and his family, leaving little surplus for sale or trade.[6]" In contrast are the commercial systems, where farm products are sold and the income thereby generated used to purchase consumption goods for the farm family.

This distinction is more readily understood when interpreted in terms of *marketing margins*. A marketing margin may be defined as the difference between the price of a product (or an input) on the farm and the price in the market where it is sold. This difference is associated with real marketing costs such as transportation, storage, foregone interest on capital, and spoilage.

[6] Britannica information about subsistence farming on Answers.com. Britannica Concise Encyclopedia Copyright © 2006 by Encyclopædia Britannica, Inc. Published by Encyclopædia Britannica, Inc.

Subsistence farming is, in effect, farming performed under the conditions of high marketing margins. For subsistence farmers, it is unprofitable to produce for market sale. By the time a subsistence farmer grows a crop and pays for transport and related costs to get that crop to market, the money earned by selling the crop is not enough to cover expenses.

For example, if the market price of grain is $100[7] per tonne and marketing costs are $110 per tonne, producing grain for sale in the market makes no sense.

However, if the farmer were to buy the grain in the market and take it home, there would be a cost of $100 per tonne for the grain itself, plus an additional $110 per tonne for transport and other related costs – a total of $220 per tonne. Under these conditions, the farmer's best option is to produce grain 'so as not to have to buy'. Subsistence farmer families typically produce, at most, enough grain to ensure family food security.

One implication is that a person can be a 'subsistence farmer' for a low-value commodity but a 'commercial farmer' for another, higher-value commodity. Subsistence farmers for low-value food grains may be commercial farmers for high-value, low-bulk products such as nuts or dried fruits. Few farmers in developing countries are purely subsistence farmers.

Marketing margins also affect the on-farm price of inputs. High marketing margins raise the farm-gate cost of purchased inputs – sometimes to the point where input use of any kind becomes economically unattractive. This is one reason why crop yields often are lower in subsistence farming relative to commercial farming.

The distinction between subsistence and commercial farming has many implications for rainfed farming intensity and productivity. Other things being equal, subsistence farmers facing high marketing margins are less likely to:

- *use inorganic fertilisers but more likely to use organic manures or compost (often, however, in very limited amounts)*[8]
- *use chemicals such as herbicides and insecticides*
- *be affected by market risk associated with price instability but more likely to be affected by production risk associated with weather events*[9]
- *produce livestock for market sale but more likely to maintain livestock as a store of value and to help manage production risk.*[10]

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[7] The $ symbol here refers to a unit of value, not to any particular national currency.

[8] The inability of farmers in southern Africa to obtain inorganic fertilisers at attractive prices has re-focused attention on soil fertility management based on organic sources, e.g. green manures, legumes, compost, and farm yard manure. See Kumwenda et al. (1996), Waddington (1999) or similar sources.

[9] de Janvry et al. (1995) give an example of how high marketing margins insulate subsistence maize farmers in Mexico from the effects of cheap maize imports into Mexico from the USA, associated with the introduction of NAFTA (North American Free Trade Agreement).

[10] There is a considerable literature on the store-of-value, risk-management, and other functions of livestock in subsistence farming, e.g. McCarthy et al. (2004). The role of livestock in rainfed systems is further discussed in Chap. 11.

2.5.2 Market Access

Issues of market access may affect product markets, input markets, or both. The specific question of marketing margins, discussed above, is but one dimension in the much broader question of market access. Apart from high marketing margins, farmer access to markets may be hindered by a lack of access to:

- information on product quality standards, or an inability to meet these quality standards (e.g. mycotoxin levels in groundnuts produced for export)
- market information (e.g. price trends for different products)
- technologies (e.g. internet communication) or extension support (e.g. education on marketing)
- credit, or to formal and informal marketing arrangements.

There may also be problems of market access in a more literal sense, e.g. when wholesalers are reluctant to deal with the combined output (of varying levels of quality) from large numbers of small farmers, or when marketing arrangements are based on formal contracts between farmers and buyers with greater marketing power. Physical access may also be a problem – poor roads and lack of appropriate transport.

Problems with access to inputs can be particularly troublesome. As seen above, input use may sometimes be unprofitable simply because of high marketing margins, often associated with a lack of supplies of fertiliser or other chemicals in local markets. But input use can also be discouraged by policies and institutions that hinder input availability in other ways, e.g. through exchange rate or tariff policies that increase the cost to farmers of imported inputs, officially-supported input supply monopolies, or pricing policies that in other ways increase the market-level price of inputs.

> Other things being equal, farmers with poor market access are less likely to be able to take advantage of opportunities for increasing farm system intensity and productivity through system diversification, shifts in enterprise selection, or the adoption of new technologies.

2.5.3 Tenure Status and Property Rights

Investments in land and water conservation usually lead to gradual improvement in the intensity and productivity of a farm system. Security of tenure, however, is normally a necessary condition for such investments to be made because the benefits accrue over an extended period of time. Farm families have little incentive to invest in conserving a resource from which they subsequently may be excluded (Anderson and Thampapillai 1990). This has been shown to be true for such diverse environments as the USA (Soule et al. 2000), Java (Barbier 1990), Rwanda (Clay et al. 1998), and Chiapas in Mexico (Erenstein 1997).

The notion of ‘tenure’, however, has several meanings. Sometimes it is most useful to regard it in the broader sense of ‘property rights’. Security of land tenure is not the same as outright land ownership. It is possible for renters or sharecroppers to be secure enough in their use rights to a farm field that they are willing to invest in its improvement. However, a farm family may have secure tenure to a plot of land but not the right to utilise adjacent water resources, or they may have the right to plant and harvest a food crop, but not an exclusive right to crop residues. The latter can happen when community institutions allow open grazing of residues. The inability of a farm family to manage their own crop residues is in many areas a serious constraint to the adoption of conservation agriculture.

> Other things being equal, farmers with secure land tenure are more likely to invest in resource conservation and thereby to have more productive and intensive farm systems. Farmers with exclusive rights to their own crop residues are more likely to take advantage of opportunities to introduce conservation agriculture.

2.5.4 Migration and Remittances

In many parts of the world, it is common for some members of a farm family to engage in off-farm or non-agricultural employment, often in locations far from home. Income earned through such migrant labour may be an important element in the livelihood strategies of farm households. It has been argued that labour migration from rainfed farms, especially in developing countries, is the norm, not the exception (De Haan and Rogaly 2002).

Labour migration affects the productivity and sustainability of farm systems in two opposing ways – by making labour more scarce and by making financial capital more abundant. Family members working in a distant urban center are not available to help with farm work and, as a consequence, some tasks may be performed late or not at all. Cultivated area may decline, or sowing and weeding may be done later than optimal. When a large proportion of the local agricultural labour force migrates, local wages may increase, resulting in farmer investment in labour-saving machinery or practices.

> Financial remittances from migrant labourers can enable farm families to invest in practices that increase the intensity and productivity of farm systems. Remittances are not necessarily used for such purposes, however. Sometimes they are used to purchase consumer goods or to enhance the family’s social status.

Examples from China suggest that the use of remittances is influenced by the kind of village from which migrant labourers emerge. They typically are a *supplement* to agricultural income in richer areas, a *subsidy* for agriculture and non-agricultural activities in mid-income areas, and a *substitute* for agriculture in poor and remote regions (Croll and Ping 1997).

An unusual twist on migration and remittances is the modern phenomenon of part-time or hobby farming. Urban professionals, for example, may purchase and manage a relatively small farm, even though the resulting income is small (or even negative!).

Urban wages can be said to subsidise the farm operation–but a better explanation might simply be that the farm represents a lifestyle choice (or a tax dodge) rather than a source of income.

2.5.5 Policies and Institutions

As with virtually all economic enterprises, rainfed farming is hugely affected by a broad array of government policies and institutional arrangements. This is true for subsistence as well as for commercial farms.

Policies affect in countless ways the opportunities open to farmers. At the global level, treaties such as GATS (General Agreement on Trade and Services) or NAFTA (North American Free Trade Agreement) influence agricultural trade and competition among member countries. Among other things, these treaties affect the extent to which food imports from developed countries may affect local market prices in developing countries. For example, one effect of the North America Free Trade Agreement (NAFTA) has been the influx of (subsidised) US maize into Mexico. Many small Mexican commercial farmers, unable to compete, have simply gone out of business. (By the same token, other Mexican farmers have taken advantage of NAFTA to expand exports to the US of winter fruits and vegetables.) There have been many instances in which the livelihoods of poor farmers in developing countries have been undermined by the dumping of surplus, subsidised production from the US or the European Union.[11]

At the national level, exchange rate policies make domestic agricultural production more or less competitive in world markets, by increasing or decreasing the value of production as well as farm-level input costs.

Some policies impact farmers in clear and direct ways, e.g. taxes or price supports on inputs or agricultural products. The Green Revolution in south Asia was partly made possible by subsidies on fertiliser and price supports for rice and wheat. Unexpected side effects of these subsidies included a decline in the area under pulses and legumes, the emergence of continuous rice-wheat rotations and, in general, a reduction in farming system diversification. Subsidies on corn and other crops in the US have led to similar distortions in crop selection. In sub-Saharan Africa, a removal of subsidies on fertilisers has been cited as one reason for stagnating productivity (Mwangi 1997).[12]

Government policies and priorities on agricultural research and development can also affect rainfed farm system intensity and productivity. When adequate financial and human resources are devoted by governments to the development and adaptation of new output-increasing, cost-saving or resource-conserving technologies, the pay-off to farmers can be substantial.

[11] An example involving meat imports from the EU into West Africa is provided by McCarthy et al. (2000).

[12] Institutional and policy factors affecting fertiliser supply and pricing in sub-Saharan Africa are summarized in Poulton et al. (2006).

Another area where policies directly influence farm system performance is infrastructure development. Investments in roads, bridges, communication systems and market facilities reduce marketing margins and improve market access. This increases farm-level profits and enables some farmers who had been producing for subsistence to move towards production for the market. Road construction, however, can also accelerate processes of resource degradation. Policies supporting road construction were one of several factors found to be related to conversion of forest to pasture in Central America (Kaimowitz 1995).[13]

The effect of other policies may be more subtle. For example, policies and institutions can influence tenure arrangements, including the extent to which poor farmers have access to common property resources, e.g. water, common pasture, or forests. They also influence how conflicts over common property resources are resolved.

Some emerging areas of policy are just now beginning to affect agriculture and food production but may have major consequences in the years and decades to come. An example is the range of policies being used to subsidise and, in other ways, promote the production and use of bio-fuels. The use of grain to produce fuel may increase market prices received by commercial farmers – at the expense, however, of food consumers in developing and developed countries alike.

In general, policies affect rainfed farm system intensity and productivity in at least three ways:

- They influence the boundary between commercial and subsistence farming by affecting marketing margins and market access.
- They influence input and product prices, levels of input use, and profits earned by commercial farmers.
- They influence farmer selection of crop and livestock enterprises and production technologies, as well as decisions regarding choice of continuous cropping or mixed crop–livestock farming.

Policies and institutional arrangements can encourage or impede improvements in farm system intensity and productivity.

2.6 Interrelationships Among Factors and Their Effect on System Intensity and Productivity

In the above sections, biophysical and socioeconomic factors affecting farm system intensity and productivity were discussed. These factors are interrelated in numerous ways.

The most direct influences on farm system intensity and productivity are climate, soil, enterprise selection, and decisions on enterprise management. Climatic constraints

[13] Other factors were policies to increase prices for livestock products, subsidise credit for livestock production, reduce timber values, redefine land tenure, and introduce new breeds of cattle.

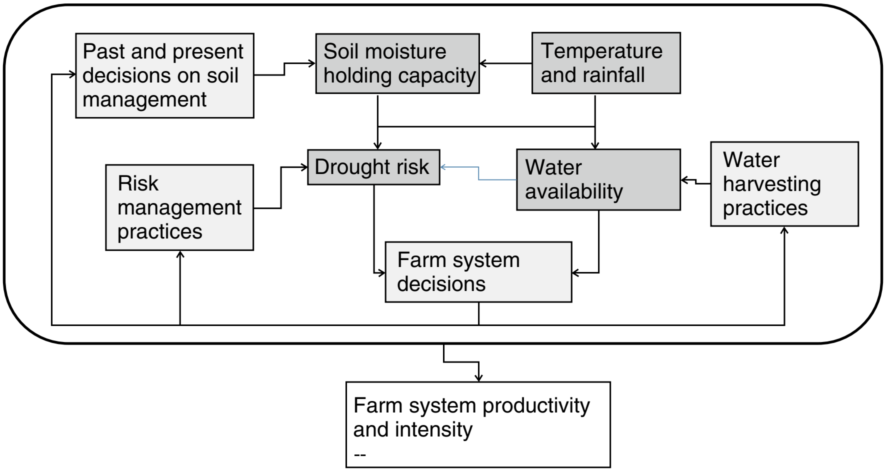

Fig. 2.2 Interrelationships among some factors affecting drought risk, water availability, and therefore system intensity and productivity

can be partially ameliorated through improvements in soil management, rainwater harvesting, the selection of resilient enterprises, and management decisions that take account of risk of loss. These in turn are affected by a whole range of factors affecting market access and input and product prices. Finally, all of the above are influenced by institutions (including informal institutions governing resource access) and policies.

One of the most important questions for rainfed systems is the extent to which system productivity and efficiency are water-constrained. Figure 2.2 illustrates how drought risk and water availability (factors influencing system intensity and productivity) are affected by water harvesting practices, risk management practices, soil moisture holding capacity, and rainfall patterns and other climate variables. Figure 2.3 builds on this, expanding the list of farm system decisions and showing how they are affected, not only by drought risk and water availability, but also by policy, institutional and market factors. Farm system decisions, taken in the context of biophysical and socioeconomic factors, determine system intensity and productivity.

2.7 Farmer's Practices

The various interrelated agroclimatic and socioeconomic factors described above affect farm-level decisions on matters such as which crops to grow and in which rotations, how to integrate livestock with cropping – and increasingly – on whether to adopt resource-conserving practices such as conservation agriculture.

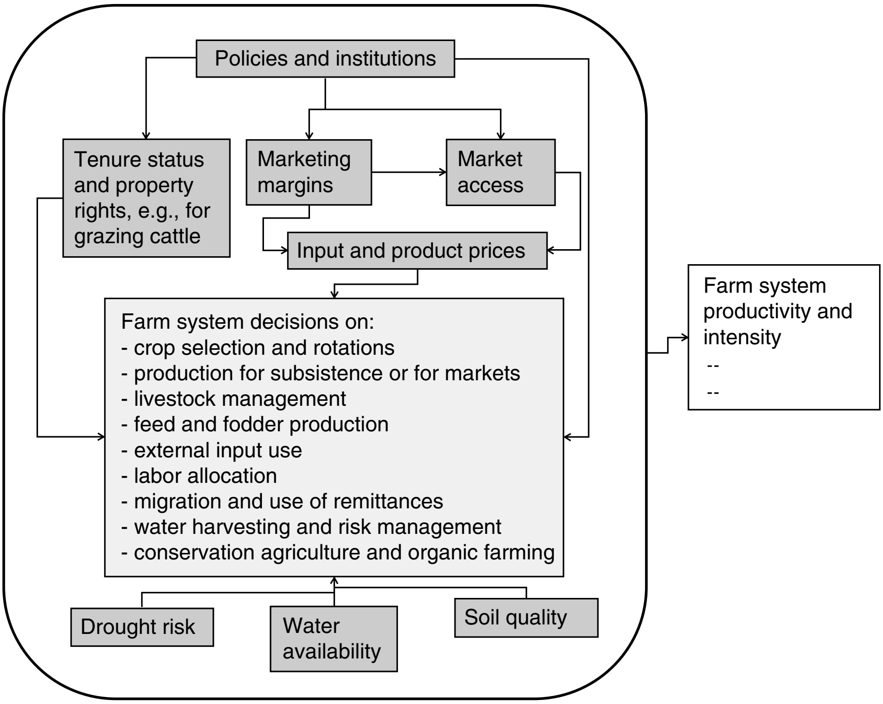

Fig. 2.3 Interrelationships among some factors affecting rainfed farming system intensity and productivity

2.7.1 Crop Selection and Rotations

One of the most important decisions to be made in rainfed farming is that of which crops to grow, and in what sequence and combination. These decisions are heavily influenced by the whole range of agroclimatic, socioeconomic, and agronomic factors described above. Because these factors combine in countless ways, farm system diversity is immense, and boundaries among different kinds of rainfed systems, and between rainfed systems and other kinds of systems, are often poorly defined.

Crop selection and crop rotations almost always vary across space and over time. Within a region, crop selection will vary according to rainfall patterns, soil characteristics, the need for a pest/disease 'break', weed control and available markets. Even within a single farm, farmers may use different ecological niches for different purposes.

In southern Africa, for example, farmers distinguish among three land types or niches: wetlands ('vleis' or 'dambos'), home gardens, and 'toplands'. The latter are at the top to the toposequence and have thin, light-textured, infertile soils, while the former are at the bottom of the toposequence, with deeper, heavier soils. Run-off from toplands is a major source of water for vleis. Vleis are used for many crops, including rice and maize; they are used to water cattle and some are even used for aquaculture. Toplands are restricted to low-yielding millet or sorghum; many are so infertile that they are not used at all. Farm family livelihoods are influenced by the extent to which there is access to vleis. (Home gardens are small areas that benefit from crop and household organic residue and are farmed more intensively than other land types.)

Crop selection may also vary from one year to the next. A late onset to the rainy season may cause farmers to decide to plant sorghum instead of maize. Or an increase in the price of groundnut relative to the price of maize may induce some (commercial) farmers to plant more groundnuts. Over longer periods of time, farmers may observe weed, pest and disease build-up, or land degradation and declining productivity, and make suitable adjustments to crop selection and crop management to overcome these problems.

Further specific examples of crop selection and rotations used in different categories of rainfed farming systems are provided in Sect. 2.8.

Crop rotations and individual crops grown (diversification) vary greatly over space and time. They are an important method for adapting farming systems to ecological niches, and to physical (water, soil, weeds, pests and diseases) and economic changes.

2.7.2 Livestock, Feed and Fodder

In rainfed areas, crop–livestock integration can help increase farm system intensity and productivity when it: fosters diversification into high-value products; replaces human labour with draft power; adds value to crop residues; helps maintain soil fertility through recycling of nutrients in manure; and helps control risk.

Some common inter-relationships between livestock, crops, soils and water, and farm livelihoods are as follows:

2.7.2.1 Livestock Produce Meat, Dairy, Eggs, Wool and Hides

A principal reason to maintain livestock is to take advantage of their valuable products through market sale and/or home consumption. These products may be in the form of milk, cheese and eggs for local markets, pork or beef for export; wool for local manufacture of high-value carpets; and so on. In some specialised systems, animals are purchased, fattened and sold all in a few weeks or months. In other systems, only livestock products are sold, rarely the animals themselves (except under extreme conditions, e.g. major drought).

2.7.2.2 Livestock Are a Source of Draft Power

Various species of livestock have long been used as a source of farm power for tillage, threshing or the cartage of inputs or products. When added to farming practices based entirely on human labour, animal traction can help farmers expand cultivated area and raise yields by allowing more timely land preparation, sowing and weeding, and more efficient threshing and conveyance of products to markets. In these cases, animal traction can raise both land and labour productivity. Improved cartage of inputs and products reduces marketing margins and allows farmers to participate more effectively in the market economy.

The introduction of tractors has reduced this role of animal traction in some countries, though it persists in many developing areas with broken topography or high marketing margins, or where higher opportunity cost of land has made it increasingly difficult to set aside land for fodder production.

2.7.2.3 Livestock Consume Crop Residues, Feed or Fodder Crops

Frequently, farmers in rainfed areas use crop residues and by-products to feed their animals. These residues include straw or stover remaining after harvest or threshing as well as protein-rich cake left after oil extraction from crops such as mustard, cotton, sunflower or groundnuts. In many communities, farmers release their animals for post-harvest open grazing on weeds and crop residues, or even cut and carry waste-land weeds or tree pods for feed. In other cases, e.g. ley systems, farmers fit specific fodder crops or pastures into their rotations. For example, in some rainfed areas in Pakistan, farmers may sow up to 25% of their farm to fodder crops. The Australian ley farming system, discussed in Chap. 1, is a notable example of a crop–legume pasture (cereal–sheep) system.

In marginal and hilly areas, sheep and goats may be allowed to roam the countryside in search of food under the care of a young herder. At the other extreme, large dairy operations such as those found in the Canadian prairies may be self-contained, producing forage and annual crops for feed – or they may be so specialised as to purchase all feed requirements so they can focus exclusively on the livestock enterprise itself.

The practice of producing grains for lot feeding of cattle (rather than their use for human consumption) is a characteristic of some high input/intensive agricultural systems (see Chap. 20).

Not all domestic livestock are ruminants. Chickens and pigs are highly valued in many eastern cultures; they are able to take advantage of grain that has spoiled or has otherwise become unusable for direct consumption by the farm family.

2.7.2.4 Livestock Produce Manure, Which Has Multiple Uses

Farm yard manure is used in many rainfed systems as a source of nutrients to increase soil fertility. Its effectiveness depends on factors that include:

- the number of animals per unit area of land (small numbers of animals on large farms do not produce enough manure to cover more than a fraction of the farmed area)

- its nutrient content (which often depends on feed quality and the animal species – poultry manure is much richer than cattle manure)
- manure management practices (composting, and timing of manure application with respect to the cropping season)
- application costs (transporting manure to distant fields is costly so its use may be concentrated in areas such as home gardens)
- the presence of alternative methods of maintaining soil fertility (e.g. green manures, rotations which include crop or pasture legumes, inorganic fertilisers)
- alternative uses for the manure itself (e.g. in south Asia, much dried animal dung is used for household fuel).

2.7.2.5 Livestock Are a Store of Value

In many subsistence-oriented rainfed systems where there are few institutional mechanisms (e.g. banks) for savings and capital accumulation, livestock, especially cattle, are often used as a storehouse of value. Farmers typically do not routinely raise and sell cattle for cash income, but they may choose to raise cash by selling one or more animals from time to time and for special occasions (for example to pay wedding expenses or school fees). In drought years, selling livestock, even at depressed prices, may help a farm family survive, and so contribute to farmers' risk management strategies.[14]

2.7.2.6 Livestock Are Sources of Air and Water Pollution

Intensive livestock production is notorious for its potential to pollute water resources, affecting downstream water consumers. In many developed countries, farms are strictly monitored and water movement is controlled. This problem is likely to be somewhat less acute in rainfed areas where population density is low and subsistence farming prevails. From the global viewpoint, methane emissions from ruminants are acknowledged to contribute substantially to climate change.

> In summary, integration of cropping and livestock in rainfed areas can help increase farm system intensity and productivity (as well as stability and sustainability) when it increases farm system diversification, augments sources of farm power, contributes to the maintenance of soil fertility, and reduces risk (von Kaufmann and Fitzhugh 2004).

[14] Examples from Zimbabwe of livestock as a store of value and livestock sales for different purposes are given in Scoones (1996).

2.7.3 Conservation Agriculture[15]

Conservation agriculture (CA) is here defined as farming that combines three practices:

- improved soil cover, particularly through retaining crop residues
- minimum soil movement through reduced or zero tillage
- sensible, profitable rotations to improve soil organic matter and to break cycles of plant disease and weeds.

The specific components of a CA system, such as establishment methods, farm implement selection, crops in the rotation, crop residue and mulch management, and plant variety selection, vary across environments. Below are some examples from three areas, to be supplemented by information from other parts of the world in later Chaps. 31, 33, 34, 39 and 40.

2.7.3.1 Conservation Agriculture in Latin America

Conservation agriculture has been most successful in the South American countries of Brazil and Argentina. In these countries, 45–60% of all agricultural land is said to be managed by conservation agriculture systems (Derpsch 2005). In the 2001–2002 seasons, CA practices are estimated to have been used on more than 18 million hectares in Argentina and 23 million hectares in Brazil. These practices include the use of specialised, locally-adapted no-till planters, crop establishment into a layer of mulch left on the soil surface, and suitable crop rotations. See also Chap. 39.

2.7.3.2 Conservation Agriculture in Sub-Saharan Africa

Whereas conservation agriculture in Brazil and Argentina has largely taken hold in high-rainfall areas, it has been harder to implement in drier environments, such as semi-arid climates in sub-Saharan Africa. A summary of constraints to farmer adoption of conservation agriculture in southern Africa – and some ways to overcome these constraints – was provided by Steiner (2002). Some of these constraints and solutions (in brackets) are given below. Such solutions may not be feasible in all farm systems.

- Problems with weed control, such as no access to herbicides. (Use intercropping.)
- Lack of credit to buy specialised no-till sowing implements. (Develop farmer organisations from which smallholder farmers can hire no-till establishment services.)

[15] This section draws on Harrington and Erenstein (2005).

- Insufficient residual moisture for cover crops to provide additional soil cover. (Use intercropping or relay cropping[16] of green manure or cover crops.)
- Crop residues carried and fed to livestock, and not retained as soil cover. (Use feedlots, or introduce agroforestry[17] to produce green fodder for livestock).
- Uncontrolled livestock grazing of residues after harvest. (Foster community-level rules governing grazing or introduce alternative fodder sources such as legume-based pastures.)

This last constraint is often considered to be the most important. It may be impossible to maintain soil cover if the fields are open to uncontrolled grazing. In Ethiopia, community-level collective management has been effective in avoiding uncontrolled overgrazing (Gebremedhin et al. 2002).

In general, conservation agriculture practices have not been adopted widely, perhaps because "…conservation technologies and the way they have been promoted have not considered the constraints faced by smallholder farmers for whom they are intended, such as shortages of equipment or labour, and draught animal availability. Consequently, less than one percent of smallholder farmers have typically adopted these technologies" (Waddington 2003).

2.7.3.3 Conservation Agriculture in China

Early work on CA in China was begun in the early 1990s by the Mechanical Engineering College of the China Agricultural University, and the Shanxi Xinjiang Machinery Factory. This focused on northern China, in response to widespread problems of drought, poor soil fertility, and heavy wind and water erosion in the north China plain, over parts of Heibei, Henan, Shandong provinces, and the city provinces of Beijing and Tianjin. During the late 1980s, these problems were being further exacerbated by the shift from animal to mechanised traction, so a project was started to develop and disseminate CA practices. This project enjoyed financial support from Australia (ACIAR) and technical mentoring from the University of Queensland (ACIAR 2005).

Much attention was paid to the development of suitable implements for direct sowing. These implements had to achieve good crop establishment, with seed and fertiliser drilled at different depths in the soil, while sowing into high levels of crop residues in very small fields, and using low horsepower tractors. The latest generations of sowing implements could give good crop establishment into 15 tonnes/ha of chopped residue. Widespread adoption of these practices has been traced to the advances in machinery, together with strong promotion by the Shanxi Agricultural

[16] See glossary for definitions.

[17] Managed use of woody perennials (trees, shrubs, bamboo, etc.) within agricultural or pastoral land use systems. (http://www.fao.org/docrep/X5327e/x5327e03.htm).

Machinery Bureau and the Chinese Ministry of Agriculture. Effects on the intensity and productivity of rainfed farm systems are so far not clear.

> The extent to which conservation agriculture can help sustainably improve the intensity and productivity of rainfed farming systems depends on how effectively CA principles can be adapted to local environments. Of special concern is the issue of growing and maintaining adequate biomass for soil cover, and providing suitable specialised machinery, training and other support.

2.8 Main Rainfed Farming Systems

In Sect. 2.2, four main categories of rainfed farming systems were introduced. Two categories were built on an earlier FAO taxonomy of tropical and subtropical farming systems, with the other two representing temperate systems. In this section, these four farming systems are described in more detail, including location, common practices, and ranges of intensity and productivity. The four categories are:

1. High-latitude rainfed systems with cold winters
2. Mid-latitude rainfed systems with mild winters
3. Subtropical and tropical highland rainfed systems
4. Semi-arid tropical and subtropical rainfed systems.

2.8.1 High-Latitude Rainfed Systems with Cold Winters

These include large-scale, commercial farm systems in the USA, Canada and Russia; they are typically highly mechanised and well-linked to markets through bulk transport. Maize, winter and spring wheat, barley and canola dominate cropping patterns. Marketing margins are low and farm input use relatively high; some of the production is sent directly to markets while some is used locally for commercial dairy and livestock production. There is usually a low level of crop–livestock integration.

Population density is usually very low. Land and labour productivity both tend to be high. In the US and Canada, conservation agriculture is widely used. The policy environment is generally supportive, and uncertainties related to land tenure are rarely a problem.

Few examples of farm systems in this category fall into the ‘low intensity and productivity’ sub-category.

2.8.2 Mid-Latitude Rainfed Systems with Mild Winters

2.8.2.1 Mediterranean-Type Climates

These climates occur around the Mediterranean basin and on the western side of continents between latitudes of 30° and 45°. They support large commercial farm systems in southern Australia and smaller farm systems in parts of central and western Asia and the Mediterranean Zone. Wheat and barley[18] are the main cereals. At the 'wetter' end of the spectrum, tree crops (e.g. olives, figs, stone fruits, vines) are of importance. With intermediate rainfall, pulses (chickpeas, lentils and faba beans) and oilseed crops (canola, linseed etc.) are grown. Also fodder crops and pastures (vetches, clovers, and medics) are sometimes grown in rotation with other crops (mainly in Australia but also in South Africa). At the 'drier' end, there are fewer options; barley and wheat are often grown in a rotation that includes a one- or two-year fallow. In good years, barley is grown for grain but if there is inadequate moisture for grain to develop, the green barley plants may be fed to livestock. In Australia some medic cultivars have been bred to grow where annual rainfall is less than 300 mm.

These crops and pastures can be grown in all environments with Mediterranean type climates. However there are large differences in intensity and productivity between developed and developing countries. Developing regions are a mixture of small, low intensity/low productivity farms and more intensive and productive farms. There is a general movement towards the latter due to population pressures to produce more food (see Chap. 15). In developed countries (such as in southern Australia), farms have relatively high levels of intensity and productivity as far as rainfall permits (See Chaps. 19, 20, 25 and 26).

In southern Australia, a 'winter-dominant' (Mediterranean–type) rainfall pattern restricts crops to winter-growing annuals, especially wheat (and barley and oats). Wheat has been grown in numerous rotations, including wheat–wheat (one crop per year), wheat–fallow (one crop every two years), wheat–legume pasture (or 'ley' systems) and, more recently, wheat–grain legume (such as faba bean and chickpea) and wheat–oilseeds (e.g. canola). These crops can be grown in winter–spring because of the mild winter temperatures. A similar pattern occurs in parts of South Africa (see Chap. 16).

2.8.2.2 Year-Round Rainfall

This includes northern New South Wales of Australia and the Pampas region of South America. In northern New South Wales, rainfall patterns become slightly summer-dominant, although summer rainfall is more variable and cropping in that season more risky. Numerous rotations are used, including ley farming, long-term crop–pasture rotations (e.g. three years of cropping followed by several years of clover or lucerne for sheep or cattle grazing), and a host of continuous cropping combinations of either one or occasionally two crops per year, featuring summer crops (e.g. sunflower, sorghum, cowpea, mungbean, maize) and/or winter crops (wheat, triticale, barley, canola).[19] In most systems, crop and livestock enterprises are closely integrated. For further detail, see Chaps. 4, 25 and 45.

[18] See Glossary for botanical names.

[19] Information in this paragraph was drawn from Tow and Schultz (1991).

Labour productivity is typically high (due to high use of machinery and inputs), but land productivity is often low (due to low rainfall). Low marketing margins and a supportive policy environment are common, although systems based on subsistence strategies may still be found in central and western Asia. (These latter are more likely to fall into the 'low intensity and productivity' sub-category.)

2.8.3 Subtropical and Tropical Rainfed Highland Farm Systems in Dry Areas

These include small subsistence and commercial farm systems in drier parts of areas as diverse as the Andes, central Mexico, East African highlands, the Himalayas, and southwestern China and adjacent areas in Laos, Myanmar, Thailand and Vietnam. Many of these areas are densely populated. Low-rainfall systems (emphasised in this book) are often found in a mosaic with high-rainfall systems and irrigated systems.

Crop systems are often relatively complex, with considerable spatial variation, even across small areas. Rotations may be based on potato, maize, wheat, barley or 'teff'. Crop selection and rotations are often tailored to landscape 'niches' where temperature plays as important a role as soils or water availability. Crops and livestock are usually closely integrated, with livestock playing multiple roles in farm family livelihood systems, including as a 'store of value'. Often, remittances from family members living elsewhere are important components of livelihood systems.

Seasonal water scarcity is exacerbated by past and on-going processes of land degradation. Nonetheless, most farm systems harvest at least one crop per year. Infrastructure is usually poorly developed, so marketing margins are high and external inputs relatively expensive. Labour productivity is usually low, and land productivity may also be relatively low. In contrast, energy productivity is often relatively high. Lack of land tenure security is often a problem.

Relatively few examples of farm systems in this category fall into the 'high intensity and productivity' sub-category.

2.8.4 Semi-Arid Tropical and Subtropical Farming Systems

These are mostly composed of small subsistence farm systems in semi-arid sub-Saharan Africa and semi-arid rainfed areas of central India; and larger farms in western parts of the cropping zones of southern Queensland/northern New South Wales, southern USA and northern Mexico.

In Africa and India, cropping systems are dominated by millet, sorghum, maize and a variety of grain legumes. Marketing margins tend to be high, and market access low. Soils are often thin and infertile, with low moisture-holding capacity (although there are some exceptions such as the deep vertisols in central India).

There is a single cropping season with high year-to-year variability in rainfall patterns. Rainfall uncertainty and drought are major sources of production risk. Some farmers use field-level water-harvesting practices to improve productivity and reduce the risk of crop loss. Watershed-level water control structures are not common.

Livelihood strategies include income generation from crops, livestock and remittances from family members working outside the farm. Cropping is mainly of millet and sorghum, but crops of maize, tobacco, rice, pulses and oilseeds are typically grown in favorable soil and water 'niches' within farms, e.g. low-lying wetlands. Cattle and other livestock are used as a store of value, and may be sold when cash is needed for special occasions.

In these developing countries there is generally a lack of supporting policies and institutions for farmers managing these systems; inputs tend to be expensive and/or unavailable.

Many farmers attempt to maintain soil fertility through crop rotations featuring legumes, and the application of composts that include farm yard manure. These organic amendments are often insufficient for the area being farmed; many soils continue to decline in fertility and some are abandoned.

The prolonged dry season, combined with low biomass production in the cropping season, and the use of crop residues for livestock feed, means that residue retention for soil cover is extremely difficult to achieve. This deters the use of conservation agriculture strategies that might otherwise reduce risk and improve water productivity. The combination of rainfall with high kinetic energy, the lack of soil cover, and soils with varying degrees of erodibility, result in widespread processes of land degradation.

There are examples of farm systems that fall into the 'high intensity and productivity' sub-category, for example in southern Queensland and northern New South Wales, in Texas and similar areas in the southern USA and in northern Mexico.

2.9 Conclusions

This chapter has distinguished four main categories of rainfed farming systems. These categories were largely defined in terms of climatic conditions associated with latitude, altitude, rainfall patterns and temperature. Geographical areas of concentration, characteristic farming practices and typical levels of intensity and productivity were given for each.

Within each system, however, there are a number of biophysical and socioeconomic factors that influence system performance, many of which are discussed in previous sections. These factors typically are interrelated in highly complex and subtle ways, with numerous cause-and-effect links. Farm systems analysis can diagnose and understand these inter-relationships, resulting in an improved understanding of why some farmers are more productive than others within a farm system category. Such analysis can also identify opportunities–leverage points–for changes in policies, institutions, markets and technologies capable of raising productivity, increasing food production, improving farm family livelihoods, enhancing system resilience, and conserving resources.

Sometimes a single change in a policy, institution or technology releases a cascade of other beneficial changes. For example, a policy adjustment that favors conservation agriculture may lead to changes in crop selection, crop management, residue management (residue retention replacing residue burning) and livestock grazing practices. At other times, holistic strategies may be needed that integrate policy, institutions, markets and technologies. These strategies are most effectively designed when account is taken of interrelationships among factors influencing system intensity and productivity.

The classification system of rainfed farm systems, then, features four main rainfed farm system categories, each one with an overlay of interacting complementary biophysical and socioeconomic factors that influence farm intensity and productivity. Taken as a whole, this classification system is considered to be useful in the identification of relevant factors and also for comparative, predictive and management purposes.

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Chapter 3
A Systems Approach to Climate Risk in Rainfed Farming Systems

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Abstract Climate is a major source of risk in rainfed farming systems. Systems thinking from natural sciences is used to define and explore concepts of weather, climate and climate change before discussion of how climate data can be used in simulation models of agricultural production systems. We then use systems engineering to consider the nature of climate risk and the use of seasonal climate forecasts in managing risk in rainfed cropping decisions in case studies from Australia and the Philippines. Finally, we consider some of the human factors in managing climate risk using soft systems methodology.

Keywords Climate risk • Weather • Climate variability • Climate change • Vulnerability • Resilience • Systems approaches

3.1 Introduction – Climate Risk and Systems Thinking

Rainfed farming is risky. Perhaps the simplest notion of risk is the frustration many rainfed farmers have with planning and budgeting, leading to the complaint that the only accurate item on a budget is the date. Charles Stern listed some of the risks facing farmers in southern USA in the late 1870s: *Returns are subject to several*

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_3,

contingencies, such as follows. Your corn may not be planted early enough. The hogs may destroy one-fourth of it, the rains an eighth, and the thieves an eighth; and the drought a large portion of the remaining one half. Your cotton may not come up well, and you may not get a good stand to begin with. It may rain too little, and it may rain too much; and it may be overrun by the grass. Or the rust may take it, the army worm, and the grasshoppers may commence their ravages: or other worms may strip the stalk of its foliage, and then an early frost may nip it in the bud. But if none of these things occur, you are quite likely to get good crops; and then if none of it is stolen, and your gin house does not burn down, you may be fairly recompensed for your labour. But if any of these things happen, your profits of course will be less. (Charles Sterns 1872 cited in McGuire and Higgs 1977).

Risk is more than the notion that things can go wrong; rather it refers to outcomes (both good and bad) for any decision. Giddens (2002) maintains that the idea of risk came to the English language through Spanish or Portuguese where it referred to sailing into unchartered waters, with the chance of great gain weighed against the chance of loss. Along with risk came the value of information, not as provided by soothsayers or prophecies of the future, but as risk assessments and forecasts. Success and failure in rainfed farming has much to do with taking both the risks and the opportunities presented by climate.

This chapter addresses ways that a systems approach can be used to think about managing climate risk in rainfed farming systems. The risks from climate range from extreme weather events such as a heatwave or a frost, to year-to-year climate variability manifest in the timing and amount of rainfall in the growing season, decadal climate cycles and climate change. For understanding and managing climate risk in rainfed farming systems, systems concepts outlined in Chap. 1, such as defining the goal of a farm enterprise, looking for interactions and feedbacks within the farming system and between the farm and natural systems, are useful. When considering the notions of climate variability and climate change systems concepts such as stability, sustainability, flexibility, adaptability and resilience can be powerful tools.

Perhaps the most common use of climate information in relation to farming systems is in classifying them according to their average annual pattern of rainfall and temperature, for example Mediterranean or subtropical farming systems (Tow 1991, Chap. 2 this volume). The long-term climate characteristics of a region are key determinants of strategic choices such as the appropriate enterprise mix to pursue (ratio of livestock to cropping), which crops to grow (summer- or winter-growing crops and long duration or short-duration ones) and the optimum sowing times. Such climatic information can be derived from geographical and long-term meteorological data. Access to good historical meteorological data is essential for modelling and quantitative risk assessment. Extrapolating data from weather stations that are unrepresentative for the particular farm introduces new sources of risk. As discussed in more detail later in this chapter, climate change means that care needs to be taken when decisions are based on any historical data set.

Agroclimatic information is tied to experiences, and this may vary from generation to generation. For example, farmers may be enticed to use crops or practices suited to the rainfall and temperatures they have experienced over, say, a decade of benign climate. If such a climate is experienced during a farmer's formative years, it may be regarded as 'normal', but this experience can mislead perceptions of 'normal' rainfall. Thus, although farmers may be aware of rainfall variation from one generational period to the next, they may still regard the climate of their own period as normal in their approach to climatic risk. In a social history account of development on the southern high plains of America, Opie (1993) argued that one of the difficulties for the frontier farmer was separating the useful information (signal) from the misleading information (noise) – the long history of the arid region being the signal and the temporarily good seasons, the noise. Mabutt (1981) reviewed the movement of cropping into the northern lands of South Australia in the last quarter of the nineteenth century (past the Goyder line[1]) and into the Mallee lands of South Australia and Victoria during the first half of the twentieth century. He argued that the Australian situation was analogous to North America whereby initial optimism was boosted by a run of better seasons which the new settlers perceived as normal. McKeon et al. (2004) traced the history of degradation in Australian rangelands and showed that degradation was episodic and followed the pattern of a run of good seasons when stocking rates increased followed by a severe drought and collapse in carrying capacity. With long-term climate change, a general principle is that ecosystems are likely to move higher in altitude and poleward; ecological studies suggest that this is what has happened in past warming events. The boundaries of agroclimatic zones will therefore shift in a changing climate (Cline 2007; Howden et al. 2007) and this will present a series of risks and opportunities.

In addition to variability on a decadal scale and climate change on a multi-decadal scale, year-to-year variability influences which crop can be grown as well as tactical decisions such as sowing dates and fertiliser rates. Decision making is difficult as farmers must allocate scarce resources each season on the basis of their expectation of the coming season; hence the interest in assessing and managing climate risk and using tools such as seasonal climate forecasts and simulation models. Later in the chapter we will discuss an example of how seasonal climate forecasts and simulation models have been used in rainfed farming in case studies from Australia and the Philippines.

In writing this chapter, we are assuming that the reader has access to the many texts describing and comparing climates of different rainfed farming systems. More recent texts describe the drivers of climate variability such as the El Niño[2]–Southern Oscillation (ENSO) phenomenon. There has also been an exponential increase in works on the science of climate change and its projected impacts on rainfed farming systems. In recent years, there has been a change from a shortage of good information on the effects of climate on agriculture to an information overload. Systems thinking can provide a framework to deal with this overload.

[1] See Glossary.

[2] See Glossary for explanation.

Rainfed farmers dealing with climate risk are unlikely to use terms such as ‘system thinking’ yet, in many ways, farmers are practitioners of systems thinking. Conway (1985) maintained that farmers, of necessity, adopted a multi-disciplinary, holistic approach to their work and argued that those working with farmers also needed to adopt a systems approach to be relevant. Systems thinking may be an important way for the disciplines of climate applications and agricultural science to make their information relevant to farmers and their production systems, in a variable and changing climate.

3.1.1 What Is Meant by Systems Thinking in Agriculture?

The case for a systems approach or bringing the ‘science of wholeness’ to management problems in agriculture has been frequently stated (Dent and Blackie 1975; Spedding 1979; Squires 1991; Bawden and Packham 1991; Ison 1998 and in Chap. 1 of this book). Not only has the systems approach been deemed appropriate for general problems of agricultural production, it has been specifically applied to managing climate risk. For example, Parry and Carter (1988) argued that the climate impact studies, which dominated the literature until the mid-1970s, treated agriculture as passively exposed to climate. They called for a systems approach which emphasised the need of agriculture to interact with, and adapt to, a variable climate. Similarly, Hammer and Nicholls (1996) maintained that a systems approach was essential to ensure that available climate information was appropriate for management decisions. Much of the recent discussion on the response of agricultural systems to climate change (their resilience, vulnerability and productivity and the need to develop adaptive learning capacity in farmers) has roots in systems thinking (e.g. Walker and Salt 2006; Howden et al. 2007; Nelson et al. 2008).

For the purposes of this chapter, three different traditions of systems thinking will be used:

1. *The natural science*, which provide many of the key concepts and examples of systems thinking; this is evident in agroecosystem analysis (Conway 1985) and in many aspects of climate science. Concepts covered in Chap. 1 such as emergent properties, boundaries and feedback are relevant to climate science and to the application of climate science to farming systems. Resilience is the ability of a system to absorb disturbance and still retain its basic structure and function (Walker and Salt 2006) and this is similar to the notion of stability used by Conway (1985). These ideas are used to think through the impact of climate on rainfed farming systems.
2. *Systems engineering and applications such as Operations Research* – which have more to do with manufacturing than natural systems – have provided most of the tools for assessing and managing risk in rainfed farming systems. Concepts such as system optimisation, efficiency and productivity underpin these tools. Techniques such as influence diagrams that can be used to map the key risks and key decision points are powerful for moving beyond describing the impact of

climate on farming systems to managing the impact. An important way of moving from impact of climate on farming to management of climate risk is to identify leverage points where decisions can make a difference – this might simply be time of sowing or choice of crop. Systems analysis is valuable in identifying trade-offs; for example, a high input crop may give higher returns but this comes with higher risk. The case studies in Sects. 4 and 5 of this chapter give examples of systems analysis.

3. *Soft systems*[3] *methodology* recognises the complexity of human involvement in farming systems. These methods have much that is relevant to managing risk as it explicitly allows for different people's perspectives on the issue of characterising and managing risk. These methodologies recognise that people's worldview will colour their sense of priorities. Whereas systems engineering may try problem mapping, soft systems methodologies are more likely to refer to issue mapping to build up a rich picture which can be improved rather than isolate and solve a problem.

A brief summary is provided in Table 3.1. The differences between Hard and Soft Systems in the context of land use planning in India is discussed in Nidumolu et al. (2006). They found that land use planning tended to have a much greater emphasis on biophysical data and hard systems approaches whereas soft systems provided a greater understanding of why farmers used land in different ways. Rather than enter into arguments about which systems framework is the best for studying the management of climate risk, the different views within different frameworks in a complex multifaceted area can each be regarded as useful.

Table 3.1 Characteristics of three traditions of systems thinking used in this chapter[4]

Applying concepts from ecology of natural systems	
Purpose	Understand and predict the impact of climate and variations in climate on farming as a biophysical system.
Concepts	System boundaries, emergent properties, feedback, stability and resilience
Tools	Climate models, agricultural production simulation models
Applying concepts from systems engineering	
Purpose	Identify decision points in rainfed farming systems that can be used to manage climate risk
Concepts	Systems optimisation, trade-offs between decisions , productivity, efficiency
Tools	Problem mapping, simulation modelling, influence diagrams, decision analysis
Applying concepts from soft systems methodology	
Purpose	Explore different people's perspectives on climate risk-
Concepts	System purpose, worldview, social and ecological resilience
Tools	Surveys, semi-structured interviews, issue mapping

[3] See Glossary for definitions of Hard and Soft Systems methodology.

[4] See glossary for any unfamiliar terms.

3.2 Using Systems Approaches from Natural Sciences to Understand Weather, Climate Risk and Farming Systems

3.2.1 Climate at Different Scales

System thinking has been likened to an enzyme converting indigestible complexity into something more easily understood (Wilson 1988). Climate is complex – partly because there are so many interactions between the atmosphere, land and the oceans. Furthermore, there are both fast-moving variables in the atmosphere and slow-moving variables such as soil moisture and sea surface temperature. Concepts of boundaries, hierarchies, emergent properties, feedback, and interaction between sub-systems are important in modelling and understanding climate. These concepts are also useful in the task of disentangling concepts of weather, year-to-year climate variability and climate change and their associated risks. Not only are there different decisions made on a time scale of weather, seasonal climate and decadal climate change, there are important differences in the sort of information available from climate science at these scales.

Figure 3.1 shows atmospheric phenomena ranging from a small-scale short-duration local event to global, long-term ones. We experience climate through local weather events. While the strongest evidence of a changing climate lies in the steady increases in global temperature, the most dramatic impact is through weather events such as cyclones and heat-waves and seasonal events such as droughts. Thus in Fig. 3.1, local weather events are in the bottom left-hand corner, yet the strongest

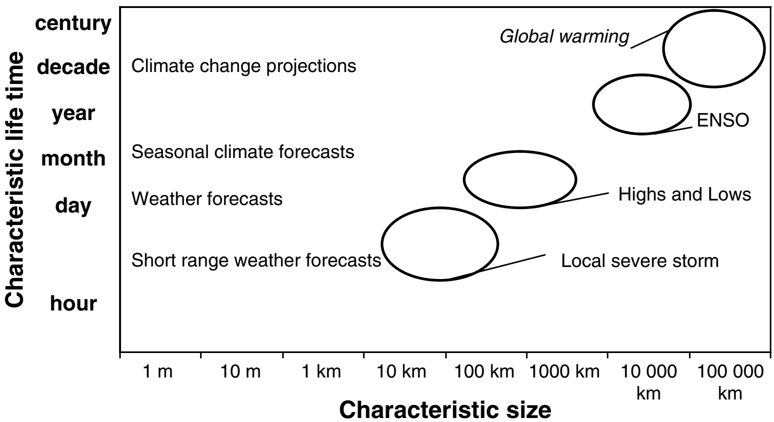

Fig. 3.1 Time and space scale of atmospheric phenomena (modified from WMO graphic). Both axes are logarithmic, a local severe storm may be forecast and have an impact in a radius of 10–100 km, whereas high-pressure systems that cross Australia are 2,000–3,000 km across. The impact of ENSO is at a continent scale and, as the name suggests, global warming affects the planet

evidence for changing climate is from global aggregated data (top right-hand corner). The different boundaries in terms of time and space are associated with different impacts; a single weather event such as a frost or heat-wave is likely to have an impact only on a region; droughts, especially El Niño-related droughts, often have an impact at a national and international level; climate change is global and will have different impacts on different farming systems around the world, and will also influence the non-farming sectors such as energy and transport. The nature and complexity of the risks change at the different levels; a local weather event such as an untimely frost contributes to production risk, widespread drought can influence production and price risk and global climate change will contribute to production, price and input cost risk. Many rainfed farmers find that their most profitable years are when production risk somewhere else has created reduced output and led to increased prices.

3.2.2 Concepts of Weather, Climate and Climate Change

Weather is a 'snap shot' of the atmosphere at a particular time. If climate is what is generally most likely to occur (i.e. what you expect); weather is what you get. Weather is understood to be determined by the timing of individual synoptic events such as a cold front or high-pressure systems and can last between a few hours and a week. The conventional time for climate is 30 years (often the period 1960–1990) which may be too short for analysis of drought, especially if using the fifth percentile or 1 in 20 event to define drought. In much of Australia, the 30 years from1960 to 1990 received rainfall above the long-term median and hence can be misleading for risk management if taken as the 'normal' climate.

Climate change is any long-term significant change in the 'average weather' that a given region experiences. It involves changes in the variability or average state of the atmosphere over durations ranging from decades to millions of years. These changes can be caused by dynamic processes on Earth, external forces including variations in solar intensity and, more recently, by human activities. We will return to a systems understanding of the causes of climate change shortly, but first it is important to recognise that climate has always varied on all time scales and hence is a source of uncertainty and risk for decision making on different time scales. Surveys with rainfed farmers in both Australia (Hayman et al. 2007) and the Philippines (Predo et al. 2008) indicate confusion between weather, climate and climate change. The distinction is important to understand the information available from climate science and the decisions made in farming systems.

While climate is often expressed as the average or most common conditions, this can lead to the mistaken concept that climate is constant year by year and decade by decade; thus it is important for descriptions of climate to include extremes and frequencies of events such as droughts, heatwaves or frosts. Maunder (1989) asserted that the climate archive was rarely used for planning and risk assessment until the 1950s because, although treating climate as constant was at odds with experience, it was convenient for planning. The Sahel drought of the 1970s is widely recognised as having a major impact on global opinion about climate variability and possible climate change. The discussion of expanding deserts (desertification) opened up the distinction between cyclical drought and a longer-term process of creeping aridity or desiccation, described by Hare (1987) as *"a prolonged, gradually intensifying nightmare from 1968 to 1984",* only to be relieved with good rains in 1985 and 1986. Unfortunately recent conditions in the Sahel are dry, again implying an effect of climate change (Dai et al. 2004a).

UNESCO (1977) defined bioclimatic zones based on the aridity index P/ETP, where P = precipitation and ETP = evapotranspiration. The hyperarid zone (P/ETP ≤ 0.03) is desert with ephemerals and shrubs in river beds; the arid zone (0.03 < P/ETP < 0.20) has sparse perennial and annual vegetation utilised by grazing systems; the semi-arid zone (0.20 < P/ETP < 0.5) is a region where rainfed farming is widely practiced but plants suffer water stress during some part of the growing season. The sub-humid zone (0.5 < P/ETP < 0.75) is more favourable for rainfed farming. The Food and Agriculture Organization of the United Nations (FAO 1978) categorises climate on the length of the growing period (days when the mean temperature is warmer than 5° and precipitation exceeds half the potential evapotranspiration). Less than 59 days is considered arid, 60–119 days semi-arid, 180–269 as sub-humid and more than 270 as humid (Fischer et al. 2002).

Such zonation schemes are useful tools to define boundaries and understand rainfed farming systems but, when a key parameter is rainfall, long-term mean monthly data hide important parameters such as variability from year to year in the timing and amount of rainfall. Thus locations with similar predictions of plant growth based on long-term mean data can have very different probabilities of good pasture growth and cropping success.

3.2.3 Weather and Climate Forecasting

The difference in time scale between weather and climate is also important in understanding the process of developing a forecast. Weather forecasts are mostly based on numerical models; these are initiated from the current state of the atmosphere and used to predict future states of the atmosphere, including the timing and amount of rainfall for up to 10 days ahead. Rainfed farmers have little difficulty using these categorical weather forecasts for up to 4 or 5 days in advance.

In contrast, seasonal climate forecasts typically give the chance (probability) of the next 3–6 months being wetter or drier (or hotter or cooler) than the long-term average. Rather than being based on prediction from the inherently chaotic dynamics of the atmosphere, they tend to be based on patterns of the sea surface temperature (SST) or associated atmospheric characteristics. There is good scientific evidence that changes in the patterns of sea-surface temperatures have an impact on the behaviour of the atmosphere for months ahead and over widespread regions. Nicholls and Wong (1990) showed that regions of the world that are influenced by

El Niño–Southern Oscillation[5] (ENSO) tend to have greater interannual variability than other regions at the same latitude and annual rainfall, but have a greater capacity to predict interannual variability in seasonal rainfall. Many decision makers would like categorical long-range weather forecasts that would tell them the day that the rainy season will start or rainfall on a given day, rather than seasonal climate forecasts; this is not possible. Using seasonal climate forecasts is better than guessing but well short of perfect knowledge. Using seasonal climate forecasts increases the chances of making a good decision—even though it may turn out not to be the most lucky one.

3.2.4 Climate Change

Climate change projections are different again from seasonal climate forecasts in that they have the added complexity of assumptions about future emissions of greenhouse gasses. About half of the uncertainty in forecasts of temperature by the end of this century is due to uncertainty about emissions; the other half is due to scientific uncertainty represented by alternative models of global climate processes.

Climate can be studied as a complex system. The Intergovernmental Panel on Climate Change (IPCC) suggests five sub-systems: the atmosphere, the hydrosphere (water in oceans, rivers and underground), the cryosphere (snow, ice and frozen ground including permafrost), the land surface (lithosphere) and biosphere. There are three sources of change for this climate system:

1. The climate system will change and evolve over time due to interactions between component parts; for example, El Niño events are naturally occurring shifts in energy in the tropical Pacific Ocean that have impacts on most continents (Ropelewaski and Halpert 1987). A run of decades with a higher frequency of El Niño events can have far reaching impacts on the climate system. It is important to recognise decadal variability – for example, the major impact of a decade of low rainfall on American rainfed farming systems creating the 1930s 'dust bowl'.
2. Natural external influences such as solar variations due to the orbital tilt of the earth, sunspot activity or volcanic eruptions – well understood to cause climate change. As the world warms due to the orbital tilt, the oceans release carbon dioxide which provides a positive feedback on the warming process.
3. Human-induced changes due to increased greenhouse gases, land use change and aerosols. The argument of climate science is that recent warming cannot be explained by internal forcing or by natural forcing, and that most of the recent warming is due to greenhouse gasses released by human activity.

'Global warming' is defined as the gradual increase in global average surface temperature as one of the consequences of increased greenhouse gases. The term

[5] See Glossary.

'climate change' is more commonly used than global warming because of the many changes to other climatic parameters such as rainfall, wind and evaporation.

The importance of greenhouse gas emissions from agriculture (carbon dioxide, methane and nitrous oxide) has highlighted that, not only does climate influence farming, farming practices also influence climate. Agricultural science now has had to look increasingly beyond artificially tight boundaries around production systems and consider off-site impacts on the surrounding environment of land and water (Chap. 13). The emerging challenge is to consider off-site impacts of farming on the atmosphere through the release of greenhouse gasses. These interactions become further complicated when considering the role of agriculture as a means of sequestering carbon in the soil, in crop residues, in pastures and through agroforestry. Even further complexity is added as agriculture is considered as a source of biofuels. The role of agriculture in production for biofuels has raised the need for lifecycle analysis[6] of the energy involved in making the fertiliser to grow the crops that are used for biofuel production. Further, it has highlighted the interactions between the area of land cropped and international agricultural commodity prices. When asked about risks and opportunities from climate change, some rainfed farmers and analysts see the greatest risks and opportunities coming from national and international policies to reduce greenhouse gasses. This is apparent when agriculture is considered both as a source of greenhouse gases and also a sink for carbon in soils and plants and a supplier of biofuels (Keating and Carberry 2008; Keogh 2008).

Figure 3.2 provides a framework for considering confidence and uncertainty with respect to climate change. The vertical arrows represent a high level of confidence in the evidence that global climate is changing and strong evidence that most, but not all, of this change is due to changes in greenhouse gasses in the atmosphere. It also stands to reason that changes to global climate will have an impact at

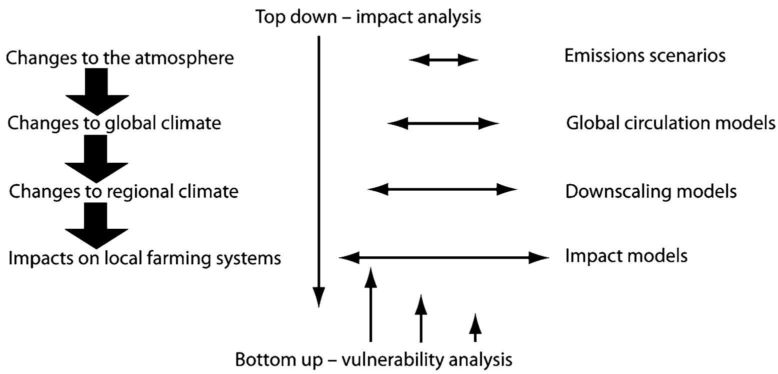

Fig. 3.2 The cascading uncertainty in climate change projections; the solid vertical arrows represent the links between the different levels and the changing length horizontal arrows represent the increasing uncertainty – adapted from Schneider (2004)

[6] See Glossary.

regional and local levels as indicated with the vertical arrows and this will have an impact on activities that are sensitive and exposed to climate such as rainfed farming systems.

When it comes to impacts of climate change at a regional level, each horizontal arrow is wider than the level above; in other words there is cascading uncertainty. The different levels of greenhouse gasses or emission scenarios provide uncertainty which is further increased by the way alternative global circulation models translate an increase in greenhouse gasses to global warming. There are further differences in the projections of global circulation models to regional climate and then questions of how these changes in climate will influence rainfed farming. Climate science tends to use the term projection rather than the more common term prediction. This is because about half the uncertainty in what the global temperature will be in 2,100 is due to the level of greenhouse gasses in the atmosphere at that time and half is due to scientific uncertainty on the impact of a given level of greenhouse gasses on global temperature. Unlike predicting the weather for tomorrow, the climate in 2,100 depends on the level of population growth, and the greenhouse gas emissions associated with future economic growth.

As shown in Fig. 3.2, there are two complementary approaches to considering the impacts of climate change. The first is a top-down[7] approach of getting the projections and considering what impact they will have on agriculture and the second is to consider a bottom-up approach to identifying what level of changes in climate will make the farming system vulnerable to failure.

Figure 3.2 has four levels: changes to the atmosphere; changes to global climate; changes to local climate; and impacts on local farming systems. As individuals and societies we have a choice about the changes to the atmosphere; however, the next two levels in Fig. 3.2 relate to scientific uncertainty on how sensitive the climate system is to different levels of greenhouse forcing and how the global change in climate will manifest at a regional level. While we can conduct research on these questions to reduce the uncertainty, we cannot change the final outcome. However, it is possible to influence the outcome at the fourth (farm) level in Fig. 3.2. The better prepared and resourced local farming systems are, the less they are likely to suffer from climate change. Climate variability will continue and, in some situations become more extreme, over the decades as the climate changes. The best preparation by a farmer for the early stages of climate change is to understand how to manage climate variability.

A consequence of warmer mean growing-season temperatures will be a longer growing season in regions where low temperature is the limit – as in many cereal growing regions of the Northern hemisphere. In some regions of the cereal belt of Australia where hot, dry conditions end the growing season, warmer temperatures will reduce its length. Because most plants effectively measure time by temperature, modelled as degree days, increased mean temperature will lead to faster development. Because crop development is dependent on cumulative temperature, even small

[7] See Glossary for definitions of top down and bottom up approaches.

changes in temperature add up to significant changes in wheat phenology (Sadras and Monzon 2006). Not only will crops develop faster but, since the lifecycle of insects is also temperature dependent, there are likely to be important changes in pest incidence.

Changes in extreme temperatures such as heatwaves are likely to cause major damage to crops, pastures and livestock. Although frosts are likely to decrease in the longer run, it is possible that the warmer average temperatures will shift sensitive crop stages into earlier higher frost risk times of the year.

Although less certain than changes in temperature, changes in rainfall are also likely, with an expectation of increased frequency of drought across many parts of the world (Dai et al. 2004b; IPCC 2007). Changes in evaporation are complex outcomes of changes in radiation, windspeed and temperature. If radiation and windspeed were to stay the same, potential evaporation will increase by about 4% per °C of warming.

One of the tools used to understand the interaction of climate change in farming systems is simulation modelling based on the four key environmental inputs for crop growth namely water, temperature, incident solar radiation and nutrients. Simulation modelling provides a quantitative way of accounting for how these environmental inputs interact with plant growth, development and, for crop plants, yield partitioning. The impact of climate on rainfed farming can be represented formally through detailed simulation models, such as CERES, APSIM or GRASSGRO,[8] using daily climate data. Simulation models have relied on the understanding of interactions occurring in natural systems, and are a powerful way to describe the impact of a warmer, drier world. They can also be used to understand the essential role of management in adapting to climate change and managing year-to-year variability. An example is the use of the cropping simulation model APSIM Yield Prophet (Hunt et al. 2008) where farmers can enter details from their own fields through the season and access updates of simulated yield via the internet (see Chap. 37). The application of simulation modelling to the challenge of climate variability and climate change has been within the framework of systems engineering.

3.3 Using Systems Engineering to Manage Climate Risk

Agricultural science, despite obvious links with biology, has primarily adopted the engineering treatment of systems, largely based on a machine metaphor. This is not surprising given the applied nature of agricultural science and the industrial treatment of a farm as a factory converting inputs – whether natural (radiation and water) or synthetic (fertilisers and fuel) into outputs. McCown et al. (1993) drew attention to the strong links between operational research (OR) and the systems approach familiar to most agriculturalists since the early 1960s. They pointed out that the main similarities were: (a) the problem of

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[8] See Glossary for description of various simulation models.

researching complex systems where risk is important; and (b) the method of using simulation experiments based on process models.

Case studies later in this chapter show how simulation models such as APSIM and CERES, used with historic weather data, are powerful quantitative tools to compare management options and their associated risks. These tools can also be used to explore how seasonal climate forecasts can be used in management (Meinke and Stone 2005; Meinke et al. 2003).

Seasonal climate forecasts (SCF) are potentially a powerful tool available to agricultural producers to manage production or other risk. SCFs offer skilful, but uncertain, information on future climate conditions, expressed as probabilities for periods of generally 3–6 months duration. We use the term 'skilful' to mean that the forecasts provide a better indication of a coming season than simply relying on the all-year, long-term climate record.

Because climate will always contain uncertainty, SCFs are best interpreted as shifts of the climatological probability distribution (Hansen 2002). These new probability distributions are potentially valuable if they enable the decision-maker to allocate resources better between poor years and good years.

One of the tools of operations research is decision analysis, which identifies the outcome (profit), the decision nodes (e.g. fertiliser rates) and the chance nodes (e.g. the seasonal rainfall). A probabilistic forecast of seasonal rainfall, or of wheat yields under different fertiliser rates, is likely to lead to better decisions and higher profits over the long term. A seasonal forecast might be in the form of '70% chance of above-median rainfall'. Care should be taken to not just select a single year when the forecast was followed and a good outcome occurred. For example, if extra fertiliser is applied when above-median rainfall is forecast, this will lead to gains in 70% of the years (but no change or losses in 30% of the years). Most studies of the economic value of seasonal climate forecasts have been cast within the framework of Expected Utility Theory[9] and assume a Bayesian[10] revision of probabilities of particular climatic states (Marshall et al. 1996). The value of the climate forecast is the change in expected utility resulting from the more informed decision. In the following sections, this basic framework has been applied to decisions of crop choice of wheat or sorghum on the Liverpool Plains in eastern Australia and of corn or grazed fallow in the central Philippines.

3.4 Example from Liverpool Plains in NSW

Situated in northern NSW in the southern edge of the northern cropping belt (see Fig. 3.3), the Liverpool Plains are amongst the most productive farming regions in Australia. This is largely due to the combination of fertile, high water-holding

[9] See Glossary for explanation.

[10] Bayes' theorem relates the conditional and marginal probabilities of two random events. It is often used to compute posterior probabilities, given observations.

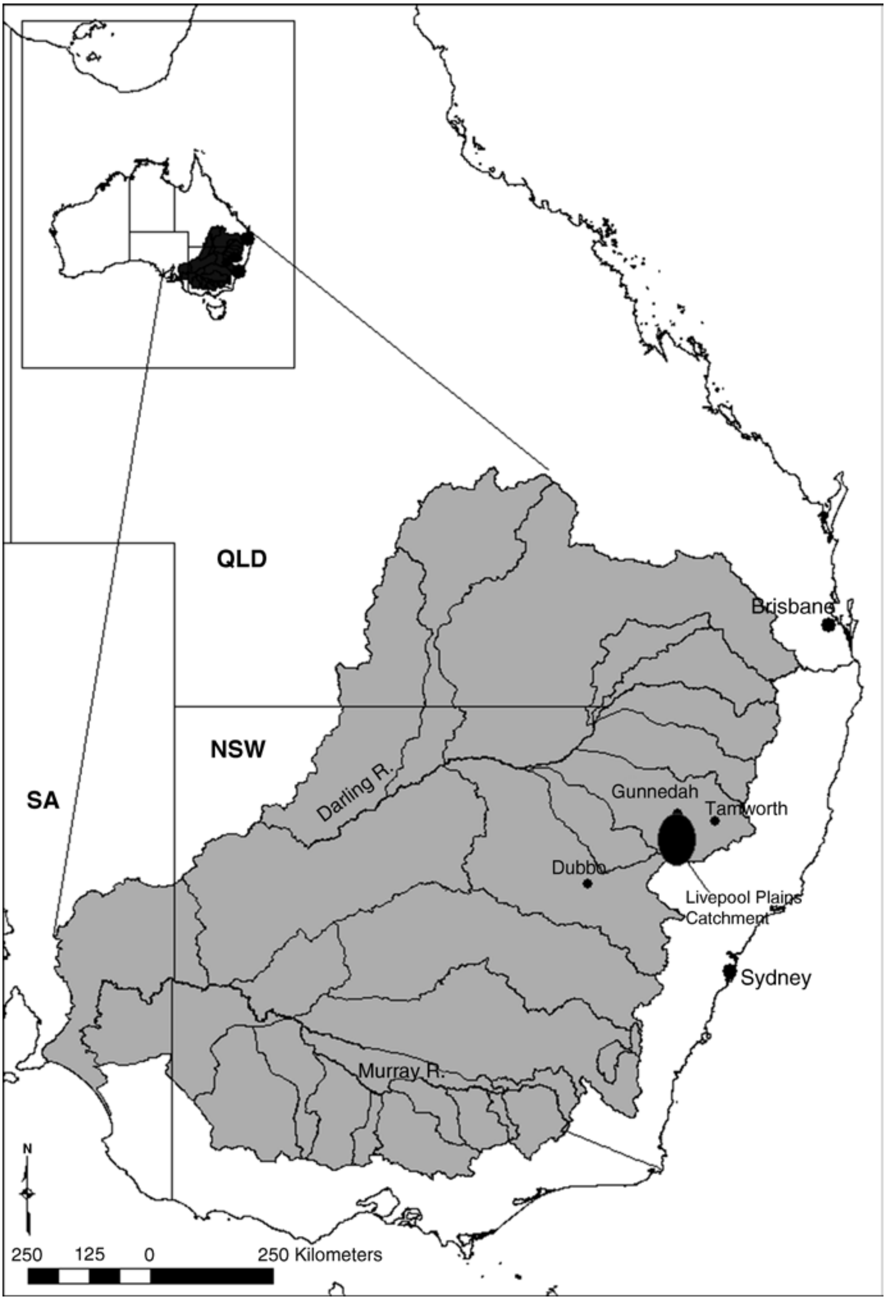

Fig. 3.3 Liverpool Plains Catchment – part of the Murray Darling Basin (*shaded*). Generated from data originally from Geosciences Australia

Table 3.2 Mean monthly rainfall (mm), pan evaporation (mm) and maximum and minimum temperature (°C) for Gunnedah, NSW (Source: Rainman-Clewett 2003)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rain	72	66	48	38	43	44	43	42	40	55	60	68
Evap	279	221	189	135	90	66	78	96	117	164	234	298
T^{max}	32	32	30	26	21	17	17	18	22	25	28	32
T^{min}	19	19	16	12	8	5	4	5	8	12	14	17

capacity soils and a climate that allows both winter and summer cropping. The mean annual rainfall is relatively high (580–680 mm). However, rainfall is variable with an average of 60% occurring during summer, and mean evaporation rates exceed mean rainfall in every month of the year (Table 3.2). Reliable cropping depends on storing water over a fallow for use by the subsequent crop.

The Liverpool Plains provide an interesting case study for managing climate risk in rainfed farming systems because of the contrast between (1) conservative but inefficient risk management through long periods of fallow and (2) an approach that responds to the variable climate and sows a crop whenever soil moisture reserves are judged by the farmer to be adequate. This is known as opportunity cropping, or sometimes as response cropping or flexi-cropping.

Long fallow–wheat–sorghum rotations have been widely practiced in the region since the 1970s. In this system, wheat is harvested in early December and the land is left fallow over the coming summer *and* winter months. Sorghum is then planted in the following November and harvested in March. The land is then left fallow for the winter and the following summer before wheat is planted in June. This means that one crop of wheat and one of sorghum is grown over a 3-year period. Long-fallow rotations are simple to implement, provide good disease and weed control and minimise cropping risk by ensuring crops are generally sown on a nearly full profile of water. While building up adequate soil water reserves under fallow may take up to 12 months in a dry year, 1 or 2 wet months under fallow can be adequate to fill the soil profile. Long-fallow systems can waste potentially profitable cropping opportunities, and are thought to be contributing to excessive deep drainage and possible salinity through rising water tables because of the limited time in which crops are actively growing.

In contrast to long-fallow systems, the practice of opportunity cropping involves sowing a summer or winter crop whenever stored soil moisture levels are considered to be adequate. Studies of opportunity cropping suggest that tighter cropping sequences lead to higher profit and reduce erosion and deep drainage[11]; but they are more risky because there is greater chance of crop failure when crops are planted on less than a full soil moisture profile. Growers have developed various sowing rules for opportunity cropping based on availability of some minimum level of soil moisture. This minimal soil moisture level will vary with location, crop prices,

[11] Deep drainage is important in this case as it may raise watertables and introduce salt into the root zone.

production costs and technologies, expectations of growing season rainfall and the grower's attitude toward risk. A common opportunity cropping system is based on a 70 W/90 S rule (sow with 70 cm of wet soil for wheat and 90 cm for sorghum) (Scott et al. 2004). Sowing rules of either 50 W/70 S or 70 W/90 S appear to provide a good compromise between reducing deep drainage from full profiles and having enough soil moisture to ensure profitability (Ringrose-Voase et al. 2003). The depth of wet soil is measured with a metal rod pushed into the ground; as a guide for these clay soils every 10 cm of wet soil equals 18 mm of stored soil water.

Under opportunity cropping, crop yields and financial return are influenced both by the level of stored soil moisture at planting and by in-crop rainfalls. An accurate forecast of growing season rainfall, as well as information on the level of soil moisture, could help growers decide whether a crop should be grown now or delayed to the next opportunity (either a rainfall event or changed forecast). Figure 3.4 shows wheat yields simulated by the cropping systems model APSIM under a range of phases of the Southern Oscillation Index (SOI)[12] that allow a forecast of seasonal rainfall to be made at the end of May. Simulated wheat yields using long-term climate data show that in the years when the SOI is rising (higher in May than April) simulated wheat yields have been higher; and when it is negative in April and May, yields have been lower.

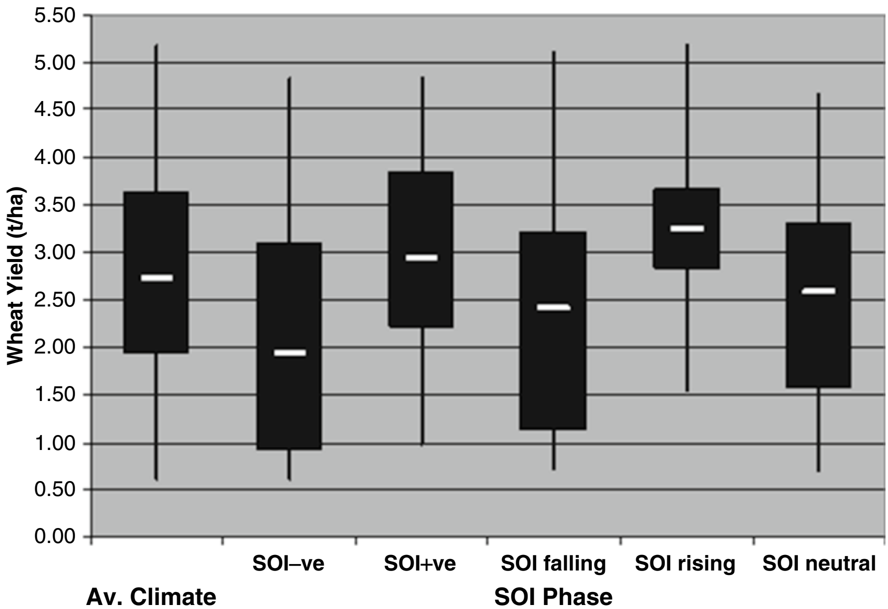

Fig. 3.4 APSIM simulated wheat yields for June sowing based on five SOI phases at the end of May. The box plots cover the 20th and 80th percentile, white line is median and the vertical lines show the 5th and 95th percentile. The box plot represents the distribution of simulated wheat yields under average climate and the years when SOI was in different phases at the end of May

[12] See Glossary for explanation.

The simulated wheat yields in Fig. 3.4 are all based on 100 mm of water in the soil at sowing. When there is less water in the soil, the yield difference between phases of the SOI is greater and when there is more water in the soil, the effect is dampened.

Because climate forecasts are imperfect, there are years when decisions taken in light of a forecast make the grower worse off rather than better off. Provided the forecast has some relevance and possesses some skill, over a long period of time, the benefits of following the forecast should exceed the costs. However, if a failure occurs in the first year that a farmer uses SCF, it may take a long time to recover the benefits calculated in a 100-year simulation, and the farmer may lose confidence in the forecast method (Robinson and Butler 2002). The forecast needs to indicate a significantly different probability distribution to the probability distribution based on all years. In other words, a farmer using the forecast has a different view of the risk profile of the coming season than a farmer who is just using the long-term climate record. Figure 3.4 shows that this is the case for wheat when the SOI is rising. In other words, for the 100 year record, not all of the 16 years when the SOI was rising had higher yields, but a greater portion were high yielding, as reflected in the distribution. However, under some circumstances of the relative prices of wheat and sorghum, it may be optimal to plant wheat, even without the forecast. In this case although the forecasts offers confirmation, it is difficult to put an economic value on the forecast because a farmer who used the forecast would take the same action as other farmers who did not have access to the forecast.

The greatest value of the forecast was that it moderated some of the risk of opportunity cropping. Opportunity cropping is a responsive form of rainfed farming that relies on responding to the status of the paddock in the form of disease, weeds and soil moisture, to the market signals for different crops and to the atmospheric signals for the SOI. A systems approach highlights that all of these, as well as other whole farm considerations, need to be thought through before making a decision.

3.5 Example of Corn Decision Making from the Philippines

In the Philippines, corn is the most important rainfed crop, second only to rice. About 30% of Filipino farmers grow corn as the primary crop and 20% of the population relies on corn as the staple food, especially in the central and southern islands of the archipelago. The main climatic limit to successful crop growth is rainfall, as air and soil temperature are always warm enough for germination and growth.

The Philippines is greatly affected by the El Niño–Southern Oscillation with the main impact being in the months from October to March (Harger 1995; Jose 2002; Hilario et al. 2008). The 1997/1998 El Niño event dramatically reduced both rice and corn production (Albarece 2000). Seasonal climate forecasting has been shown to have a potential benefit for risk assessment and decision making in both rainfed rice production in the Philippines (Abedullah and Pandey 1998) and corn production in the northern island of Isabella (Lansigan 2003).

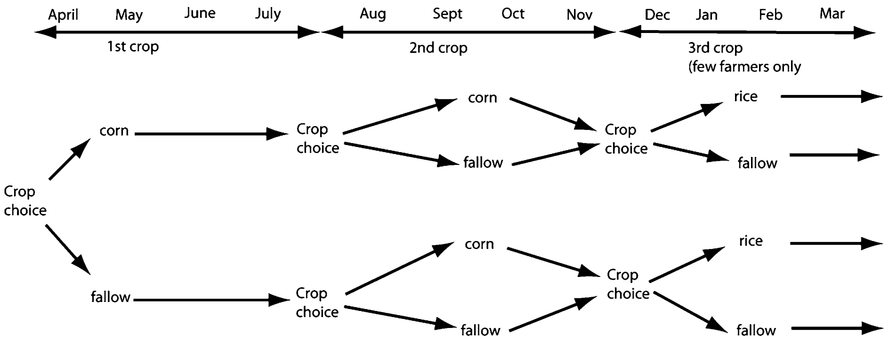

Fig. 3.5 Climatically-sensitive decision points for corn farmers in Leyte, Southern Philippines

Figure 3.5 shows the climatically-sensitive decision points for rainfed corn production in the study area of Mahaplag in the island of Leyte in the central islands of the Philippines, the Visayas. The fallow is a grazed fallow where livestock feed on volunteer pasture and weeds and is a low-risk, low-return option. The decision to fallow will mean that there is more water stored in the profile for the subsequent crop, but the main impact will be the mineralised soil nitrogen. The decision to plant corn in April or May needs to be made in March. The Philippine national meteorological service PAGASA issues 3-monthly forecasts and declares the states of El Niño and La Niña based on information from a number of international climate centres and models. In August, there is a second planting choice that will have been influenced in part by the choice in April whether to plant a crop or not, but also it will be influenced by the price of corn in August and the expectations of rainfall in the approaching season. A few farmers will consider a third crop planted in the wet season in January which could be corn or rice, but most will have a fallow and plan for corn the following April.

In the study area of Mahaplag, traditional varieties of white corn are the most commonly grown, followed by commercially available open-pollinated varieties, and then hybrid varieties. Hybrid varieties are potentially high return, but the cost of the seed and fertiliser also makes them high risk. Interviews with farmers indicate that climate risk is the primary barrier to growing hybrid varieties, especially when they have to purchase the seed and fertiliser on credit.

Figure 3.6a shows a time series from 1980 to 2007 of simulation results from CERES-Maize model within DSSAT v4[13] using local climate, soil and crop

[13] Decision Support System for Agrotechnology Transfer Version 4.0 CERES-Maize (Crop Environment Resource Synthesis) model is a predictive, deterministic model designed to simulate corn growth, soil, water and temperature and soil nitrogen dynamics at a field scale for one growing season. The model is used for basic and applied research on the effects of climate (thermal regime, water stress) and management (fertiliser practices, irrigation) on the growth and yield of corn. It is also used to evaluate effects of nitrogen fertiliser practices on nitrogen uptake and nitrogen leaching from soil; and in global climate change research, to evaluate the potential effects of climate warming and changes in precipitation and water use efficiency due to increased atmospheric CO_2.

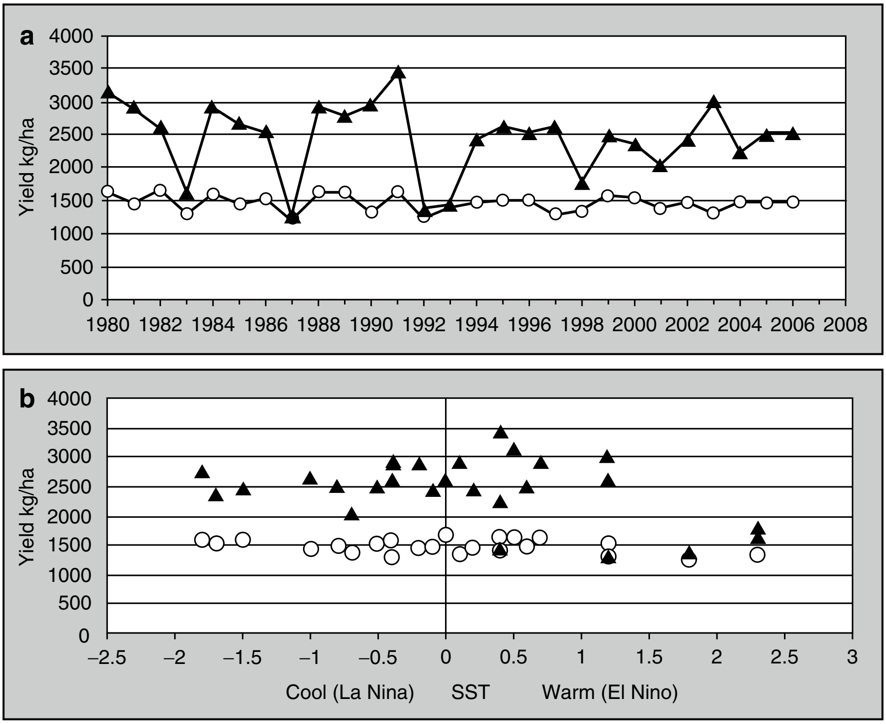

Fig. 3.6 CERES-Maize simulated corn yield showing hybrid corn with high fertiliser (*closed triangles*) and the traditional 'native' corn (*open circles*). Upper panel (**a**) shows simulated yield plotted as a time series and lower panel (**b**) shows the simulated yield plotted against an indicator of ENSO (Niño 3.4 sea surface temperature anomaly between December and February – see text for description)

development inputs. These results are for the first cropping season in Fig. 3.5. This shows that, on average, hybrid corn with the extra fertiliser is much more productive than the traditional variety. However, in some years (many but not all El Niño years) the yield of the hybrid corn is the same as the traditional variety and the high input costs lead to substantial losses. Although there is a range of definitions of El Niño years from different centres, the 1982/1983, 1986/1987, 1991/1992/1993, 1997/1998 and 2002 events show up as poor production years. 2006 was also an El Niño year but there was no dramatic impact on simulated corn production.

Figure 3.6b shows the same simulated yield data plotted against the sea surface temperature anomaly between December and February of Niño region 3.4[14] available from the Climate Prediction Centre of the National Oceanographic and Atmosphere Administration (NOAA). An anomaly that is more than 0.5° warmer

[14] See US National weather service Climate Prediction Centre .http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/nino_regions.shtml.

can be categorised as a warm event or El Niño and more than 0.5° cooler as a La Niña event. It is important to note that the SST data are available before the decision to plant corn or to choose the variety. The primary message from Fig. 3.6b is that extreme warm events in the tropical Pacific Ocean (>1.5°C) are associated with the worst outcomes for hybrid corn. ENSO-based forecasts have the potential for picking the low-yielding seasons and this should be of value to risk-averse farmers. The challenging message from Fig. 3.6 is that there will be mild El Niño events (greater than 0.5°C or even greater than 1°C) that do not lead to low yields. These false alarms may persuade a farmer not to plant corn or not to use hybrids. An example was the 2006 El Niño event when some farmers planned for a drought, but the seasonal rainfall was average. There is also one low-yielding year where the Sea Surface Temperature was only 0.4° warmer; this could be considered a bad outcome that was missed in the forecasting. A conservative approach would be to only plant hybrid corn in La Niña years (< −0.5°C), but this will result in missing many opportunities from the neutral years (> −0.5 and < +0.5). There is likely to be a benefit from following ENSO-based forecasts but the benefit will be aggregated over a number of years; in any single year, a farmer could be worse off following the forecast than another farmer who did not have access to the forecast.

3.6 Soft Systems

Managing climate risk in farming is a human activity. Many of the approaches used by agricultural science rely heavily on a systems approach from the natural sciences and systems engineering for what are essentially social activities. While all these approaches recognise that humans are involved, the question is how they are included in the description of the system. For example, an agroecosystem view tends to treat humans as an off-stage forcing function or, if included, human labour is an input and decision-making a control. Often the farmer is included as a single decision maker without reference to surrounding social and economic structures and culture. The soft systems movement contends that this is problematic. A summarising phrase for this system school is the title of Sir Geoffrey Vickers (1983) book, *Human Systems are Different*.

A logical outcome of the systems engineering approach is a decision support system that gives a farmer access to long-term climate records and combines this with simulation models whereby the outcomes of different management choices can be determined. A repeated finding from analyses of farmers' use of decision support systems is the disappointing level of their use, and much has been written on why this might be the case (Malcolm 2000; McCown et al. 2002; Hayman 2004). See also Chaps. 35–37. Ullman (1997), a computer programmer, reflecting on the limits of software for managers observed that a computer cannot look round edges as their dumb declarative nature cannot comprehend the small, chaotic accommodations to reality which keep human systems running. One of these chaotic accommodations to reality is intuitive, messy decision-making.

Decision-making is often treated as a step-by-step, conscious, logically defensible process, whereas management more often than not involves intuitive judgement which is continuous, rapid and perceptive. That is not to say that information from climate science and agricultural science is not useful; rather, it is only part of what is required for farm decision making.

One of the most challenging aspects of recognising the central role of people in farming systems highlights the point that the boundaries and emergent properties of the system are determined by the person defining the system. Flood and Jackson (1991) defined systems as 'situations perceived by people'; it follows that what is seen as part of a farming system (and what is excluded) depends on the perspectives of who is defining the system. The challenge of managing climate risk in a farming system will have different meanings for those considering the farm as (1) a biophysical ecosystem processing materials, (2) a business or production system generating income, or (3) a family farm integrated into the wider rural community. A banker might view a farm as a system in a different way from a partner in a family farm. Bawden and Packham (1991) argued that it is important to explicitly recognise that farming systems are mental constructs or figments of the imagination which are useful to structure debate. This implies that farming systems do not exist in the way a tractor or wheat crop exists; hence care must be taken in clearly defining the system and being aware that others may have alternative perspectives.

Just as there is human judgement in defining a farming system, there is human judgment involved in how a climate is described for a region and whether the emphasis is placed on averages or variability. This is apparent in discussion of drought policy (Botterill 2003; Hayman and Cox 2005; Wilhite 2005). After reviewing a series of definitions of drought, the Australian Drought Policy Review Task Force concluded that drought was essentially relative, reflecting a situation whereby there was a mismatch between the agriculturists' expectations of a normal climate and the climate at that time. Another definition is that a drought is when it is too dry for the usual agricultural enterprise. This raises the question of whether the usual enterprise is appropriate.

There is also a strongly human dimension in how we experience and remember weather and climate. As an historian, Sherratt (2005) observed that we cannot reliably remember climate because memory generates meaning – not statistics. He noted that our lives lurch between expectation and event, between the idea of climate and the reality of weather. Rainfed farmers and those working with them will always be talking about the weather, waiting for rain or worrying about too much rain at the wrong time. The composite of these events will make up their experienced understanding of the climate that they are working with. Farmers do measure rainfall and keep records of rainfall, yield and dollar returns and increasingly use spreadsheets and commercial software to reflect on different years. Nevertheless, most farmers will speak of the lived experience of drought, dust and floods.

Common terms in dealing with climate and farming systems such as risk and vulnerability are words used in everyday language but can mean quite different things to different people. In fields such as pollution and safety, scientists have been criticised for distinguishing between 'real risk' and 'perceived risk', because risk only makes sense in the individual and social and economic context of the decision maker. In one sense, all risks are perceived and all risks are real (Beck 1992). Psychological studies have identified various issues that influence the perception of risk including the subject's sense of control and worldview, whether a risk is voluntary, and the distribution of costs and benefits. Hazards judged as dreadful and unknown are also judged as the most risky. Climate is an interesting case in point; we all know that climate varies and that moving to another location involves a change in climate, but the notion of global climate change has a sense of dread, especially the notion of dangerous climate change. Identifying dangerous climate change for the planet as a whole is challenging. Identifying dangerous climate change for rainfed farming systems is more difficult than for natural systems such as a rainforest or the Great Barrier Reef because there are clever humans involved who will engage in active adaptation. Clearly there is a level of climate change that will be almost impossible to adapt to, for example Cline (2007) modelled the impact of 4° rise in global temperatures and showed that if this occurs, along with ecosystem destruction and massive flooding of low lying regions, that the world will face significant food shortages. The more difficult question is the impact of 1.0–1.5° warming that is expected by 2030.

Vulnerability in the context of climate change is usually viewed as the endpoint or residual of climate change impacts minus adaptation. However, vulnerability can also be a starting point characteristic generated by multiple factors and processes (O'Brien et al. 2004). The vulnerability of Australian and Philippine farmers to climate change depends on the likely changes to climate and how close their production systems are to climatic thresholds. It also depends on their wealth, resources and access to information. Successful rainfed farming systems have characteristics that make them resilient, but they can only absorb a certain number of disturbances before there are major changes to their basic function. Much of the thinking about farming systems has involved a notion of a variable, but stationary, climate. The implicit assumption is that there is a static envelope within which climate will vary. A changing climate implies a non-stationary envelope, and this requires adaptive management at the farm, regional and policy level (Nelson et al. 2008). Milly et al. (2008) noted that accepting non-stationarity would require a major rethink for teaching, research and the practice of water management. The same is true for rainfed farming systems where there is, up to now, an expectation that within any decade there will be some dry years, but these will always be interspersed with average and wet years; this fails to recognise decadal variability where certain decades are drier or wetter or the bigger challenge of climate change.

3.7 Conclusion

By definition, rainfed farming has to deal with climate risk. Systems approaches are useful to understand the interaction between farming systems and climate systems and to harness the enormous amount of information from climate science to minimise the risks and maximise the opportunities in rainfed farming. Understanding how climate interacts with farming systems will benefit from systems frameworks from ecology and biology; the task of managing climate risk will benefit from systems engineering but to understand how rainfed farmers manage risk will require methods from soft systems approaches.

Climate change takes us beyond classic risk management because more and more will be unknown. Accepting a non-stationary climate and a situation where uncertainty replaces risk assessments involves a shift from 'knowing' what will happen to learning from what happens and setting a range of hypotheses about what might happen and what the best response will be. This is the process of adaptive management. Systems thinking will be essential to this process.

Acknowledgements Crean and Predo's time was funded by the ACIAR project 'Bridging the Gap Between Seasonal Climate Forecasts and Decision Makers in Australia and The Philippines.' Hayman's time was funded by the same ACIAR project and a project with the Centre for Natural Resource Management. Dr Uday Nidumolu contributed useful discussion on soft and hard systems and the image for Fig. 3.3.

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Chapter 4
Water Availability and Use in Rainfed Farming Systems

Their Relationship to System Structure, Operation and Management

Garry J. O'Leary, Sue Walker, N.L. Joshi, and Jeff W. White

Abstract There is great diversity in rainfed farming systems with climate and soil type dictating, to a large degree, their primary structure. Profitable crop production requires efficient collection of water and then its effective extraction by the crop with minimal losses to evaporation, runoff, drainage and weed competition. The supply of water for rainfed crop production is primarily controlled by the seasonal pattern (summer or winter dominance), by intensity of precipitation and its interaction with the absorptive capacity of the soil. The relationship between water use and crop yield is close and positive and forms the basis of crop water production functions. In relation to the structure, operation and management of rainfed farming systems, we focus on optimisation of four primary components: (1) the delivery of water; (2) the capture of rainfall; (3) the portion of water available for crop production; and (4) the efficiency of conversion of water to a usable product, and how these can be used. Optimising the availability of water and its use is complex but subject to straightforward analyses. Management is aimed at maximising water supply and its efficiency of use. The ways that water availability is managed are diverse but strongly interconnected, and reflect differing biophysical and economic conditions. Our examples, from both developed and developing countries show that there is a common strategy despite the diversity.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_4,

Keywords Transpiration • Evaporation • Crop yield • Agronomic management • Weed control • Rainwater harvesting • Precision agriculture • Water productivity

4.1 Introduction

In semi-arid environments where water supply is the major factor limiting crop yield, management options can change the amount, pattern and efficiency of crop water use in order to increase or stabilise yield. These options include selection of drought-tolerant species, manipulation of crop morphology, reduction of weeds, pests and diseases and the use of cultural practices such as sequences of different crops, time of sowing, intercropping, use of fertilisers, fallowing, reduced tillage, stubble retention and water harvesting. While the availability of water through rainfall and soil storage influences the farming system, the design, operation and management of the whole system and its parts will affect subsequent water availability and efficiency of use.

Although genetic characteristics of crops will be important in optimising water use, agronomic options that directly impact water availability have even greater potential. Successful management of the interaction of crops with their water supply will provide enduring cropping systems.

The structure, operation and management of rainfed farming systems focus on increasing four primary components of their water economy: (1) the delivery of water; (2) the capture of rainfall; (3) the proportion of water available for crop production; and (4) the efficiency of conversion of water to a usable product.

4.2 Maximising Water Availability for Crops and Pastures and Water Use Efficiency

4.2.1 Water Use Efficiency (See Also Chap. 1)

Use of water in crops and pastures includes both transpiration (T) and soil evaporation (Es). Figure 4.1 shows that while crop yield increases with total water use (evapotranspiration, runoff and drainage) it is most closely related to transpiration. Maximising availability of water to the plant and its transpiration therefore depends in part on reducing losses due to Es, runoff and drainage.

A significant amount of water is used by crops before any grain is produced. During grain development, yield increases almost linearly with increase in water use (Fig. 4.1). Partitioning evapotranspiration (ET) into soil evaporation (Es) and crop transpiration (T) clarifies how improvements in overall water-use efficiency (WUE = yield/ET) can be achieved by reducing Es (Chap. 1). Soil evaporation varies according to the soil type and proportion of soil shaded by the crop canopy, but

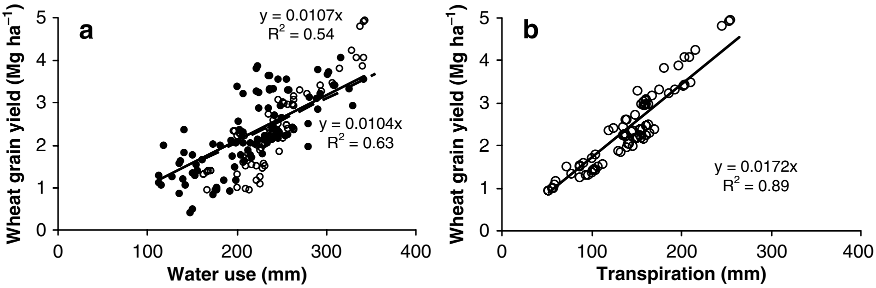

Fig. 4.1 The strong positive linear relationship between water use and wheat yield, (**a**) from 16 years of experimental results (●, —) and simulation modelling of water use results (○, – –) in southern Australia (from Latta and O'Leary 2003); (**b**) The close relationship between transpiration and wheat grain yield is shown by excluding soil evaporation and drainage losses through modelling

more importantly, according to the proportion of small rainfall events, which leave most of the water exposed close to the soil surface.

Transpiration efficiency (TE = yield/T) remains relatively stable in a given season. Any variability is related to TE being inversely dependent upon vapour pressure deficit (VPD) and related climate variables. Reducing Es remains the major way by which management can increase the proportion of water used in T and crop growth, and thereby increase WUE (Ritchie 1983; Cooper and Gregory 1987). A semi-arid environment provides more scope to reduce Es than an arid environment because crop canopies are typically larger and rainfall is more frequent (Yunusa et al. 1993).

Water production functions such as those shown in Fig. 4.1 define relationships between maximum or potential yield and water use, ET or T. They have been used, for example in southern Africa since the early 1970s, being developed from field measurements of the soil water balance components and crop yields for a wide range of crops, including wheat, maize, cotton, groundnut, lucerne and various vegetables. The functions were also compared across a wide range of climatic conditions (Streutker 1983a, b). They have been used in modelling, the effect of local climate being reduced by standardisation of the potential evaporation Eo following de Wit's method (Streutker 1980).

While any limiting factor affects system productivity, in semi-arid environments one of the most important influences on crop performance and the efficiency of water use is the interaction between available water and nitrogen (N) (Cornish and Murray 1989; Angus et al. 1993). In any season, there is an optimum supply of N for the available water and for maximum expression of yield potential (Joshi 1997). The analysis, measurement and management of this interaction of water and N supply for crop production are crucial in system design and management.

The concept of efficient use of water is largely scale independent, having relevance at scales from large mechanised production to small-scale subsistence agriculture. In India, a systems approach that integrates improved land, water and nutrient management in rainfed agriculture has demonstrated persistent increase in

WUE and yield (Wani et al. 2007). Different strategies will be applicable to minimise soil water losses in different climatic zones and soil types. Agronomic practices that change soil structure and crop geometry can alter the components of water use and therefore the productivity of the crop and WUE (Joshi 1999a, b).

The concept of water use efficiency (WUE) was made popular among Australian farmers by French and Schultz (1984a), who estimated a potential WUE of 20 kg/ha/mm transpiration for wheat. This enabled farmers to determine how close their crop yields were to the potential, whatever the rainfall. For situations where yields were clearly below potential, French and Schultz (1984b) identified a range of likely limiting factors which guided farmers to better manage their crops and their whole system. The benefit to the Australian grains industry was a focused effort by farmers to increase WUE, and therefore yield, towards its potential for a given water availability.

In the winter rainfall dominant regions where Es is related to frequent small rainfall events, more emphasis has been placed on increasing T by reducing Es. In summer dominant rainfall regions where winter crops grow on largely stored water, (Es thus being low), efficient water use is still needed (Richards et al. 2002). The aim is to maximise T whilst minimising Es. Maximising TE and overall WUE can be achieved together and are not mutually exclusive; both are achieved by raising yield per unit of water use.

4.2.2 Effects of Climate on Water Availability

Farming system structure depends on both amount and distribution of rainfall, as illustrated by examples given below. In the Mediterranean semi-arid climatic regions of the world (e.g. southern Australia; the Middle East and North Africa; parts of California; Chile and parts of the Southern Cape Province of South Africa) where most rain falls in the winter months, crop production depends mainly on in-crop rainfall.

In subtropical semi-arid regions, summer-dominant rainfall supports summer grown crops, but winter crops can also be grown if enough summer rain can be stored in the soil for use in winter–spring (as in southern India, and southern Queensland, Australia). In areas where rainfall is more evenly distributed, evaporative demand determines the amount of rain needed for crop production and therefore the time of year when crops can be successfully grown. For example, at Walpeup in south-eastern Australia, rainfall is only slightly winter dominant (Fig. 4.2) but high evaporation during summer confines the effective rainfall to a winter distribution. This supports annual crops only in winter, although perennial pastures such as lucerne can also use summer rain.

4.2.2.1 Example from India

Rainfall in India comes from the South-West summer monsoon which lasts for about 3 months. In the wetter, sub-humid zone (mean annual rainfall of about 1,000–1,500 mm)

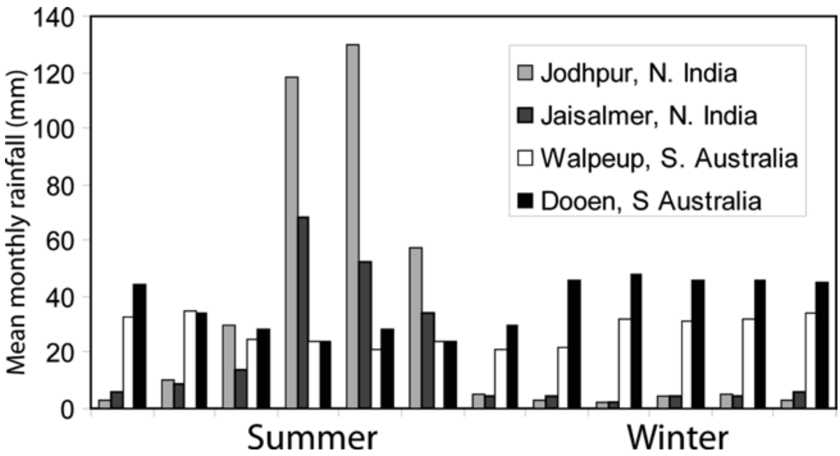

Fig. 4.2 Mean monthly rainfall patterns of two semi-arid rainfed farming regions in southern Australia and in northern India. Comparatively small differences in rainfall between near sites can result in quite different farming systems. (Note that because the Australian and Indian sites are in different hemispheres, their summers are in different calendar months)

Table 4.1 Mean annual rainfall, coefficient of variation (CV) and probability of occurrence of deficit rainfall in India (Singh et al. 2000)

Station	Zone	Mean annual rainfall (mm)	CV of annual rainfall (%)	Probability of occurrence of deficit rainfall (<75% of normal)
Jodhpur	Semi-arid northern India	369	55	51
Anantpur	Semi-arid northern India	568	30	38
Hyderabad	Semi-arid central India	767	29	31
Varanasi	Sub-humid southern India	1026	25	25
Ranchi	Sub-humid southern India	1434	21	20

in the southern peninsula, 90% of the rain falls during this monsoon season, beginning in June, and with a growing season of 120–150 days. The monsoon also extends to the northern semi-arid zone with about a 1 month lag. There, annual rainfall is about 300–600 mm, and the crop growing period is 90–120 days. During an active monsoon season, day temperatures remain around 28–30°C. Variability in precipitation increases with decreasing rainfall (Table 4.1).

Monsoon rainfall is generally inadequate to sustain high crop yields because high annual evapotranspiration ranges between 1,300 and 1,900 mm. The high crop water requirements and spatial or temporal variability in rainfall mean that severe water deficits typically occur 1 year in three. Crops and cropping systems are therefore chosen to match water availability and length of growing period in the region (Singh et al. 2000). For example, in southern India (high rainfall), the choice of crops for both the monsoon and dry seasons is wide, and includes groundnut, rice, pigeonpea, maize, castor bean, chickpea, gram, and lentil.[1] In the Rajasthan desert in the north, crops are grown only in the monsoon season. Pearl millet is the main crop but opportunistic crops of pigeonpea and gram are also grown.

4.2.2.2 Example from Southern Africa

The semi-arid regions of southern Africa have high rainfall variability which also increases with decreasing annual amount. The winter-dominant regions are in the southern part of South Africa, where the main crops are grape vines and barley. The largest grain-producing areas are, however, in the summer-dominant regions in the equatorial parts of the continent as well as the northern and central parts of South Africa (see also Chap. 16). In the summer-rainfall areas, little soil water is held over from the previous season, and planting must be delayed until the first rains. The onset of the rains triggers land preparation and planting. However, there is often a 'false start' when a small amount of rain is followed by a long dry spell. Crops planted in such situations may yield poorly or have to be replanted. In much of southern Africa, resource-poor farmers are able to plough only after the first rains, and any delay after this reduces yields.

In the higher elevation (>1,200 masl) semi-arid regions, the summer growing period is also limited by the timing of the first and last frosts. Even if the spring rains come early, the crop cannot be planted as the young seedlings could be damaged by frost. Thus much of this early rainfall cannot be used by the crop as it is lost as Es.

The climatic conditions in both Africa and India, whilst different, are managed with strategies that focus firstly on the water supply and then on other risks to production, such as frost or heat stress. The crop choice and tillage practices reflect the local farmer responses.

4.2.3 Effects of Climate Change

Recent concern over climate change has called into question the reliability of historical climatic patterns as predictors of future climate (IPCC 2001). Thus our understanding of climate patterns and crop response will likely evolve over time. Understanding crop response to the critical factors of water supply, temperature,

[1] See Glossary for botanical names.

radiation, CO_2, vapour pressure deficit (VPD) and nutrition are essential for assessing the impacts of climate change. However, any realistic assessment has to presume that the changes in local climatic conditions can be predicted at a useful level of accuracy (see also Chap. 3 for a more detailed treatment of climatic risk).

4.2.4 Effects of Soil Types on Water Availability

Soil type affects water availability in two important ways – storage capacity and subsoil constraints.

4.2.4.1 Soil Water Storage Capacity

Soil water storage capacity increases with soil depth and clay content. Stored water is particularly important for use following the end of the rainfall season and following fallow periods.

The effect of different soil texture on wheat yield after fallow is shown by a comparison between two locations, Dooen and Walpeup (Victoria, Australia). While there is no great difference in their rainfall distributions (Fig. 4.2), the yield responses to 18-month-long winter fallow are very different (Fig. 4.3). Figure 4.3 shows the relationship between fallow-period rainfall and subsequent yield of a wheat crop grown under both a conventionally-tilled system (no stubble and conventional tillage, NSCT) and a zero-tilled system (stubble retained and no tillage, SRNT). At Dooen, the slopes (17–23 kg/ha/mm) were higher than at Walpeup (6–13 kg/ha/mm).

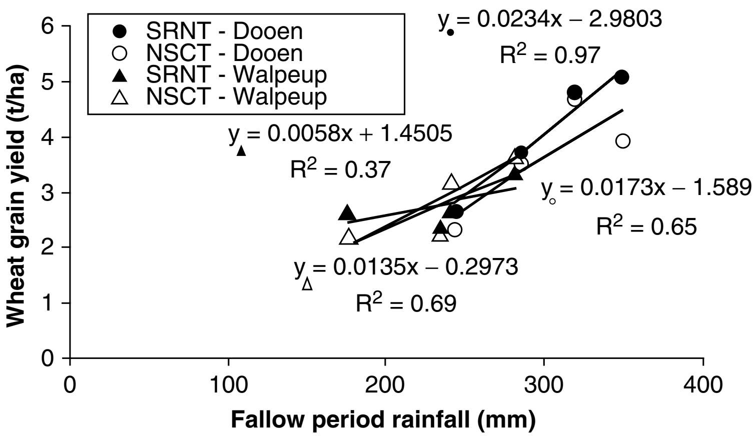

Fig. 4.3 The relationship between fallow period rainfall and wheat grain yield showing significant differences between localities, Dooen (*circles*) and Walpeup (*triangles*) on a conventionally-tilled system (*NSCT* no stubble and conventional tillage) and a zero-tilled system (*SRNT* stubble retention and no tillage). Data re-analysed from O'Leary and Connor (1997a, c)

These differences are attributed to both the higher fallow period rainfall and the heavier textured clay soils at Dooen, resulting in higher water storage than under the lower fallow rainfall and sandy soil at Walpeup. The greatest response to fallow can be expected where the rainfall during fallow is high compared to that during the crop growth season and on soils that can store large quantities of water.

Similarly, there are seven soil order associations for arable lands and ten production systems across the semi-arid tropics of India (Laryea et al. 1998). These cropping systems are adapted to exploit the limited water supplies across diverse soil and agro-climatic conditions (Singh et al. 2000). Fallow is the most widespread strategy on nearly 7.4 million hectares of land planted in both the monsoon and post-monsoon seasons across the rainfed agricultural regions of India.

4.2.4.2 Subsoil Constraints

Subsoil constraints such as excess salt reduce crop water uptake (T) through osmotic forces retaining more water in the soil, and effectively limit further exploitation of the soil by new roots. Other chemical constraints, such as excess boron, appear mainly to reduce TE rather than water uptake (O'Leary et al. 2002). Soil compaction can also reduce root growth and subsequent water use (Sadras et al. 2005).

Subsoil water unable to be used by the crop can be detected by direct measurement (e.g. core sampling or neutron probes). However, other methods more suited to spatial mapping such as electromagnetic induction (EM) technology can be employed (O'Leary et al. 2003b). Figure 4.4 shows a field that was mapped using EM; areas affected by high salt are indicated by dark grey and black shades (0.4–1.5 EC levels).

By identifying serious subsoil constraints not amenable to removal, farmers should be able to improve overall efficiency by reducing production inputs in these areas while increasing inputs to more responsive areas of their fields. This is the concept behind precision agriculture.

4.2.5 Maximising Water Availability to Crops by Minimising Losses

For a given climate and soil type, water supply can be increased or losses minimised. Finding new sources of water is generally not a practical option for farmers in the semi-arid regions, but opportunities exist for increasing the capture of rainfall and maximising its efficiency of use. Once a set amount of water is available for crop production, losses must be minimised. Among practices that can reduce losses are stubble retention to reduce runoff and Es, reduced tillage, weed control and nutrient management to allow crops to cover the soil surface quickly after emergence.

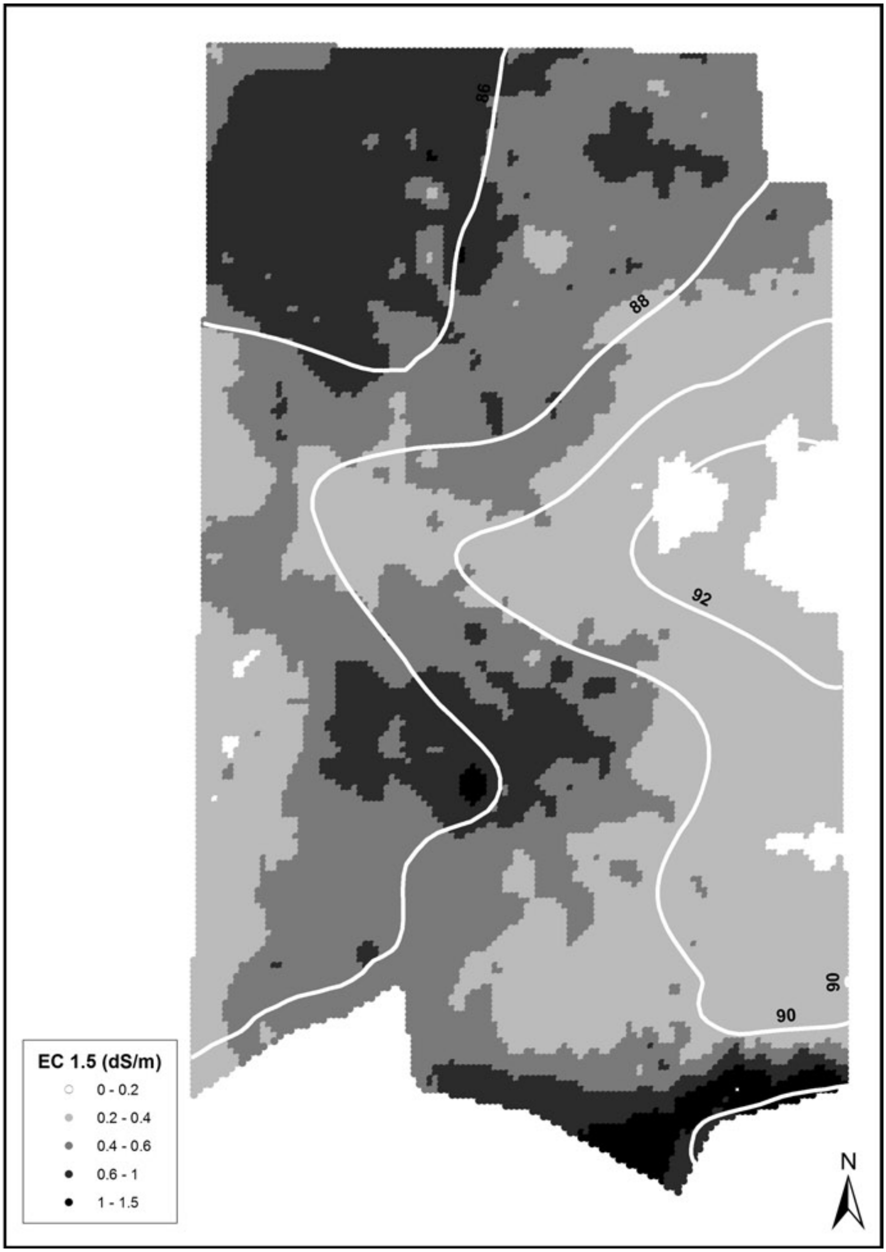

Fig. 4.4 A map of soil EC1:5 derived from a calibrated electromagnetic survey of a 50 ha wheat field in north western Victoria, south-eastern Australia. Elevation (m) contours above mean sea level are also shown (G.J. O'Leary, unpublished data)

4.2.5.1 Management of Stubble, Tillage and Weeds to Minimise Water Loss

Stubble protects fallowed fields from evaporation, wind and water erosion and improves the capacity of soil to accumulate water. Tillage increases evaporation losses whereas reducing tillage offers the opportunity to reduce losses. Reduced-tillage systems allow retention of stubble to various extents. Chemical (no-till) fallows retain most stubble; the amount of stubble is reduced in proportion to the severity and frequency of tillage. In many systems, stubble is burnt to facilitate tillage, particularly in short fallows where there is less time to reduce it before sowing, and where suitable planting machinery is not available. Burning stubble increases water loss.

Weeds use soil water that could contribute to useful crop growth, and can be a major factor limiting crop production. Weeds must be controlled before they compete with the crop for water, nutrients and radiation. In trials in Masvingo, Zimbabwe, no weeding led to the driest soil profile and lowest maize yield (Twomlow et al. 1997). Early weeding resulted in maize yields 40% higher than under traditional Zimbabwe practices where weed control is often minimal because of lack of labour (Shumba et al. 1992). Weeding in the first month of crop growth is critical; even in a dry season, maize yield can be decreased by 45% when weeds are allowed to grow for 15 days (Nel and Elhers 1987) and by nearly 80% if weeds are left for 30 days within the vegetative stage of the maize. Under semi-arid conditions, percentage yield losses are even greater when no fertiliser is applied (Gerbrands 1981).

Weed control in fallow is essential to accumulate water and mineral N for subsequent crops. It has traditionally been done with tillage, frequency depending upon continuing weed emergence and growth. Early and effective weed control will limit water losses. Herbicides allow weed control on fallows without tillage while maintaining heavy cover of crop residues. Whilst herbicides enable zero or reduced tillage, total reliance on one or two herbicides can generate herbicide resistance in crop weeds (Powles and Howat 1990). Thus, some tillage is often used for ongoing effective weed control (Arshad et al. 1994). (Weed management is discussed in Chap. 8.)

4.2.5.2 Optimising Use of Crop Nutrients

An adequate supply of mineral nutrients is fundamental for the efficient use of limited water supplies, and, where soil nutrients are deficient, they need to be supplemented by fertiliser. Stubble retention and tillage interact and may have opposing effects on soil water retention and N levels (Smika 1983); for example, microorganisms have first call on available N in decomposing stubble, when water is available.

Tillage stimulates N mineralisation, primarily by more effective exposure of substrate (stubble and other soil carbon sources) to soil microbial activity (Stein et al. 1987).

The reverse occurs with no-till, where the retention of stubble can aggravate N deficiency because microbial activity utilises and immobilises N, particularly if substrates have relatively high C:N ratios (e.g. >35:1) (Thompson and Troeh 1978). Temporary immobilisation of N is typically overcome with application of N fertiliser. In cereal crops, after sowing, the opportunities for tactical applications of fertiliser N are limited to a narrow window of time prior to stem elongation.

Stubble retention reduces rainfall run-off, increasing soil water storage, and perhaps nutrient leaching. The effect of the interaction of water supply, tillage system and stubble retention on soil mineral N (SMN) depends on relative levels and patterns of supply of water and microbial substrate (Turner et al. 1987). Thus agronomic practices that affect the water supply, such as fallowing, tillage, stubble retention and weed control, are strongly linked to the mineralisation and immobilisation processes of the N cycle (see also Chap. 6).

The balance in the supply of N is also determined by the crops in a rotation and the products removed. The optimal strategy in nutrient management is to match the nutrient supply to the water supply. If the level of soil organic N is high (through growing legumes in the crop rotation) the immobilisation phase due to high C:N ratio in crop residues will be brief and unlikely to greatly affect the mineral N supply. This will also result in higher yields of following cereal crops. For example in Zimbabwe sorghum yields are higher after legumes even in the drier seasons, and can be two times greater in wetter seasons (Ncube et al. 2007).

Greater cropping frequency and a reduction in fallowing have, in the latter part of the twentieth century, reduced soil total and mineral N content throughout much of the Australian wheat belt. This resulted in concern for a decline in soil fertility, grain yield and grain quality (Hamblin and Kyneur 1993). Reduced soil mineral N also leads to lower crop biomass and ground cover early in the season and thus to increased losses of water by soil evaporation. This problem has been overcome by applying additional nutrients as fertiliser, and by zero-till, increased cropping intensity and appropriate rotations. In water-limited environments nutrient levels must be matched to the available water and not allowed to decline. Monitoring of soil/crop nutrient status will be an increasing requirement to maintain high water-use efficiency for crop production in the semi-arid regions.

4.2.5.3 Effects of Previous Crops

Crops that act as disease breaks are also crucial to efficient water use. These crops include the legumes (e.g. annual clover and medic pastures, chickpea, field pea) and crucifers (e.g. canola, mustard). Not only is there a ‘break crop’ effect, but these crops typically have shallower rooting depths than cereals and do not extract all the available subsoil water, thus leaving some reserves for subsequent deeper rooting crops. (See Chap. 6 for more detail on the management of biological factors that reduce the incidence of crop disease).

4.3 Strategies to Increase Water Delivery and Capture

The volume of water that can be delivered to farms cannot be increased easily. Groundwater or other supplementary irrigation sources are often not available to rainfed farmers due to either the lack of suitable supplies or to regulatory restrictions. Artificial rainmaking by cloud seeding is another potential means of boosting water delivery, although not practical for individual farmers. Indeed, the potential of cloud seeding is doubtful in times of drought when environmental conditions (low humidity and high atmospheric stability) are not conducive to rain making.

4.3.1 Ex-Field Rainwater Harvesting

Ex-field rainwater harvesting is based on the use of rainfall runoff from a catchment. This water is collected or diverted into a storage facility which may be the soil profile of the cropping land itself or a structure such as a farm dam (Ngigi 2003; Oweis et al. 1999). Examples exist in every rainfed farming region of the world.

Catchments vary in size. Large-scale macro-catchments use flood diversion structures to collect and divert waters, such as in Eritrea (Abraha 2008). Medium-sized catchments include adjacent fields, hills, roads or bare rock areas. The smallest catchment is the micro or in-field catchment where a part of the field is set aside as a runoff area and the water is transferred to another part of the field by tied ridges, small bunds, basins, pits, or *fanya juu*[2] systems (Ngigi 2003).

Many types of small-scale storage systems are used throughout Africa for small farms. In Ethiopia, runoff water is collected from nearby hills and roads and channelled into storage dams which are often underground or covered to reduce evaporation losses (Fentaw et al. 2002). In Kenya, the underground tanks may be lined with polythene or clay to reduce seepage losses and then covered with sheet iron or local materials such as grass thatch (Ngigi 2003). Sealing the tank is important but may be too expensive if concrete is needed. The potential for storage in sand dams or river beds has also been explored in Kenya and Zimbabwe (de Hamer et al. 2008). This stored water can be used for small vegetable gardens located near the river bed (Rockström et al. 2002).

Flood diversion or spreading, called 'spate irrigation' is also used in many semi-arid and arid parts of Africa and the Middle East (Abraha 2008). Surface runoff water from catchments or gullies or ephemeral water courses is diverted into cropping areas in large scale government development projects. A network of ditches, canals or weirs collect and divert water to the arable land to fill the

[2] Terraces are made by digging a trench along the contour and throwing the soil uphill to form an embankment. The embankments are stabilised with fodder grasses. The space between the embankments is cultivated. Over time, the *fanya juu* develop into bench terraces.

soil profile before planting or during the growing season (Ngigi 2003). These systems are especially useful in semi-arid environments where the rain typically comes in high-intensity, convective thunderstorms. These short-lived events generate massive runoff which would otherwise cause erosion and be lost to productive agricultural use. These types of systems are used in Eritrea (Abraha 2008), Tanzania and Kenya (Lameck 2002) and Sudan and Yemen as well as other Middle-Eastern countries (UNESCO 2003).

4.3.2 In-Field Rainwater Harvesting

Water harvesting is defined as the 'process of concentrating rainfall as runoff from a larger area for use in a smaller target area' (Oweis et al. 1999). When the harvest area and the target area are within the same field, the practice is termed 'in-field rainwater harvesting'. This technique has increased the long-term yields of maize and sunflowers by as much as 50%. Runoff water from a 2-metre wide inter-row strip can be collected in a basin between two rows of the crop and so concentrated in the crop root zone (Figs. 4.5 and 4.6).

If the runoff-concentrating area is covered with mulch of organic matter or stones, Es is reduced, further increasing the water available to the crop (Hensley et al. 2000). This system was modelled using a deterministic runoff model and a stochastic rainfall intensity model. These were combined with crop growth modelling (Tsubo et al. 2005), using initial soil water content and growing season rainfall. In the Free State province of South Africa, modelling of a large range of agronomic practices showed that, under semi-arid conditions, the in-field rain water harvesting technique provided more available water and subsequently lower risk of crop failure than conventional total tillage (Walker et al. 2005).

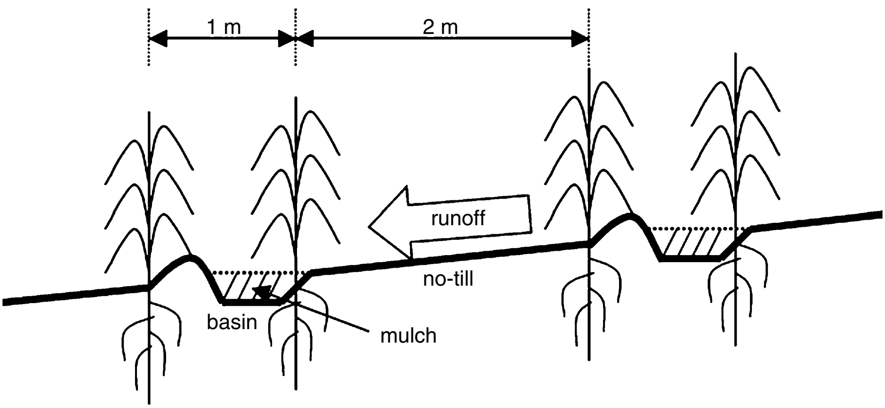

Fig. 4.5 A diagrammatic representation of the in-field rainwater harvesting production technique

Fig. 4.6 Photo of in-field rainwater harvesting at Kenilworth Experimental site, near Bloemfontein (S. Walker)

4.3.3 Capturing More Rainfall by Reducing Runoff and Evaporation and Increasing Infiltration

The climatic conditions, soil type and its condition, and cultural practices all interact to determine the water supply to rainfed crops (Loomis and Connor 1992). Numerous farming methods have evolved that increase precipitation capture. These include short (3–6 months) and long (6–18 months) weed-free fallows (Unger et al. 1991), crop residue retention (O'Leary and Connor 1997a, b), planting contour vegetative barriers (Sharma et al. 1999), minimum and zero tillage (Cantero-Martinez et al. 1995), and strategic tillage, which includes tied-ridging and sub-surface tillage (Twomlow and Bruneau 2000). The principles are straightforward. Tied-ridging allows ponding from high-intensity rainfall events to be collected and redistributed later. Simple tillage makes the soil surface rougher and acts similarly to tied-ridging. Sub-surface tillage kills weeds without damaging the often sensitive soil surface, allowing infiltration rates to remain as high as possible. In India, blade harrows known locally as 'Bakhar' are used to disturb the soil surface in fallows, to control weeds and to roughen the soil to improve water infiltration and storage.

The common practice of fallowing is an example of the 'principle of concentration of limiting resources' – such as water and N (Loomis and Connor 1992). Fallowing is a widespread traditional method of increasing the water supply to rainfed crops. Reduced-tillage systems that retain surface stubble and accumulate

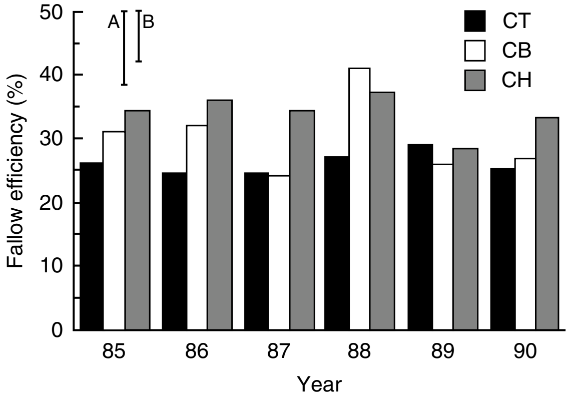

Fig. 4.7 The effect of three conservation tillage systems on the efficiency of storing water during an 18-month weed-free fallow period on a grey cracking clay soil at Dooen, southern Australia. *CT* Conventional tillage (tyned tillage with no surface residue); *CB* Blade plough fallow (sub-surface tillage with surface residue retained); *CH* Chemical fallow (zero tillage with surface residue). The LSD($P = 0.05$) is shown for comparisons between fallow systems (*A*) and between years within fallow systems (*B*). From Cantero-Martinez et al. (1995)

more water in fallows (Smika 1983) can markedly increase potential grain yield in semi-arid environments (Unger et al. 1991). This greater storage is usually attributed to less Es because of the surface mulch (Fischer 1987). Of course, long fallows of 12–18 months come at the expense of a foregone crop and this can have marked economic effects on the whole cropping system.

The additional water supply from fallow typically ranges from 10 to 60 mm (Ridge 1986), with efficiencies of soil water storage around 25% (Fig. 4.7). Tillage practices that reduce the destruction of soil aggregates and conserve crop residues can further increase storage up to about 120 mm (O'Leary and Connor 1997a), with efficiencies to 40% (Fig. 4.6; Cantero-Martinez et al. 1995). However, this can only be done on soils with high water-holding capacity and with large rainfall events that penetrate deep into the soil beyond the typical evaporative surface layer of about 30 cm. The effect of stubble retention on fallow water storage has been found to be small on sandy soils in semi-arid regions with light rainfall (O'Leary et al. 2003a), presumably because of shallow water penetration, low amounts of residue (e.g. less than 2 t/ha), and consequent high loss from evaporation. On light-textured soils in the Victorian Mallee region (Australia), where rainfall is low and winter-dominant, gains in water storage from stubble retention have been relatively small and infrequent, and stubble retention is recommended more for the control of wind erosion (Incerti et al. 1993a).

However, increased water storage has been recorded in chemical fallows of 18 months duration on cracking clay soils in the Wimmera region of Victoria, Australia (Fig. 4.7, Cantero-Martinez et al. 1995) and on the red-brown earth soils of South Australia (Schultz 1972). Cracks can play a major role in improving the water balance of reduced-tillage systems by allowing rapid water entry (Adams et al. 1969). In the summer-rainfall dominant region of southern Queensland, Australia, zero tillage has increased water storage in fallows on cracking clay soils by promoting deep water entry down wide cracks independently of the presence of stubble mulch (Felton et al. 1987; Marley and Littler 1989).

In north-west Victoria, long fallow and legume pasture leys were previously able to supply rainfed wheat crops with water and N in a balance that allowed for sustained production. There were occasional instances of imbalance, with yield reductions, when high N availability was combined with low water supply (Taylor 1965). In more recent years, this imbalance, and the associated phenomenon known as 'haying off', has become rarer – perhaps due to lower levels of available N in the soil.

The region south of Bulawayo in Zimbabwe is semi-arid with erratic rainfall and prolonged dry spells. These climate conditions make it hard for farmers to produce sufficient food for their households. The granitic, sandy soils are inherently low in fertility and highly erodible. Under the traditional rainfed systems, the fields are ploughed with donkey power following the first rains between November and December; maize is planted in every third row, skipping the others or adding intercrops. Cereals – maize, sorghum and millet – are grown on about 70% of the cultivated lands, with legumes and vegetables on the remainder or intercropped with the cereals (Twomlow et al. 2006). The rain falls in high-intensity, short-duration convective thunderstorms, mainly between October and April, with high variability both between years and spatially across the region. Small landholders must make every effort to capture and retain the rain water in the field. A number of rainwater–harvesting techniques have been used to reduce runoff from the heavy storm rains and so avoid excessive soil erosion. These techniques include planting pits of varying size, infiltration pits and furrows, together with mulching, stone bunds and tied ridges. They reduce the speed of overland flow and so retain the water in the soil profile or in some form of on-field storage pit.

Conservation agriculture has also been promoted in the region together with these water management techniques. This includes introducing cereal–legume rotations (Ncube 2007), consistent early weeding (Twomlow and Bruneau 2000) and reduced tillage (Mupangwa 2008). Trials in Zimbabwe showed that soil water was dependent on the rainfall pattern and not the previous legume crop (Ncube 2007). Using minimum tillage techniques such as tied ridges, yields could be increased by up to 85% above those from the farmers' flat, conventional tillage on sandy soils. However, occasional deep ripping with a tine attached to a donkey-drawn plough reduced surface runoff and increased the soil-available water for the maize crop (Nyagumbo 2002; Mupangwa 2008). Stubble retention has less impact on surface run-off than deep ripping, especially as much of the surface residues are grazed by livestock.

For households lacking access to draught animals, a system of small planting basins (15 cm × 15 cm and 15 cm deep) has been used. The basins are prepared before the first rains, spreading the labour demand. Since these farmers do not have to wait to borrow draught animals to plough, they can plant on time with the first effective rain. The planting basins collect the rainfall and limit the runoff losses from the fields (Mupangwa 2008) (See also example in Chap. 2). During the growing season, planting basins, ripper tillage and conventional tillage result in similar soil water dynamics. The planting basins have marginally higher soil water at the start of the season resulting from the collected water and this improves crop establishment (Mupangwa 2008). It was found that if the rainfall is evenly distributed throughout the season, the planting basins are able to produce higher maize yields than from using either the ripper or conventional tillage. Some problems were experienced with rodents eating the seed and seedlings and with waterlogging in wet years. Mulch can help produce higher yields, but as cattle compete for the crop residues, mulching may not be a viable practice. The alternative tillage systems – ripping or hand-dug planting basins – may reduce the risk of crop failure for these smallholder farmers in semi-arid region in sub-Saharan Africa (see also Chap. 2).

4.4 Strategies to Increase the Proportion of Water Available for Crop Production

Strategies to increase the proportion of water available for crop production are largely based on improving the ability of the crop to extract water from the soil profile, as opposed to losses from Es. Early sowing allows the crop to use early rain and also establish deep roots, thus using more water for transpiration and growth. Physical subsoil constraints to water availability and efficient use may be alleviated by deeper tillage. Alternatively, growers may use knowledge of the spatial distribution of the constraints to avoid problem areas or provide spatially-directed amendments, thus increasing overall field crop transpiration and TE (as done in precision agriculture). Further increasing the cropping density through means such as intercropping can reduce Es and boost the amount of water used for crop production overall.

4.4.1 Increase Rooting Depth

Deep rooting is important to exploit deep soil water reserves in rainfed farming systems. Rainfall is frequently unreliable during the grain-filling phase and crops have to rely on soil water reserves. In annual crops, early sowing provides time for developing the deepest root systems.

In the semi-arid regions of South Africa, conventional mouldboard ploughing of a sandy soil produced higher yields than shallow sweep tillage and also more than no-till with chemical weed control (Bennie et al. 1994). The higher yields were attributed to better root development following ploughing. However, shallow till or no-till gave better results on a soil with 6% higher silt-plus-clay content by providing better structure for deeper root development. Deeper tillage improved Precipitation Use Efficiency on the sandy soils because it enabled a higher proportion of the stored soil water to be used, by deeper rooting (Bennie and Hensley 2001).

4.4.2 Spatial Management of Water Supply and Use

4.4.2.1 Identifying and Managing Subsoil Constraints

The advent of the US Global Positioning System (GPS) in the early 1990s has led to the concept of Precision Agriculture, where spatially variable crop yields – measured with yield monitors – are located (georeferenced) with GPS. Characterising spatial variation in yield and soil constraints allows alternative fertiliser management strategies to be adopted for different areas or soil types of a field (O'Leary et al. 2002). These can be both strategic and tactical in nature.

Electromagnetic induction technologies are used to map soil properties and help interpret spatial variation in crop production. (Corwin and Lesch 2003; O'Leary et al. 2004). Global Positioning System technology combined with automatic yield monitors can be coupled with the old hand-held EM technology, to facilitate generation of maps of soil properties. However, problems range from the practical matters of choosing the correct parameters for mapping, to understanding how farmers might manage their paddocks better using this information. The former problem can be addressed by using mapping, standards such as the Australian EM mapping standard for the grains industry (O'Leary et al. 2006). See Chap. 34 for more detail.

4.4.2.2 Why Use EM Technology?

EM mapping has become popular as a means of interpreting crop yield variation by identifying subsoil constraints (O'Leary et al. 2003b). In the early 1990s, farmers began collecting yield maps, and it was considered that another 'data layer' that represented soil variability might help explain spatial variation in yields. However, it was found that much of the yield variation stemmed from subsoil chemical constraints such as high levels of salt or boron (Cartwright et al. 1984). High salt and alkaline pH were identified as likely causes of shallow rooting of wheat in the Victorian Mallee (Incerti and O'Leary 1990), but it was not until a decade later that it was recognised as a national problem.

EM sensors measure bulk soil apparent electrical conductivity (ECa). Other soil properties may be inferred using EM data but only if these are well correlated with ECa. For agricultural applications, suitable correlations with ECa have been found for soil water content, soil clay content and soil salinity (Johnson et al. 2001). However, air and soil temperatures and soil mineral type and content complicate calibrations. Universal calibrations, whilst theoretically attractive, prove difficult to achieve in practice (Corwin and Lesch 2003).

4.4.2.3 The Need for Calibration Against Measured Soil Properties

The lack of a workable universal calibration to relate ECa to other soil properties makes it necessary to establish these correlations for individual survey sites. This may be achieved through analysis of soil cores taken at the time of the soil conductivity survey (Corwin and Lesch 2003). Other variables, such as potential rooting depth, that are functions of water, clay and salt content may also be applicable in some places. Specific elements or compounds (e.g. phosphorus) can only be measured to the extent of the strength of their ECa co-correlation with water, salt and clay (Kitchen et al. 2000). Variables such as drainage cannot be measured directly with EM because of the complex relationship between other components of the water balance equation and time. Thus, customised calibrations must be derived after a survey to establish what can be measured with EM sensors – it is site specific (Kitchen et al. 2000).

In the quest for more precise management of crops and farmland, EM technology is being used to map soil properties that are correlated with soil ECa (Sudduth et al. 2001; Jones et al. 2008). Figure 4.8 shows an example of ECa-soil water content calibration derived from an EM survey conducted prior to sowing. In addition to the soil water content calibration, the upper and lower limit calibrations are also shown. The calibration is applicable to the whole field with a Root Mean Square Error (RMSE)[3] for water content of 20 mm/m of soil profile. This error includes the spatially explicit confounding effects of high salt and clay content and is similar to the errors obtained with neutron probes and soil core methods.

EM technology therefore offers the opportunity to identify where subsoil constraints exist. This, in turn, allows less wasteful and more efficient fertiliser application and best use of soil water.

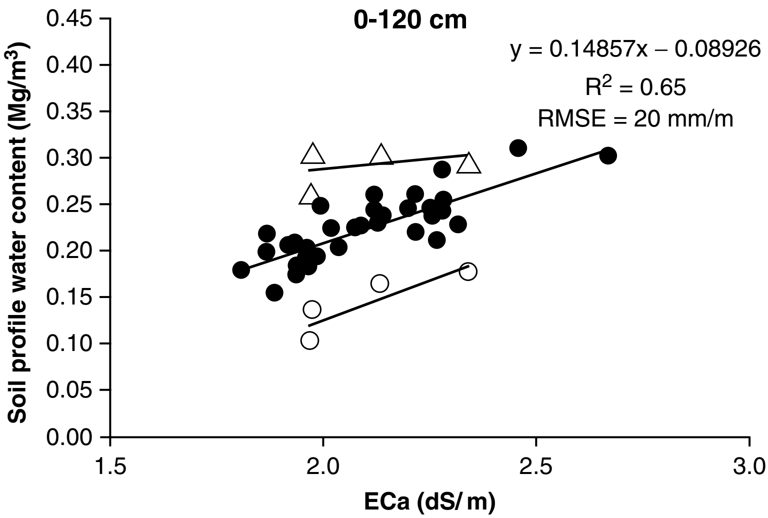

Fig. 4.8 Spatial calibration of an EM survey between the apparent electrical conductivity and volumetric soil water content of an 85 ha field (•). The upper limit (*triangles*) and lower limits (*open circles*) of crop extraction are also shown together with the Root Mean Square Error (*RMSE*) for the soil water content calibration (O'Leary et al. 2007)

[3] RMSE is a measure of the mean differences between values predicted by a model or an estimator and the values actually observed from the thing being modeled or estimated.

4.4.3 *Intercropping Increases Radiation Use Efficiency and Water Use Efficiency*

Intercropping, such as maize and beans in South Africa, can increase both the water use efficiency (WUE) and radiation use efficiency (RUE) when compared to their sole cropping (Tsubo 2000; Ogindo 2003). In maize and bean intercrops, the canopy intercepts more radiation because of the complementarity of the shoot architecture of the two species (Tsubo et al. 2001). WUE increases as the planting density is increased. A sole bean crop has a lower WUE than sole maize and intercrop systems; this is possibly related to the generally lower efficiency of the photosynthesis of C_3 plants (Tsubo et al. 2003). Intercropping is more efficient because less water is lost to evaporation due to greater ground cover and reduced weed competition.

The relationship between the RUE and WUE (Fig. 4.9) has been shown to be dependent on the soil water status (data not shown); RUE increases as the WUE increases up to a maximum RUE value for the photosynthetic process. RUE is

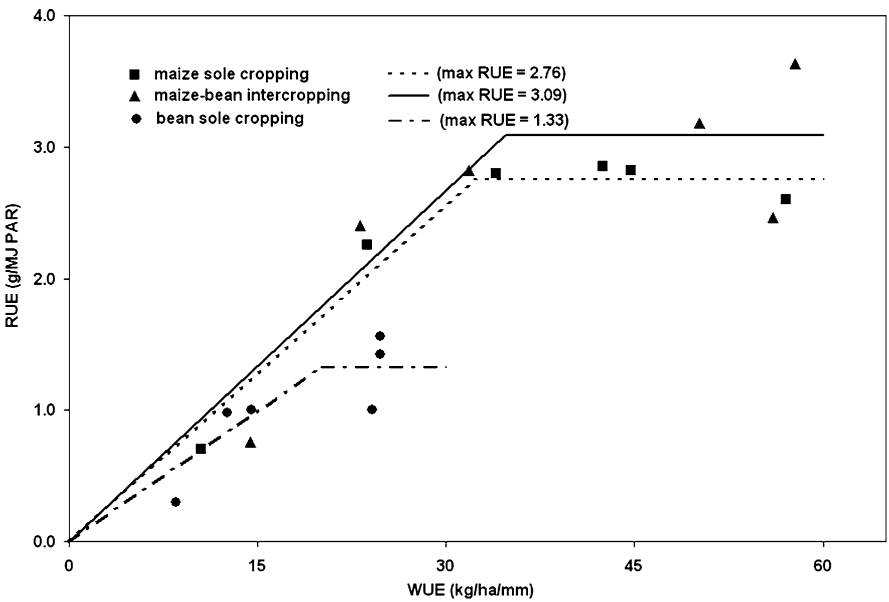

Fig. 4.9 Relationships between radiation use efficiency[4] (*RUE*) and water-use efficiency (*WUE*) of maize sole cropping, bean sole cropping and maize/bean intercropping. Using six dates of RUE for each cropping system, the maximum RUE was calculated as the average of the three highest RUE of the data set while RUE between zero and the maximum value was determined as the slope of the linear regression of the three lowest RUE of the data set with the zero intercept WUE was calculated as above ground dry matter over crop evapotranspiration (Tsubo et al. 2003)

[4] RUE is grams of biomass dry matter per unit of incident photosynthetically active radiation (MJ PAR).

lower under water-deficit conditions but constant at its maximum until the water stress starts (Tsubo et al. 2003). Thus intercropping maize and beans is more efficient than sole cropping and is recommended to small-scale farmers in semi-arid regions, where weeding and harvesting are done by hand.

4.5 Strategies to Increase the Efficiency of Conversion of Water to Usable Product

In most annual crops, the challenge is to maximise the amount of photosynthate translocated to the grain or other product. Agronomy and breeding have focused on the components of yield amenable to improvement (Passioura 2006). An important component is the number of grains per m^2, which is maximised by having a large biomass at flowering. Early sowing often permits greater biomass. The timing of flowering determines the number of grains; subsequent filling of grain with starch determines the grain size, and together they determine the final grain yield. Availability and use of deep soil-water reserves in this period assist in the attainment of a high grain yield.

4.5.1 The Design of Crops for Efficient Water Use

Crop constraints can also limit the use of water resources, and inappropriate crop design can limit yield. Numerous attempts are underway to design crops that are more drought-resistant yet yield well (Richards et al. 2002). A first step is to match crop development to the available resources of water and nutrients and to the risk of stresses such as frost or heat. With the predicted rise in mean global temperatures, realigning phenological development with the available resources may require a sustained effort by plant breeders. For example, it is calculated that a 2°C rise in mean temperatures would reduce the time from sowing to flowering of current cultivars of wheat by about 3 weeks in southern Australia.

In addition to the expected adaptive approach to plant breeding for climate change (higher temperatures, higher atmospheric CO_2 and lower rainfall), a physiological approach to these changes that relies on maximising resource use efficiency will be crucial to enable farmers to use these better adapted cultivars.

The phenology of crops is important because it dictates both the potential growth duration and the stress from frosts and high temperatures at sensitive stages. Loss of grain numbers from frost or heat stress will reduce grain yield partitioning because there are fewer grains to fill. The process is said to be 'sink limited'.[5]

[5] See Glossary for explanation.

Traditionally, farmers faced with the need for very late planting (due to late rains) will select a more rapidly developing crop (e.g. barley or sorghum) that will complete its life cycle before the full effects of end-of-season drought occur.

4.5.2 Reliance on Deep Stored Soil Water Beyond the Soil Evaporation Zone

Storing water deep beyond the evaporation zone is a way to increase transpiration and water use efficiency; the water extracted by the crop roots goes directly via the transpiration stream with no loss to Es. Thus in crops with incomplete soil cover, deep stored (fallow) water is used more efficiently. Very high TE (60 kg/ha/mm for grain) has been measured in southern Australia (Kirkegaard et al. 2007) for these conditions. Similarly, sub-surface irrigation is more efficient than surface-applied irrigation due to lower Es.

In rainfed sub-Saharan Africa, low maize yields of about 1 t/ha could be improved with better water management. Dry spells can be bridged with supplementary irrigation from on-farm storage. In some years, supplementary irrigation prevented complete crop failure from drought. Up to 85% of the rainfall is lost through soil surface evaporation, drainage and runoff (Rockström et al. 2002); increasing soil cover and reducing Es has improved water use efficiency by nearly 40% over the traditional practice of removing cover, on soils with both low (in Burkina Faso) and high water-holding capacity (in Kenya). Even small volumes of stored water at depth can significantly improve crop yields and livelihoods (Rockström et al. 2002).

4.6 Example of Spatial Management of the Crop with Respect to Its Water Supply

An example is provided below of managing the water use of a barley crop from a spatial perspective, employing simple models of yield based on estimates of transpiration.

4.6.1 Birchip, Victoria, Australia

An EM survey was conducted on a sample field near Birchip, Victoria, Australia. This was calibrated against volumetric soil water content measured at selected field positions to represent the range of soil water contents across the field (Fig. 4.8). Underlying assumptions (based on previous work) were that changes in ECa at any point in a paddock during the season were related primarily to changes in water content and that the spatial error of the soil water content from confounding factors such as salt and clay content was relatively low.

Since the French and Schultz (1984a) crop yield potential model is based on estimates of crop transpiration, this was modelled spatially from maps of soil water content, soil water extractable lower limit and Es derived from ECa surveys. The ECa data obtained from the EM survey were converted to sowing water content and crop lower limit (LL) water content via a calibration equation, then extrapolated by kriging[6] to a 10 m grid using Vesper software (Minasny et al. 1999). Water use was derived by assuming the LL would be the soil water content at harvest, subtracting this LL from the water content at sowing and adding the in-crop rainfall (195 mm in this case).

The French and Schultz (1984a) potential yield model was applied with slightly different assumptions than originally proposed. The model assumptions used in this exercise were: (1) actual (not potential) transpiration efficiency is constant at 22 kg/ha/mm for barley; (2) Es varied over the field according to soil types and annual rainfall so that a coarse sand would have 20 mm seasonal evaporation and a heavy clay 200 mm. Es increased linearly with increasing clay content, where clay content was determined by a non-linear relationship with ECa.

Figure 4.10 shows the sequence of generating a barley yield map, giving reasonable agreement with the observed barley yield map. The assumptions mentioned

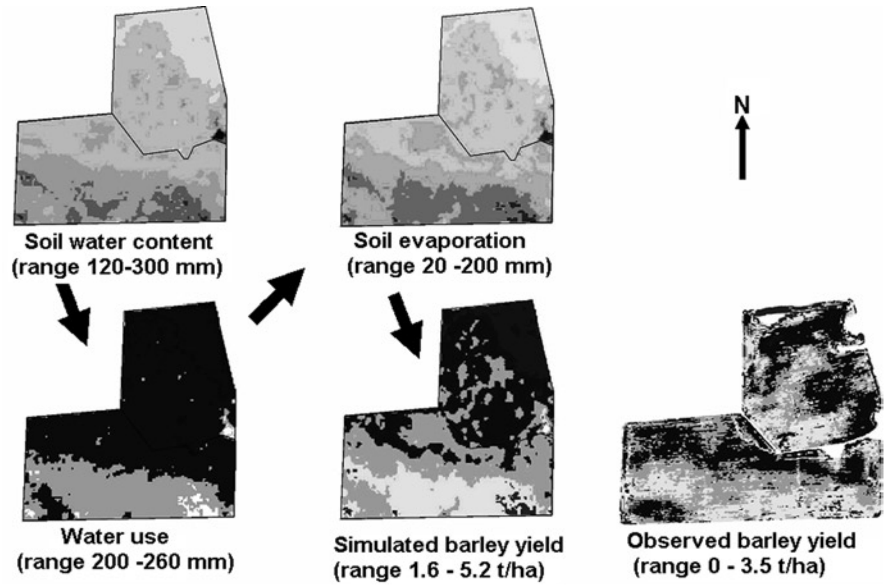

Fig. 4.10 Sequence of yield map construction for an 85 ha barley crop from soil water content, water use and soil evaporation maps derived from EM surveys. The darker colour in the yield maps indicates the highest values. Note that the areas of the maps of the lowest yield correspond with the wettest parts of the field which had significant subsoil constraints (O'Leary et al. 2007)

[6] See Glossary.

above need further testing. The most important concern is variation in Es across the field. The assumption of a linear relationship between clay content and Es appears to give realistic estimates of seasonal Es, but further work is needed to show that this is indeed a good assumption for widespread use of the model. Actual measurements of Es and ECa are needed. The assumption of a constant actual annual TE is justified (Fig. 4.1). Despite the technical uncertainties, such an approach offers new and useful ways of managing supply and use of water for field crops.

While an EM survey was used to obtain the sowing water content of the field, doing this for each field and year will not be economic. Possible short-cut methods to move up or down a previous calibration need to be successfully demonstrated. Remote sensing of canopy cover also offers yield prediction possibilities without the need for annual EM surveys.

Farmers can benefit from such analyses because the more responsive field zones can be detected and supplied with additional inputs as the season allows. The analysis also highlights the importance of subsoil constraints, identified by the convergent calibration lines between the soil water content and LL as the soil ECa increases (Fig. 4.8). In this case, the highest yield did not occur on the wettest soil because of the subsoil constraints limiting T (Fig. 4.10).

Calibrated soil property maps derived from EM surveys provide useful spatial information on crop water use and yield. The French and Schultz potential yield model appears to offer a simple method of explaining spatial variance in crop performance where water supply is the major determinant of yield, and this also applies where there are subsoil constraints such as salt. If the spatial yield model is sufficiently accurate for farmers, it can guide decisions on where to and where not to invest valuable resources. In this example, field application of large amounts of fertiliser in the low-yielding areas would not be recommended. How much fertiliser would be recommended on the more productive areas would depend on current costs and prices. Nevertheless, increasing the certainty of crop response to fertiliser is one way of increasing system yields and profitability in water-limited environments.

4.7 Conclusions

The primary considerations for rainfed agriculture in the semi-arid regions of the world are the supply of water, followed by its economy of use. The supply is determined by the seasonal rainfall distribution, and different cropping strategies are required depending on whether this distribution is of summer or winter-dominance. A winter-dominant rainfall region will emphasise methods that reduce in-season soil evaporative losses such as by stubble retention whereas, in the summer-dominant regions, strategies that use the available water more efficiently (e.g. use of C_4 crops) will be an important strategy from a biophysical point of view. Stubble retention is beneficial across all rainfed farming systems; its greatest benefit in the winter-dominant regions is reducing evaporative losses, whereas in the

Table 4.2 Methods to increase: (1) the delivery of water; (2) the capture of rainfall; (3) the proportion of water available for crop production; and (4) the efficiency of conversion of water to a usable product for rainfed cropping systems

Primary objective	Available methods	Notes and problems
Increase water delivery		
Source supplementary irrigation water	Pump ground water or divert river water to crop.	Available in limited areas only and not considered an overall solution in most arid or semi-arid areas.
Employ rainmaking	Cloud seeding by aircraft.	Not suitable in drought areas because of the lack of suitable clouds and not an economic option for individual farmers.
Ex-field rainwater harvesting	Spate irrigation. Small earth storage dams.	Suitable in areas of significant rainfall events (e.g. semi-arid tropics).
Increase capture of rainfall		
In-field rainwater harvesting	Use of runoff micro-catchments. Use of planting basins. Use of dead level furrows with storage pits.	Effective when large rain events exceed the infiltration capacity of the soil.
Reduce runoff	At the farm scale: terracing and levelling.	Depending on the scale, reducing runoff can saturate soils and lead to accelerated erosion and nutrient loss. Beware of catastrophic failure of terracing or bunds that can result in major and damaging flooding
Reduce runoff	At the field level: levelling, living barriers, contour planting, furrows and tied ridges, stubble retention.	Various forms of reducing runoff are effective in allowing longer time for infiltration.
Accumulate water	Fallowing with weed control before sowing a crop. It concentrates soil water over time by reducing water loss through unwanted vegetation. Fallow efficiency can be maximised by using surface mulch of crop residues to reduce evaporation.	Inefficient water capture (typically 25%) due to weeds and soil evaporation. Can increase weed problems by supplying water out of season to the weeds. Bare fallow poses soil erosion risks particularly on lighter textured sandy soils.
Increase soil infiltration rate	Zero or reduced tillage. Two- to ten-fold increases in infiltration possible. Surface mulches can increase infiltration by maintaining a wet surface soil.	Decreased runoff implies increased infiltration over time, but additional factors can affect how much water reaches the root zone.

(continued)

Table 4.2 (continued)

Primary objective	Available methods	Notes and problems
Reduce evaporative losses and increase water for crop use	Mulches reduce the direct energy exchange of the soil surface and, with rainfall, extend the duration of drainage into the sub soil.	Early sowing can achieve more rapid soil cover than late sowing and provide a 'living' mulch effect to reduce soil evaporation losses.
Weed control	Control weeds in and out of crop.	Weed control is known for its efficacy in increasing water use of crops.
Reduce competition from other plants	Effective weed control.	Related to above but some economic level of weed control will be necessary although the extent will vary.
Increase the proportion of water available for crop production		
Increase rooting depth	Early sowing and early vigour of crop growth.	Early sowing can also allow deeper rooting and increase subsequent water use.
Increase rooting depth	Sowing into furrows.	Furrows collect more water from infrequent rainfall and offer greater potential for survival.
Increase rooting depth	Avoid plough pans from excessive tillage.	Excessive tillage is known to damage soils (cause hardpans) and reduce root growth.
Increase rooting depth	Promote soil microfauna with mulches and reduced tillage	Soil microfauna help promote higher soil water infiltration through the development of macropores.
Increase rooting depth	Manage subsoil constraints such as salinity.	Fallows may increase deep drainage and reduce root zone salinity.
Spatial management	Apply precision agriculture principles to identified management zones that affect yields and profits.	Many of the above strategies to increase the proportion of water available for cop production can be applied in a spatial context. For example, weed control and strategic and tactical fertiliser management.
Intercropping	Efficiencies of water use are possible with intercropping of compatible crops. The length of productive seasons can also be extended by intercropping if seasonal conditions permit.	Intercropping requires crop species that have different agronomic characteristics. These include differential rooting habits and phenological development that exploit unused resources from the companion crop.
Increase the efficiency of conversion of water to usable product		
Timing of flowering and grain filling	Time sowing to avoid catastrophic losses from frosts and heat stress.	This is likely to be critical as the climate changes in various locations with increased extreme weather events.

(continued)

Table 4.2 (continued)

Primary objective	Available methods	Notes and problems
Timing of flowering and grain filling	Breed crops to better match abiotic environment including water and nutrient supply.	Research should focus on both the agronomic and breeding objectives that together address shortages of nutrients and water supplies.
Reliance on deep stored soil water beyond the soil evaporation zone	Fallowing increases subsoil water reserves; skip row techniques force the crop to explore more soil volume.	Reliance on fallow and its various forms will continue to be important in the arid and semi-arid regions.
Reliance on deep stored soil water beyond the soil evaporation zone	Deep ripping to break plough pan.	Deep ripping can offer significant gains to untapped water and nutrients but may not always provide yield responses if other constraints are present (e.g. salinity).

summer-dominant rainfall regions, decreasing runoff and protecting the soil from erosion are more important. The complexity of rainfed farming systems which include livestock that graze crop residues changes the relative importance of strategies involving their retention.

Practices such as fallowing and rainwater harvesting can increase water supply, while controlling weeds conserves water for crop use. If rainfall and soil depth are adequate to store water deeply, its use will be crucial as crop roots develop and crops mature. Water supply, tillage, and stubble retention interact to influence the level of soil mineral N. Thus agronomic practices that affect water supply, such as fallowing, tillage, stubble retention and weed control will strongly influence soil nitrogen mineralisation and immobilisation.

Management should aim to maximise water supply and efficiency of use. Table 4.2 summarises common options available to farmers to achieve this. The practices are diverse but strongly interconnected, reflecting a range of biophysical and economic conditions. Means of increasing the availability of water in rainfed areas include sourcing supplementary irrigation water, rainmaking, and ex-field rainwater harvesting. Increasing the capture of rainfall is the primary means of boosting water availability and typically involves reducing runoff (e.g. furrows), increasing in-field rainwater harvesting (e.g. micro catchments), increasing soil infiltration rate (e.g. reduced tillage), water accumulation (e.g. fallowing) and reducing evaporative losses (e.g. mulches). The proportion of water available for crop production is enhanced by increasing rooting depth (e.g. early sowing), spatial management (e.g. precision agriculture) and intercropping (e.g. maize and beans). The efficiency of conversion of water to a usable product can be increased by better timing of flowering and grain filling (e.g. ideotype breeding) and by reliance on deep stored soil water during grain filling. Our examples, drawn both from developed and developing countries, show a common, desirable strategy for efficient water use despite the diversity of production systems and ways that they are managed.

New opportunities for the better management of the available water resources require methods that can measure the water content across the field with sufficiently accuracy to allow tactical decisions to be made. Contemporary examples are the spatial management of water supply and fertiliser application using EM and crop yield mapping. Precision Agriculture supports such technology, and should not be kept out of reach of developing countries.

Acknowledgments We thank the various institutions represented by the authors for the time to collate this chapter. Much, but not all, of the work cited has been published. We acknowledge the valuable support of the Australian Grains Research and Development Corporation together with the Department of Primary Industries, Victoria which funded much of the Australian work. In South Africa, much of the research was funded by the South African Water Research Commission, and the input from many PhD students is acknowledged. The helpful cooperation of the Birchip Cropping Group and Mallee Sustainable Farming Incorporated where the soil and yield mapping validation was carried out is gratefully acknowledged. We thank the editors and reviewers of earlier drafts for helpful suggestions.

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Chapter 5
Plant Nutrient Management in Rainfed Farming Systems

With Particular Reference to the Soils and Climate of the Mediterranean Region

John Ryan

Abstract Global population growth and land-use pressure are placing increasing emphasis on expanding crop and animal output in rainfed agriculture. Rainfed areas of the world have some common features, but some unique biophysical and socio-cultural conditions. Rainfed agriculture in the Mediterranean region is characterised by cropping systems that have evolved from antiquity. The limited and seasonally variable rainfall exerts a major influence on the farming systems, which include production of cereals (wheat and barley) in harmony with livestock (sheep and goats). The region's soils have been 'nutrient mined' for millennia and degraded through erosion; this poses constraints to output that are compounded by adverse socio-economic factors. The challenge to increase agricultural output centres on the adoption of technologies such as improved crop cultivars and enhanced crop nutrition. Chemical fertilisers are fundamental to producing more crop output from existing land in cultivation. The use of N and P, particularly has changed a once traditional low-input system to a high-input, relatively intensive one over the past 30 years. This chapter briefly examines the interactions of climatic and soil conditions in terms of how they impinge on crop nutrient use within a systems context, with emphasis on productivity and sustainability. Reference is made to the maintenance of chemical and physical fertility in rainfed cropping systems, balanced fertilisation, efficient use of nutrients in relation to crop rotations and soil moisture, exploitation of biological N fixation, implications of spatial and temporal variability, and factors conditioning change in the region's rainfed agricultural sector.

Keywords Efficient fertiliser use • Soil quality • Nutrient variability • Balanced fertilisation

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_5,

5.1 Introduction

Despite the advances that have been made in agricultural production through research and technology transfer in the past half century (see Chap. 7), many areas of the world still fail to meet the nutritional needs of their people. The food supply–demand equation has become unbalanced through excessive population growth while many of the world's poorest countries lie in low rainfall regions. In fostering agricultural output, Nobel Laureate Norman Borlaug (2003) contended that substantial gains can be made with improved tillage, water use, fertilisation, weed and pest control, and harvesting, as well as by conventional breeding and biotechnology. Particular emphasis is placed on the use of commercial chemical fertiliser as a key element. Borlaug estimated that chemical fertiliser use would have to increase several fold in the coming decades and cautioned against the erroneous public perception that organic nutrient sources could replace chemical fertiliser.

A recent analysis of world fertiliser use concluded that at least 50% of crop yields are attributable to commercial fertiliser nutrient use (Stewart et al. 2005). The other crop nutrients come from organic sources, natural soil reserves, and biological nitrogen (N) fixation. As future increases in crop production will have to come from higher yields from land already in production, the contribution of added fertiliser nutrients will be proportionally greater in the future. However, efficient fertiliser use is required to produce adequate, high-quality food while containing costs and limiting environmental impact.

Great disparities exist between countries in terms of societal wealth, access to food and medicine, general wellbeing and living standards. This chapter will study the lands around the Mediterranean, i.e. West Asia and North Africa (WANA) to explore plant nutrient management. The region is mainly arid to semi-arid; there is generally a food deficit, with only a few countries, such as Turkey and Syria, approaching self-sufficiency (Ryan et al. 2006). As in many developing countries, climatic, socio-economic, political and biophysical constraints plague agriculture in the WANA region (Kassam 1981). This is ironic since the region is the centre of origin of many of the world's crops and forage species – cereals, pulses, nuts – and where settled agriculture and civilisation began (Harlan 1992).

Recognition of the urgent needs of the region has underpinned efforts by the various national governments to promote agricultural development through applied research (Rao and Ryan 2004), in particular with the establishment of the International Center for Agricultural Research in the Dry Areas (ICARDA) in Aleppo, Syria, in 1977. The Center has a global mandate for the agronomy of some rainfed crops (lentil, barley, and faba bean) in developing countries, as well as water use efficiency, rangelands, and small ruminants in those countries. It has a regional mandate (Central and West Asia and North Africa) for wheat (bread and durum), chickpea, pasture and forage legumes, and farming systems. As in other areas of the world, improvements in food production in the mainly rainfed WANA region will depend on the application of new technologies and intensification of management of land already in cultivation. This can only occur by exploiting the synergies

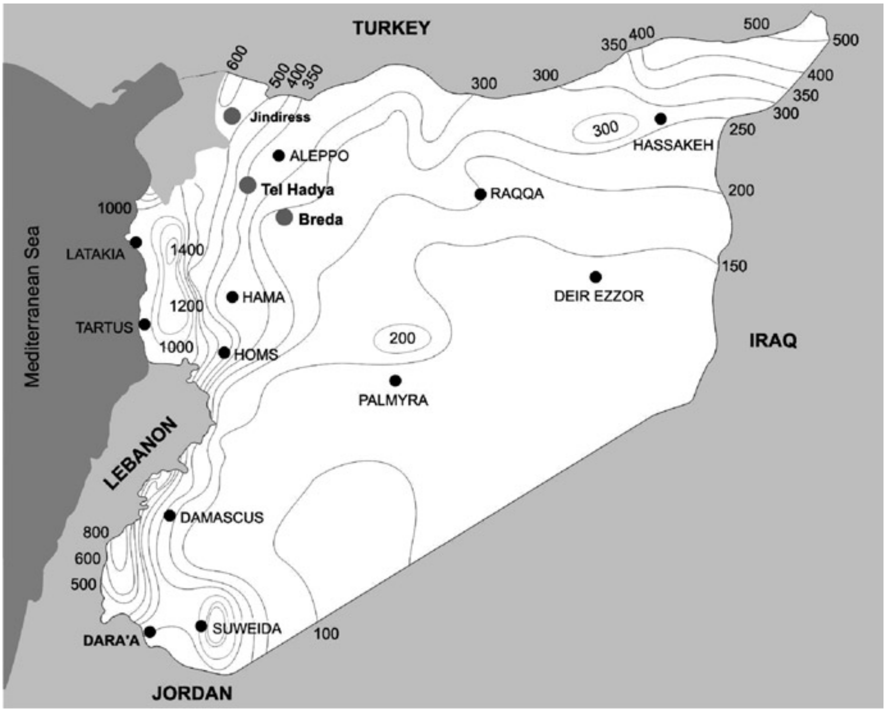

Fig. 5.1 Rainfall isohyets for Syria

between the various biophysical and human factors involved in food production within the context of global economic forces. The process of development of rainfed agriculture in the WANA region requires an understanding of both biophysical and socioeconomic constraints that impinge upon this sector.

In addressing rainfed farming systems across the entire region, ICARDA was aided by its location in northern Syria, where rainfall conditions from the very dry to the highly favourable occur within a short distance from its headquarters at Tel Hadya near Aleppo (Fig. 5.1). Consequently, many of the findings emanating from its field stations in Syria and Lebanon are applicable to the WANA region as a whole.

5.2 Climate, Soils, Cropping, and Socioeconomic Conditions

Agriculture in WANA has traditionally been subsistence rainfed farming, highly labour-intensive but with low production (Gibbon 1981, Chap. 15). The soils have been overused – perhaps for millennia – with few inputs and, in many cases, severely eroded. The addition of fertilisers and the rebuilding of soil fertility is therefore of primary importance. Fertiliser use has increased considerably in the past few decades (Ryan 2002). Farm holdings are generally small (<10 ha) and often in fragmented parcels (Shroyer et al. 1990). Effective change in land management is often hindered by traditional inheritance laws, tribal and common lands, and nomadism, while most farmers have little formal education. Support services are less than satisfactory for most rural communities; there is limited credit, poor road and distribution systems, and weak marketing and research. The private commercial sector is generally poorly developed in most countries (Ryan 2002). *Socio-economic constraints are often as insurmountable as the biophysical ones*. With increasing pressure on land use driven by high population, especially in rural areas, cropping has to be intensified as cultivable land cannot be expanded. Agriculture in the WANA region is described in detail in Chap. 15.

The vast WANA region exhibits great diversity in its landscapes, climate, natural resources and its people, but it has many common features – notably low rainfall (Kassam 1981) and a Mediterranean climate that merges into a continental climate inland. Winters are cool to cold and wet while summers are warm to hot and arid. Rainfall is generally low (200–600 mm) and variable, with periodic drought. However, rainfall concentration at the cooler time of the year (November–April) provides an opportunity for cropping (Harris 1995). Crops may depend on winter-stored soil water to complete their life cycle in spring. Invariably, there is some degree of moisture stress during the grain-filling stage (Pala et al. 2004).

Soil properties which dictate crop growth and yields include soil depth, which limits the water-holding capacity of the soil and thus its capacity to support rain-fed crops; lighter soil texture restricts soil capacity to hold moisture for crop growth. While deep clay soils are inherently productive, shallow soils are particularly vulnerable to soil erosion. The low organic matter (OM) (<1%) in the region's soils have implications for physical properties such as aggregate stability (Masri and Ryan 2006) and chemical fertility; low organic matter also implies low reserves of available soil nutrients, particularly nitrogen (Ryan and Matar 1992; Ryan 1997). Soil chemical properties such as pH (commonly alkaline in the region) also have a determining influence on nutrient dynamics and availability in soils.

The solubility relationships dictated by high pH and $CaCO_3$ combine to reduce available P in soils; and to reduce the availability of P added as a fertiliser. Consequently, the use efficiency of P is much lower than that of N, being in the order of 5–10% in the initial cropping year after fertiliser application. However, recent evidence from long-term field studies suggests that much, if not all, the P precipitated or immobilised in the soil may ultimately be taken up by the crop (Syers et al. 2008). Most soils that have not been fertilised are invariably P deficient, with severe limitation of the crop's yield potential (Matar et al. 1992). High soil pH in the Mediterranean region also reduces the plant availability of micronutrients such as zinc. Various field studies in Turkey (Cakmak 1998) and Syria (Materon and Ryan 1995) have shown crop growth responses to added zinc.

5.3 Balanced Use of Nutrients in Rainfed Cropping Systems

The concept of 'balanced fertilisation' implies meeting the individual nutrient needs of crops according to their physiological requirements and expected yields. This means the deliberate application of all nutrients that the soil cannot supply in adequate amounts for optimum crop yields. It depends on soil test values and requires estimates of what crops remove. There is no fixed recipe as it is soil and crop-specific.

The concept is old and based on Liebig's 'Law of the minimum', that is that any deficiency of one nutrient will severely limit the efficiency of others. It has been developed into two approaches to balanced fertilisation (Johnston 1997): (1) balanced nutrition by supplying nutrients in the correct physiological ratios for optimum growth of specific crops, and (2) adding nutrients in amounts that do not exceed what the crop removes. In a recent overview of optimising plant nutrition for food security, Roy et al. (2006) equated balanced fertilisation with balanced plant nutrition. The fertiliser requirements for a particular crop can be determined by the difference in the amount available (soil test) and the amount required by the crop. The ratio of individual nutrients will vary with the soil and the crop. In theory, fertiliser practices (such as providing specific crop needs, appropriate fertilisers and application methods) are developed by applied agricultural research and conveyed to farmers by extension personnel. The absence of an effective extension agency in most developing countries is a stumbling block to effective technology transfer in the area of crop fertilisation. Farmers have to depend on a variety of sources of information, including fertiliser dealers and other farmers.

The concept of balanced fertilisation has been influenced by trends in global fertiliser use. These have remained static over the past two decades or have even declined in 'developed' and 'transition' economies. The only increases have been in developing countries (IFA 2006). At the global level, only N use increased in this period, with a decline in both P and K consumption.

Data from major rainfed agriculture such as in Syria, Turkey, and Morocco are in line with global trends in fertiliser use, but are of differing magnitude (IFA 2006). Before 1970, little fertiliser was used in these countries, but this was followed by a rapid increase in use of N and P, with limited amounts of K. Both N and P use seem to be relatively stable in the last decade, although various circumstances such as internal fertiliser production, importation and marketing, can influence the amounts of fertiliser nutrients used in any 1 year.

The variability in N and P use in the region, and the minimal K use, raise the question of how appropriate are the ratios of nutrients applied to satisfy specific crop needs. In developed countries, examples of ratios of applied NPK are 1.0: 0.30: 0.30 in the UK and 1.0: 0.38: 0.44 in the USA; in the WANA region, corresponding nutrient ratios are 1.0: 0.52: 0.23 in Morocco, 1.0: 2.0: 0.50 in Jordan, 1.0: 0.41: 0.06 in Turkey, and 1.0: 0.83: 0.06 in Tunisia. Most of these countries are dominated by rainfed agriculture. These differences between countries suggest that there is an imbalance of fertiliser nutrients applied in many countries of the region.

Where use of K is minimal in intensive cropping, deficiencies of this nutrient are likely to occur and lead to 'soil mining'. When the ratio of N to P is close to, or greater than 1, either too much P is used or not enough N is used. However, balanced fertilisation has to consider site-specific conditions, especially with respect to available soil nutrient status.

5.4 Sustaining Soil Fertility and Related Physical Properties

Crop production is limited directly by nutrient availability of the soils and indirectly by physical limitations. Nutrients may be immediately available for uptake and utilisation by the growing crop or may be slowly released from less soluble inorganic sources or from mineralisation of soil organic matter. While deficiencies in fertility may be rectified by fertiliser application, improvements in physical properties are less easily obtained.

5.4.1 Nutrients for Crop Production

Crop production strategies are based on diagnosing nutrient deficiencies and establishing a rational basis for chemical fertiliser application (Brown 1987). Significant contributions have been made to both areas by the Soil Test Calibration Network that has involved most countries of WANA with significant rainfed agriculture (Ryan and Matar 1990, 1992; Ryan 1997). Measurement of both the soil and the growing crop can provide the basis for efficient fertilisation and crop nutrition (Roy et al. 2006). The main approach is through soil analysis, the initial phase of which involves developing appropriate tests with values that correlate with plant nutrient uptake.

The Olsen test was adopted as suitable for the mainly calcareous soils of the Mediterranean region; the critical range is 5–7 mg P/kg of oven dry soil. The measurement of soil nitrate to indicate N sufficiency was less reliable due to changes from fertiliser use. The DTPA test of Lindsay and Norvell[1] (1978) was deemed adequate for micronutrients and is widely used; a multi-nutrient extractant such as the ammonium bicarbonate or AB-DTPA test (Soltanpour 1985) is used in Pakistan.

The second phase of testing involves calibration or developing guidelines for fertiliser recommendations in the field; in this way, 'critical' levels can be established below which a nutrient level in soil is deficient, with a probable response to fertiliser, and a point beyond which there is no need to apply fertiliser. Other factors such as soil type, soil moisture or rainfall, and nutrient spatial variability have to be considered in practical field situations (Ryan 2004).

[1] A test for micronutrients using DPTA (diethylenetriaminepentaacetic acid).

A less reliable approach to assessing fertiliser needs involves the crop itself. Plant symptoms can indicate the severe deficiency, but other factors such as drought or disease can mask the symptoms. Analysis of the plant tissue is more reliable for a particular nutrient. Appropriate guidelines for sampling, handling and analysing the tissues, along with criteria for the range from deficiency to adequacy have been developed (Ryan et al. 1999). Quick tests designed to give results in the field without delay are based on qualitative nutrient determination in the expressed fresh plant sap. Colour meters are another cheap and easy way to quantify the need for N in a growing crop in the field based on the green colour intensity of the leaves.

While these approaches to assessing soil fertility are commonplace in developed countries, they are less frequently used in developing countries (including the WANA region) and, in some countries, not at all. The major obstacles to such approaches include a weak extension sector, the absence of laboratory facilities for analyses, and limited applied, on-farm research related to soil fertility and fertiliser use. Nevertheless, much has been done through the regional Soil Test Calibration Program to promote the awareness of the soil analysis in the agriculture of WANA (Ryan and Matar 1990, 1992; Ryan 1997). Soil analysis is likely to be adopted as a tool in fertility–crop nutrient management as crop intensification increases, especially with irrigation and the increasing use of fertilisers. However, farming in developing countries is, and will remain, a long way from a developed country situation where precision agriculture allows nutrient application to be tailored to specific parts of a field (see Chap. 34). With pressure on land use, cropping intensity in developing countries will inevitably increase, with fertilisers having a major influence.

How efficiently fertiliser is used over large areas depends on the variability of the nutrient in the field or paddock. Recognition of this spatial variability is the basic principle behind precision agriculture (Chap. 34).

Some fields are naturally flat and uniform. This tendency to uniformity may be enhanced by a history of uniform management of crops and fertiliser application rates. Small fragmented parcels of land so characteristic of developing world agriculture promote variability (Abdel Monem et al. 1989) which is compounded by grazing, hand application of fertilisers, and variable erosion. Applying a standard rate of fertiliser to a non-uniform field is inefficient; however the only solution is costly, variable rate technology.

5.4.2 Soil Physical Properties

In contrast to chemical fertility, some physical properties such as soil texture are fixed, while soil structure depends on soil and crop management. Soil aggregation is mainly influenced by the soil organic matter content. However, in typical red Mediterranean soils (Alfisols), iron oxides can be significant aggregating agents, particularly when the iron is in the amorphous state (Arshad et al. 1980). Poorly structured soils are prone to erosion. Despite the importance of soil organic matter

(SOM) in soils of the WANA region, efforts to document changes on SOM in response to management over time have been limited. SOM content in trials has been listed without elaborating its significance (Ryan 1998). Only where long-term trials have been conducted has it been possible to document the dynamic nature of soil organic matter in relation to cropping over time, as in studies of crop rotations in northern Syria (Ryan et al. 2008a). Legume-based rotations and N fertilisation can each increase total SOM as well as labile[2] and biomass C forms (Ryan et al. 2002, 2008c). However, only one study (Masri and Ryan 2006) showed that these crop/fertiliser induced changes in SOM were accompanied by improvements in soil physical properties such as aggregate stability, water infiltration and permeability (See also Chap. 15).

It is reasonable to assume that any practice that enhances soil organic matter content would also improve aggregation and related physical properties. Such practices could include fertiliser use to increase crop growth, and consequently root biomass. The effectiveness of the increased root biomass in increasing SOM depends on the extent to which tillage could influence mineralisation of the OM from the root biomass. Where there is minimum disturbance as in conservation tillage compared to conventional tillage, SOM is likely to increase (Ryan and Pala 2006). Similarly, the addition of crop residues or compost materials, or minimising stubble grazing can lead to improvements in organic matter and soil structure.

5.5 Crop Nutrients as Influenced by Rainfall and Soil Moisture

The obvious determinant of crop yields in rainfed farming systems is the amount of rainfall and the water use efficiency (WUE) (Stewart and Steiner 1990; Smith and Harris 1981). Any crop or soil management intervention (weed control, fertilising, and tillage) that contributes to increased yield under any given rainfall conditions automatically increases WUE (Matar et al. 1992). WUE can also be influenced by the particular crop sequence (Harris 1995; Pala et al. 2007).

Responses to N application increase as rainfall increases (Harmsen 1984) but, under low rainfall conditions, the relative response to P may be higher than that to N due to a stimulating effect on root growth and therefore soil moisture uptake (Cooper et al. 1987b). Nutrient use efficiency is influenced by variation in rainfall and temperature. Seasonal variability in available N is related to variation in the extent of mineralisation of soil organic matter and by any immobilisation of those nutrients.

Case studies provide an illustration of the interaction of nutrient use with moisture availability. A 4-year study of researcher-managed, on-farm field trials across the

[2] See Glossary.

rainfall zones in northern Syria showed that wheat yields were strongly correlated with seasonal rainfall (October–May), almost irrespective of soil fertility status, crop sequence or fertiliser application rate (Pala et al. 1996 See also Chap. 1, Fig. 1.9). However, there was an increase in response to applied N with increasing rainfall and with decreasing soil N. In contrast, responses to P tended to be more pronounced under lower rainfall conditions (Jones and Wahbi 1992).

Despite the more obvious interactions of fertiliser with environment (especially rainfall and temperature), there are others of a biological nature. For instance, in Morocco in the 1990s, much effort was expended on stimulating cereal output in the medium-rainfall zone with particular emphasis on control of the devastating pest, the Hessian fly (*Mayietola destructor*). In trials with wheat cultivars of varying resistance to Hessian Fly, the application of fertiliser N was shown to enhance tolerance of the pest (Ryan et al. 1991). In contrast, the addition of N had variable effects of conferring resistance to the fungal disease, Tan Spot (Jones et al. 1990).

When considering the economics of nutrient application, a more complete analysis than simple cost-benefit is required, to take into account the complex interactions of cropping system components. For example in the WANA region only one study has assessed rotations in this way (Rodriguez et al. 1999), despite the many bio-physical studies dealing with crops and soils (Ryan et al. 2008a).

5.6 Use of Legumes in Crop Sequences

Since the Mediterranean is the centre of origin of many legume species, it is likely that such crops had a significant influence in early settled agriculture (Harlan 1992). Indeed the written record from Grecian and Roman times mentions legumes in the context of rotations with cereals and the predominantly cereal–fallow systems which sustained cropping in such a water-stressed environment (Karlen et al. 1994). Both Greeks and Romans recognised that legumes benefited cereal crops without being aware that this was related to N. Despite the antiquity of legumes, their use had declined over the centuries. However, in the past century, legumes, particularly forages, have shown a resurgence in many areas of the world. In Australia forage and pasture legumes in a cereal-sheep ley farming system (Puckridge and French 1983) have supplied both fodder for livestock and mineralised N for the subsequent cereal crop (Hossain et al. 1996). Similarly, the benefits of legumes in rotation with cereals was clearly recognized in the USA for enhancing soil N (Carpenter-Boggs et al. 2000) and for providing crop diversification (Norwood 2000).

Only in more recent times has the potential of legumes in rainfed agriculture been recognized in developing countries. The rationale for the resurgence of interest in food and forage legumes was articulated by Harris (1995) in the context of the Mediterranean region, where population and land-use pressure contributed to decreasing fallow and led to continuous cereal cropping. Similarly, with increasing populations of small ruminants, increasing pressure for livestock feed was put on marginal areas with consequent risks of land degradation.

Various crop rotation studies by ICARDA (Ryan et al. 2008a) show a strong impact of rotation sequence not only on soil properties, especially SOM (Ryan et al. 2008c), but also on WUE (Pala et al. 2007) and nutrient use (discussed in detail for WANA in Chap. 15).

The inclusion of legumes, particularly forage legumes, in the cereal-based rotation leads to an increase in nitrogen rich SOM, and thus an increase in the reserve of potentially available N. Not surprisingly, these increases in total SOM are accompanied by parallel increases in total mineral N as well as both labile and biomass N forms (Ryan et al. 2008d). The outcome of the increased N in legume-based rotations is higher N availability to the alternative wheat crop, with a correspondingly lower response to and need for fertiliser N. An example of the cumulative effect of N fixation by a forage legume on cereal growth is illustrated in Fig. 5.2.

The nutrient status of a soil varies over time, partly due to nutrient removal in harvested crops. For example cereal–legume rotations require regular P application (demonstrated in a range of rainfall zones by Ryan et al. 2008b). However, in these situations, there is usually a gradual build-up in available P over time which will call for changes in the amounts of fertiliser required to maximise both economic and nutrient use efficiency.

The belief that legumes could contribute both to cropping sustainability and to relieving grazing pressure on marginal lands laid the foundation of the extensive research on N fixation and related areas from 1980 to 1995 (Harris 1995; Ryan et al. 2008a). The success of biological nitrogen fixation (BNF) by legumes depends on the correct match between the *Rhizobium* strain, host legume variety and the environment (Beck 1992). All these factors must be considered when introducing new legumes into a rotation.

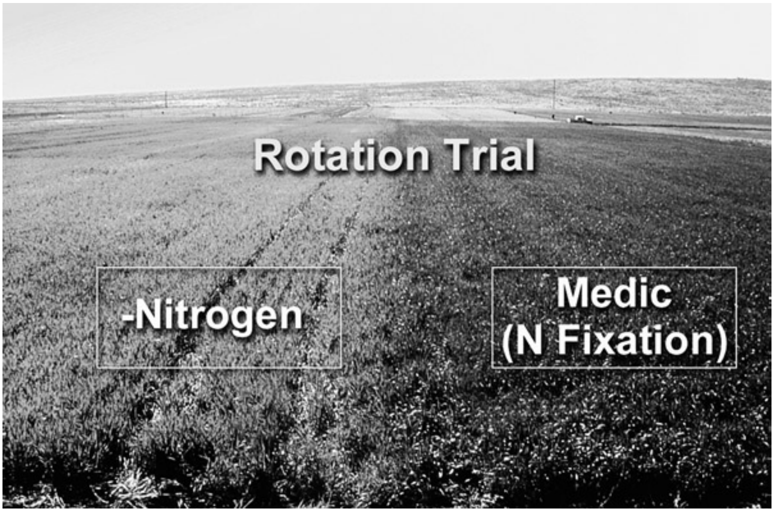

Fig. 5.2 A comparison of wheat growth in the medic rotation—medic in the alternate year (*right*), with wheat in the fallow rotation without added N

Various surveys in cropped fields throughout the WANA region (Syria, Turkey, Jordan, and Egypt) involved characterisation of the rhizobia (Moawad and Beck 1991) for tolerance to high temperature and salt, as well as antibiotic resistance. Based on the variation in the environment, legumes were inoculated with superior *Rhizobium* strains in areas where these legumes had not been previously grown. The use of ^{15}N methodology and non-nodulating chickpea[3] and barley as reference crops allowed for accurate evaluation of N_2 fixation under a wide range of environmental conditions (Beck 1992); N fixation was higher under more favourable rainfall environments than in drier areas. The goal of good crop management should be to maximise the contribution of BNF through legumes and reduce the contribution of N from the soil (Beck et al. 1991). The N from legumes contributes substantially to the subsequent crops.

The WANA region provides a wide range of naturally occurring legumes and associated rhizobial communities. This wide genetic diversity is of great potential importance to cereal–legume systems, not only for the region but around the world (Keatinge et al. 1995). For example, rhizobial cultures from Turkey and northern Africa have been selected on the basis of climatological parameters, such as average minimum and maximum temperatures in the coldest month (January).

Medic–rhizobial associations in forage and pasture have been sought for tolerance to the cold winter conditions. The pasture may grow in such cold conditions but the rhizobia should also be able to fix N under the same conditions. While cold tolerance is a factor in effectiveness of rhizobial–medic associations, nutrient deficiencies limit the growth of medics and their BNF effectiveness. The early research related to BNF in food legumes laid a firm basis for the widespread adoption of these crops. Chickpea and lentil (and vetch for forage) are now well established in the agricultural system in the region but the story of forage legumes is more chequered. Provided that a legume and rhizobium combination adapted to the climate and soils can be found, it can largely replace the need for fertiliser N. The use of legumes in the WANA region is discussed in the section on rotations in Chap. 15.

5.7 Conclusions

Achieving the correct nutrient balance is one of the keys to achieving productive and sustainable farming systems. The complex rainfed farming systems of the Middle East are a prime example. Their components include crops, livestock and forages (Fig. 5.3). As with many parts of the world, the socio-economic factors intrude on all aspects of the region's agriculture, which for many remains a way of life rather than purely an economic enterprise. As elsewhere, the region's agriculture is markedly affected by the rapidly expanding populations, especially in rural areas, combined with the limited off-farm economic opportunities for gainful employment.

[3] A strain of chickpea bred for trial purposes.

Fig. 5.3 Sheep grazing vetch in Syria

Having been farmed for millennia, the region has an element of resilience in its agricultural system. Nevertheless, the sub-optimal traditional practices are undergoing inexorable change.

Today's agriculture is more concerned with both productivity and profitability of the crop and livestock sector since subsistence and self-reliance are being replaced, albeit slowly, by a market-driven system. The pressure, by urbanisation, to intensify more output from the same area of land leads to concerns about degradation of the soil and water resource base. To produce more from less land requires more nutrients from fertilisers, as well as the use of pesticides and mechanisation. In working with nature, the diversity with respect to biological nitrogen fixation can be exploited to sustain cropping and reducing the need for fertiliser N.

In rainfed farming systems, no component can be considered in isolation. Fertilisers are pivotal to improving agricultural output, but they must be used rationally, taking into consideration constraints imposed by the limited rainfall and inherent soil properties. Sustainability of the soil resource base can be indirectly enhanced by fertiliser use, especially when used in a systems context. Balanced fertiliser application can lead to its more efficient use for production as well as for minimising adverse environmental impacts. Awareness of differences between soil types and spatial variability within soils can lead to a more rational and more efficient use of fertilisers.

In addition to the changes that are occurring within the rainfed farming sector of the WANA region, a major development has been the use of supplemental irrigation to stabilise crop yields within traditionally rainfed areas. Inevitably, that trend will be slowed or halted by limitations on groundwater and surface water sources. As most semi-arid or rainfed areas of the world are likely to be negatively impacted by climate change, the challenges to rainfed cropping in the Mediterranean region are daunting.

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Chapter 6
Principles and Management of Soil Biological Factors for Sustainable Rainfed Farming Systems

Vadakattu V.S.R. Gupta, Albert D. Rovira, and David K. Roget

Abstract Soil microflora and fauna are important for organic matter decomposition and hence nutrient cycling, organic matter turnover, disease incidence and suppression, agrochemical degradation and soil structure. Soil moisture, temperature and availability of energy source (carbon) determine the activity of these organisms. Biological activity and plant growth must be synchronised for optimum production. Control of soil-borne root pathogens is important in maximising water use efficiency. The beneficial influences of soil biota include nitrogen fixation, nutrient cycling and supply, improved soil structure, promotion of plant and root growth, and disease control or suppression. Detrimental influences include those of root pathogens and deleterious rhizobacteria.

Keywords Biological activity • Microflora • Micro-fauna • Meso-fauna • Macro-fauna • Rhizosphere • Detritusphere • Rhizobacteria • Arbuscular mycorrhizal fungi • Disease suppression • Water use efficiency

6.1 Introduction

Biological activities in the soil are important in the processes of achieving the productivity and sustainability of rainfed farming systems. These activities involve macro, meso and micro-fauna and microflora, which decompose the shoot and root

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_6,

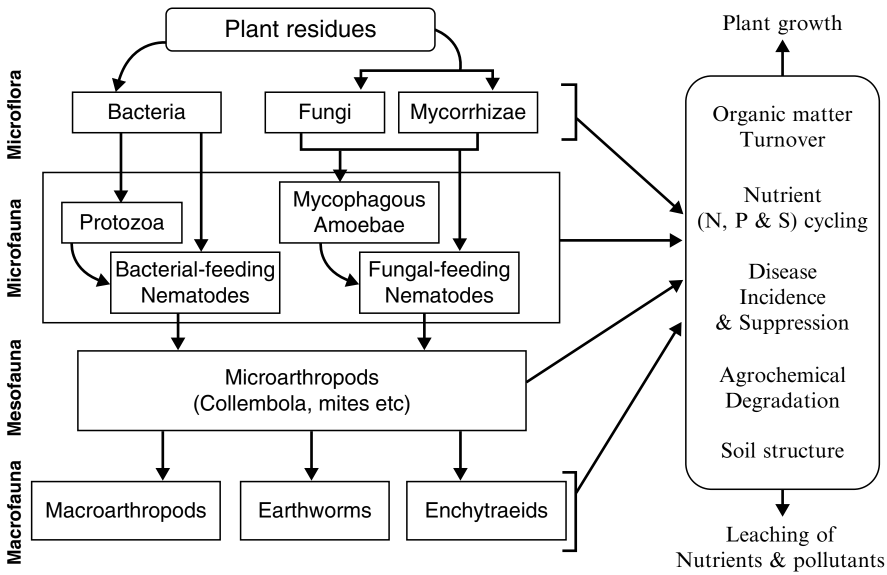

Fig. 6.1 A detritus food web showing linkages between the different groups of soil biota, and indicating their role in soil biological functions of cropping systems (modified after Gupta and Neate 1999)

residues of plants and influence plant performance. Figure 6.1 shows the components of this population of organisms and how they interact in a food chain or web to affect plant growth and losses of nutrients from the system. The optimum functioning of the majority of biological processes requires a balanced interaction between different components of soil biota both within and between major groups. The activities of all organisms and processes are affected by levels of soil organic carbon, moisture and temperature, in addition to a variety of other soil and environmental factors (Coleman et al. 2004).

6.2 Importance of Moisture, Temperature and Carbon Supply on Biological Activity in Soil

The majority of the concepts and the evidence on the importance of biota and biological processes for productive and sustainable agricultural systems presented in this chapter are derived from research in Mediterranean regions of Australia and the world which are characterised by cold wet winters and hot dry summers.

In most rainfed cropping regions, soil moisture supply and temperature can determine the populations and activity of soil microflora, microfauna and macrofauna. Most soil microbes require carbon as a source of energy; therefore carbon inputs through plant shoot and root residues have a major influence on their populations and the biological processes they mediate. This need for C is also the reason for the concentration of microbial populations in carbon-rich microsites such as rhizosphere (soil surrounding plant roots) and detritusphere (soil associated with decomposing residues) (Beare et al. 1995; Roper and Gupta 1995; Pinton et al. 2007). As many of the soils in rainfed regions are low in biologically-available organic carbon, most biological activity (>60%) is concentrated near decomposing crop residues in a thin layer of surface soil and in the rhizosphere (Gupta and Roper 1994; Bowen and Rovira 1999; Watt et al. 2006).

The composition and activity of beneficial and pathogenic microbiota are affected by plant type, available soil moisture and carbon levels. Thus benefits from biological functions are maximised if management is crop specific, especially in water-limited Mediterranean environments. The repeated wetting and drying events that are common in these environments during summer have the potential to impact on the stability (resistance and resilience) of biological functions, especially under lower available C conditions (more details in Chap. 1).

Plant–biota interactions can be characterised as: (a) constraints to root and shoot growth (for example root diseases caused by soil-borne pathogens can limit yield potential in cereal crops (Rovira and Ridge 1983)) and (b) biological interactions related to nutrition and plant health. An efficient plant–microbe interaction is critical for effective plant health management (e.g. plant nutrition, disease suppression).

Moisture, temperature and carbon availability need to be synchronised for optimal performance of a range of key biological functions that include: (1) nutrient mineralisation and uptake by plants; (2) nitrogen fixation (symbiotic and non-symbiotic); (3) control of root pathogens; (4) disease suppression; (5) promotion of soil aggregate stability and structure; and (6) agrochemical degradation. This is important for optimum plant performance, and successful management of cropping systems. For example, nutrient mineralisation–immobilisation processes need to be understood in order to synchronise nutrient availability and plant needs and also to reduce nutrient losses through leaching. Similarly, to optimise the suppression of disease organisms by other soil biota, the critical periods for the root pathogen–soil biota–plant interaction need to be identified.

The temporal dynamics of regulating factors and critical periods of biological activity must be understood to optimise management benefits to crops. For example, in winter rainfall-dominated Mediterranean environments, non-symbiotic N fixation is limited by low temperature more than by soil moisture during winter. In summer (i.e. off-season), nutrient mineralisation is generally associated with intermittent rainfall periods only and the immobilisation–mineralisation processes which favour a slower net accumulation of mineral N are preferred in order to reduce leaching losses. In southern Australian rainfed regions, this situation occurs in conservation farming systems involving retention of crop residues and reduced tillage.

Figure 6.2 shows the effect of rainfall on the level and duration of microbial activity, measured *in situ*, in a Calcic Xerosol soil in a Mediterranean environment, at Avon in South Australia. The top graph shows how microbial activity is increased and prolonged with increasing rainfall. The lower graph shows how microbial

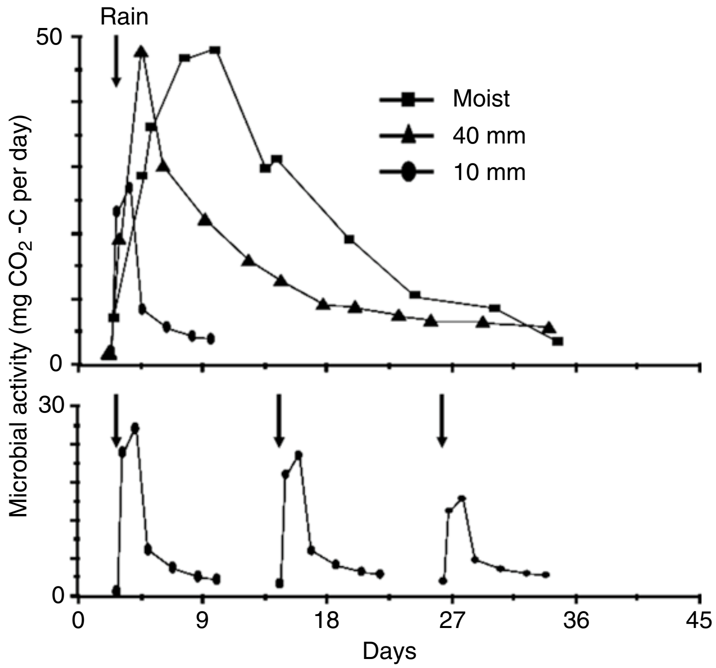

Fig. 6.2 Effect of amount of rainfall received on the level and duration of microbial activity (Gupta VVSR and Roget DK, unpublished data). Soil in the 'Moist' treatment (*top diagram*) received four successive 25 mm per week rainfall events

activity rises briefly with each of three inputs of 10 mm rain, although the maximum level of activity declines with each succeeding rainfall (Gupta VVSR and Roget DK, unpublished data). The duration of moist soil conditions also determines the various groups of biota that can make a positive contribution to biological processes. For example, fast-growing microorganisms (e.g. copiotrophs[1] such as cellulolytic microorganisms) can be activated quickly after rainfall, utilise available substrates and contribute to a biological process even when the moist period lasts for only 2–3 days. In contrast, slow-growing organisms such as autotrophic, ammonia-oxidising bacteria require longer periods of moist soil. They may be unable to be activated in sufficient numbers within a short period so are functionally less significant.

In the examples of Fig. 6.2, the type of biota activated, in terms of phenotypic or functional groups, is determined by the habitat condition, e.g. structure of water-filled pore-space, and the duration of moist conditions. For example, small rainfall events (of 10 mm) can maintain a moist environment for periods of only a few hours to a couple of days depending on temperature and solar radiation; this may

[1] See Glossary.

be sufficient for some copiotrophic microorganisms but not for slow growers or soil fauna. Such events may support decomposition processes (i.e. C turnover) but not nitrification and faunal activity. The reduction in the level of microbial respiration with successive 10 mm rainfall events can be attributed to the decline in biologically available C. Larger rainfall events (more than 25–40 mm in South Australia) may be needed for most soil biota to make a significant contribution to a biological function. In southern Australia, large but infrequent rainfall events generally occur in summer whereas small and intermittent rainfall events are common during both winter and summer. The effect of similar amounts of rainfall differs in terms of their impact on a variety of biological processes. Therefore, the functional significance of the water received, i.e. in terms of nutrient supply, decomposition, pathogen survival and growth, from small events is different to that received in large downpours.

The impact of a soil biological process within the farming system may depend on when it occurs in relation to the crop growth. The benefits from microbial communities that promote root growth are best gained when these organisms are more active during early seedling growth. Organisms involved in N mineralisation are active in both the off-season and the in-crop season (Fig. 6.3 and Table 6.1). Therefore N mineralised during the off-season may accumulate and/or be lost through leaching, denitrification or weed uptake whereas the N mineralised during the growing season in the rhizosphere may be utilised immediately by the crop.

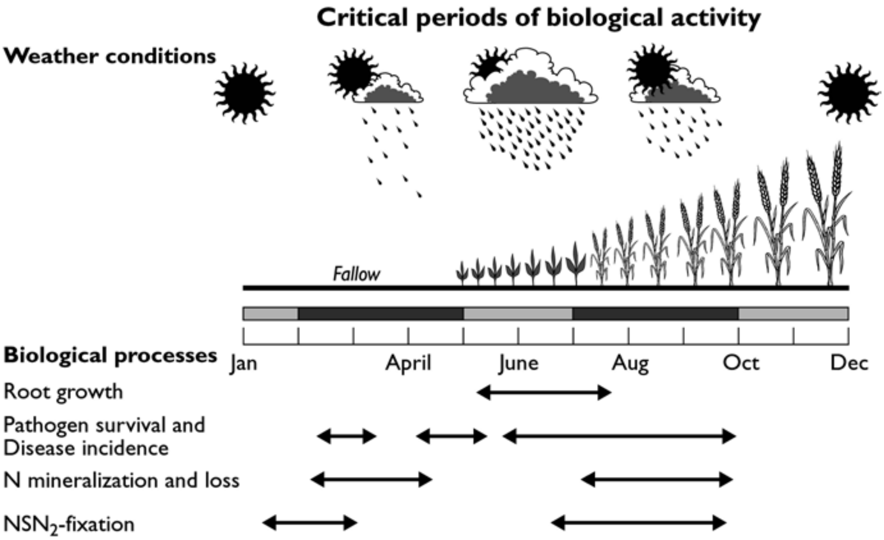

Fig. 6.3 A conceptual model describing the significance of soil biological processes and their impact within the farming system in a Mediterranean climate in the southern Australian cropping region. The crop is generally planted between April and June, depending on occurrence of adequate rain. Harvest is in December

Table 6.1 Seasonal soil processes indicated in Fig. 6.3

Biological processes during off-season (over summer)	Biological processes during crop season (winter and spring)
Beneficial:	*Nutritional:*
N Mineralisation and leaching	Mineralisation, nutrient availability and uptake
Soil Aggregation and erosion	Root and shoot growth
Non-symbiotic N_2-fixation	Non-symbiotic N_2-fixation
Degradation of non-target chemicals e.g. herbicides	Symbiotic N_2-fixation
Pathogen suppression	
Deleterious:	*Plant health related:*
Survival of pathogenic organisms	Pathogen growth and disease incidence
	Disease suppression

6.3 Water Use Efficiency (WUE)

The term 'water use efficiency' generally refers to commodity (e.g. grain or dry matter) yield per unit of growing season rainfall, minus an estimate of the water lost through soil evaporation (see Chap. 1). Traditional farming systems in Mediterranean regions including southern Australia were largely low-input and low-risk, and operated considerably below the attainable WUE – partly due to the inefficient management of biological and biophysical factors (French and Schultz 1984a, b).

In a survey by Sadras and Angus (2006), most crops in South Australia were found to achieve only 30–50% of their yield potential but WUE could be increased by removing constraints such as poor nutrition and root disease. Most rainfed crops in China, the Mediterranean Basin, the North American Great Plains and south-eastern Australia had WUEs at 31–44% of their potential.

Low WUE has been attributed to many management and biological factors (French and Schultz 1984a, b). In the low-rainfall Mallee region of south-eastern Australia, low WUE could be attributed to: (1) failure to manage the soil biota to maximise nitrogen availability; (2) diseases from soil-borne root pathogens; and (3) poor management such as untimely sowing or inadequate fertiliser application. In the Pacific Northwest region of the USA, soil-borne root pathogens reduced WUE in rainfed cropping systems under conservation tillage (Cook and Haglund 1991). In southern Australia, control of two major root pathogens – Take-all and Rhizoctonia root rot – by rotation, tillage practices and adding nitrogen through legume–*Rhizobium* symbiosis lifted WUE from 30% to 100% (Fig. 6.4) (Rovira, unpublished).

The variability in total rainfall (193–523 mm) and April–October rainfall (154–364 mm) at Avon is typical of the Mediterranean-type climate and emphasises the need to develop management options for farming systems that can maximise WUE under such conditions. If, as projected, global warming increases rainfall variability and winter temperatures, effects may include more variable mineralisation of soil N and increased seedling diseases.

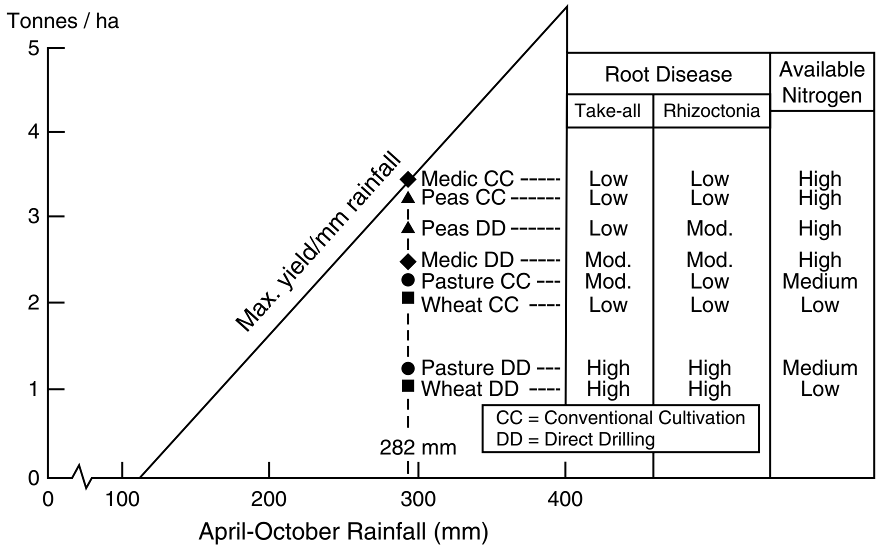

Fig. 6.4 The effect of rotation and tillage practice on yield of wheat through their influence on different biological constraints to plant growth and productivity (Avon, SA in 1984). Grain yields for the particular rainfall in 1984 are compared with the French-Schultz estimates of potential yields (*sloping line*)

6.4 Beneficial Effects of Soil Biota on Factors Influencing Productivity and Sustainability

6.4.1 Biological Nitrogen Fixation

Biological nitrogen fixation, both symbiotic (SNF) and non-symbiotic (NSNF), is highly beneficial for both the economic and the environmental sustainability of crop production, especially in low-input rainfed farming systems. The increasing cost of fertiliser N and the threat from increased greenhouse gas loads (including N gases) emphasise the need to maximise N inputs from natural processes.

6.4.1.1 Symbiotic Nitrogen Fixation

Until N fertiliser became commonly used, grain and pasture legumes were important contributors of symbiotically fixed N. For instance, the productivity of rainfed farming in southern Australia for the past 100 years has depended on the symbiotic association between legumes (crop, forage and fodder) and root-nodulating bacteria belonging to genera *Rhizobium*, *Bradyrhizobium*, *Ensifer* and *Mesorhizobium* (Murrell and Kennedy 1988).

Nitrogen fixation by legumes produces around 80% of the nitrogen in Australian grains, with a value estimated at $AUD 3 billion each year (Howieson and Herridge 2005). Globally, annual inputs of fixed N for crop legume–rhizobia symbioses are estimated as 2.95 million tonnes for pulses and 18.5 million tonnes for oilseed legumes.[2] Estimates for forage and fodder legumes ranged widely (12–21 million tonnes) (Herridge et al. 2008).

It is estimated that for each tonne of legume dry matter some 25 kg of nitrogen is fixed (Peoples and Baldock 2001), and a well-grown rainfed legume–grass pasture in eastern Australia will fix annually around 125 kg of nitrogen/ha (equivalent to 270 kg of urea).

Pasture legumes have recently been adversely affected by factors such as lower P-fertiliser inputs, soil-borne pathogens at plant establishment, diseases and insect pests and inappropriate herbicide use. Such factors have reduced annual N inputs through symbiotic N_2 fixation to less than 25 kg/ha N (Drew et al. 2004).

Medicago species have grown well on the alkaline soils in southern and south-eastern Australia, but not in the large cropping areas of acid soils of Western Australia until acid-tolerant *Medicago* species and acid-tolerant rhizobia were introduced (Howieson and Ewing 1986). However, strains of rhizobia with lower nitrogen-fixing ability now compete with the initially highly effective acid-tolerant rhizobia (Nandasena et al. 2007).

Liming has had an overriding positive influence on the rhizobial populations and N fixation in lucerne and medic pastures on an acidic chromosol in central NSW (Roesner et al. 2005). In addition, the rhizobial numbers were higher where homologous pasture species were grown, for example the *Medicago* species lucerne and annual medic, which use the same rhizobia, and various *Trifolium* species which use the same clover rhizobia. The benefits of liming were due both to the correction of low soil pH and to increased levels of Ca (Roesner et al. 2005). Based on a survey of 71 sites in south-western Victoria, Riffkin et al. (1999) concluded that both chemical (soil potassium, total N and extractable P) and biological (density of plant parasitic nematodes and rhizobia numbers) factors influenced N fixation in clover-based dairy pastures, and the effects varied with soil texture.

In order to design more efficient nutrient cycles and overcome vulnerabilities (e.g. economic returns and nutrient loss) of legume-based rotations (especially grain legume) Peoples et al. (2009) proposed a variety of changes to traditional cropping systems: (1) delaying cultivation of legume phases from autumn to spring; (2) intercropping legumes with cereals; and (3) including non-leguminous species and perennials in legume-based pastures.

6.4.1.2 Non-symbiotic Nitrogen Fixation (NSNF)

The potential for NSNF by free-living bacteria varies according to the availability of energy sources, soil temperature and moisture conditions. Thus it is significant

[2] e.g. peanuts and soybeans.

only near decomposing crop residues (Lynch and Harper 1983; Roper and Ladha 1995) and in the rhizosphere (Dobereiner 1992; Li and Macrae 1991). The numbers of NSNF bacteria present in soils are highest near crop residues with high C:N ratios. Some nitrogen-fixing bacteria can utilise components of cereal stubble directly (Halsall 1993) but most rely on the decomposition of cellulose to simpler intermediates by other members of the microbial population (Halsall and Gibson 1989). NSNF microorganisms utilise available sources of N before fixing new nitrogen.

If optimum soil moisture and high C availability do not occur together during the warm off-season (as in Mediterranean-type environments), NSNF can still contribute N during the moist but cooler cropping season. Root exudates from growing plants provide an ideal source of readily available C which can enhance populations and activities of a diverse group of microbiota in the rhizosphere (Bowen and Rovira 1999). Free-living N-fixing bacteria (e.g. *Azospirillum* spp., *Azotobacter* spp., *Acetobacter diazotrophicus*, *Herbaspirillum* spp., *Bacillus* spp., *Azoarcus* sp.) are found in the rhizosphere and rhizoplane[3] environments of cereal crops (Dobereiner 1992; Steenhoudt and Vanderleyden 2000; Boddey et al. 2001; Wood et al. 2001; Andrews et al. 2003; Buckley et al. 2007). Non-rhizobial N-fixing bacteria have also been reported to grow as endophytes in a number of grasses (Cocking 2003; Lupwayi and Clayton 2004).

However, the contribution of rhizosphere- and endophyte-associated N fixation in Australia is uncertain. In southern Australia, maximum soil temperatures in the rhizosphere during early periods of crop growth (June–August) are too low (<20°C) to support significant nitrogenase activity, and by the time the soil temperatures increase to a more desirable level (>25°C during September), the soil moisture is generally insufficient. However, large-size rain events that maintain soil moisture at desirable levels for NSNF activity during late winter and early spring can contribute to plant N requirement significantly. Since a large amount of C (20–40% of plant photosynthetic productivity) is released through rhizodeposition by growing plants (Lynch and Whipps 1990; Bertin et al. 2003), rhizosphere-associated NSNF has the potential to be exploited further.

The potential areas for NSNF in southern Australia have been mapped using estimates based on the known relationships between rainfall, temperature and NSNF (Fig. 6.5) (Gupta et al. 2006). Each region has its own maximum period for NSNF. The highest rates occur where both temperature and moisture are suitable i.e. in summer in summer-dominant rainfall zones. These estimates concurred well with field measurement of NSNF during summer at Gunnedah, NSW (12.3 kg N/ha fixed over 22 days under optimum moisture conditions) (Roper 1983).

Carbon availability was assumed to be non-limiting through plant residues from previous season cereal crops (Gupta et al. 2006). With the onset of autumn and winter rains, the potential for NSNF increased in the Mediterranean regions in southern and western Australia. This type of information could be useful for selecting the most potentially responsive areas for NSNF research and maximising its benefits.

[3] See Glossary for definition.

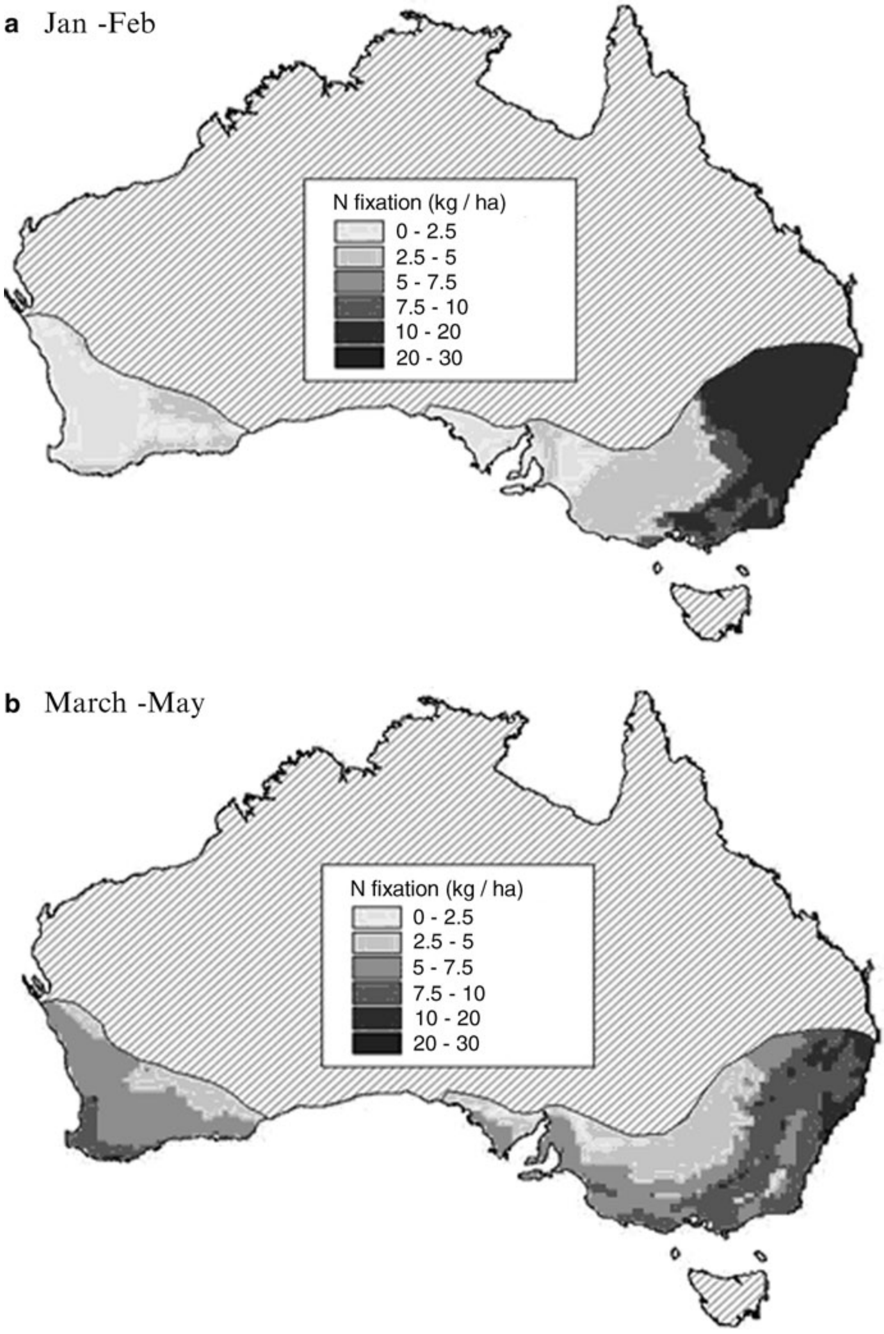

Fig. 6.5 Potential for non-symbiotic nitrogen fixation as influenced by rainfall and temperature in southern Australian cropping regions. (**a**) January–February; (**b**) March–May (reproduced from Gupta et al. 2006)

It could also be useful for agronomists and extension officers to help explain changes in N status within specific farming systems and to provide more accurate advice on N fertiliser requirements, particularly in low-input farming systems.

6.4.2 Nutrient Cycling and Supply

The total amount of N in the surface soil and the timing of its availability (i.e. synchrony between the rate of supply and crop demand) within a farming system are the product of a variety of soil biological processes including mineralisation and immobilisation, nitrogen fixation, decomposition of organic matter and denitrification. The complex interactions between the various microbial populations influenced by edaphic and environmental factors could result in a lack of synchrony between nutrient supply and demand, causing crop deficiencies or loss. Improving synchrony between these processes is critical both for efficient nutrient use, improved plant production and reduced risks from N-loss related environmental hazards (Crews and Peoples 2005).

Soils in rainfed farming areas under traditional, low-input crop–pasture and crop–fallow rotations are usually low in organic matter. Examples occur in the low rainfall Mallee region of southern Australia and cereal growing regions of Western Australia. However, soil biological functions can be improved by increasing biologically-available carbon through more intensive cropping, crop residue retention, strategic grazing and no-till practices (Roget and Gupta 2004). Crop productivity can be increased by better matching the N supply, both from biological processes and external fertiliser inputs, to the available water and hence increasing the water use efficiency. Changes to the N supply can come from higher levels of soil microbial biomass, increased NSNF, and associated higher mineralisation potential (Gupta and Roget 2004). The timing of net mineralisation can be delayed in order to synchronise N release and plant demand. Delaying net mineralisation from summer to autumn through high stubble loads after harvest can reduce leaching losses, increase the opportunity for NSNF and improve the capacity of the soil to suppress activity of soil-borne root pathogens.

Management practices such as cultivation, stubble management and grazing applied during the off-season can influence rate of nutrient release and thus its synchrony with crop demand. For example, cultivation accelerates decomposition and mineralisation, resulting in the accumulation of mineral N well before the crop demand (Crews and Peoples 2005; Gupta et al. 2009). In contrast, net mineralisation is generally slower under a no-till system, in particular following cereal stubble retention. Under crop, this can be influenced by root architecture, rhizodeposition and rhizosphere plant–microbe interactions, all of which can be manipulated through plant type and variety (Singh et al. 2004; Gupta et al. 2004).

An important aspect of soil biology in rainfed agriculture is the role of legume-fixed nitrogen as a source of nitrogen for subsequent crops. This is illustrated in Fig. 6.6 which shows the pathways for gains and losses of nitrogen for cropping soils.

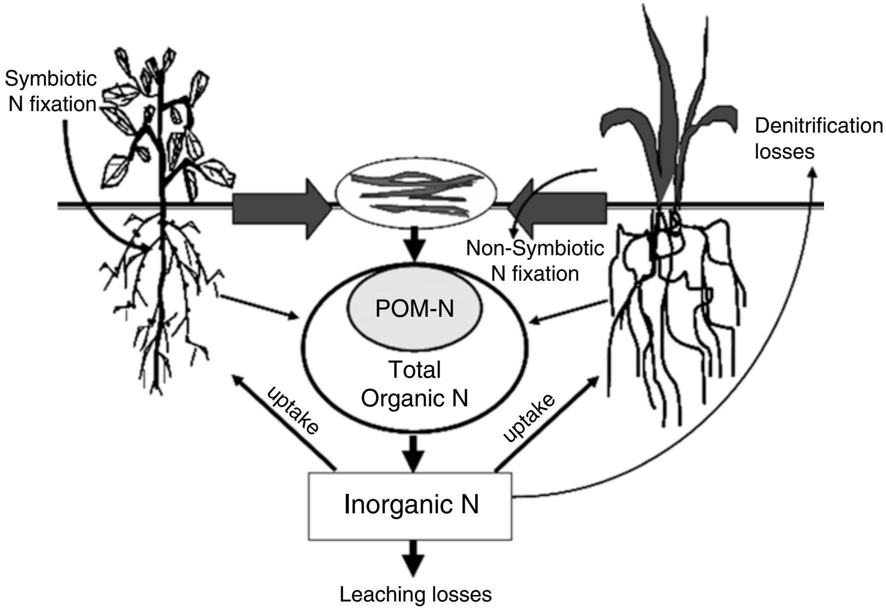

Fig. 6.6 A pictorial diagram showing various pathways for gains and losses of nitrogen in agricultural systems. *POM-N* particulate organic matter nitrogen

Rainfed crops may recover more N from fertiliser N, but more legume N is retained in the soil (Crews and Peoples 2005). ^{15}N-labelled N has been used to follow these pathways. However, N 'pool substitution' may occur when the newly applied ^{15}N-labelled legume N is immobilised in microbial biomass and unlabelled N released. This could explain the underestimation of uptake efficiencies from legume residues (Ladd et al. 1986; Harris et al. 1994).

N fixation by legumes is reduced in soils with high available soil N contents. However, in soils with a low N content, the amount of N fixed is proportional to the legume dry matter produced (Ladd et al. 1986). Some (10–25%) of this nitrogen may be taken up by wheat in the year following medic pasture, with the amount depending upon the rainfall and the grain yield; the remainder is incorporated into the soil organic matter pool to be released in subsequent years (Fig. 6.7). Peoples et al. (2009) summarised that less than 30% of the legume N is commonly taken up by a subsequent crop. The build-up of N in the soil organic matter pool is important in rainfed cropping systems on low organic matter sands and sandy loam soils to meet the late-season N demand by cereal crops following late season (spring) rainfall.

Lack of synchronisation between crop demand and N supply and the consequent loss of mineralised N by leaching or immobilisation is a major bottleneck associated with cropping systems – both rainfed and irrigated (Crews and Peoples 2005). For example, in low-fertility light-textured soils in the Mallee region of southern

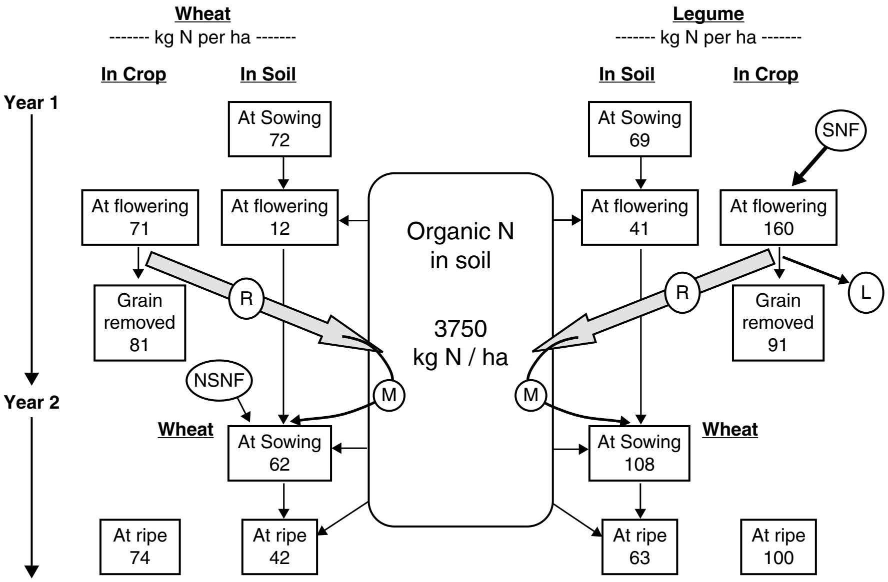

Fig. 6.7 Nitrogen dynamics in Wheat–Wheat and Pasture legume–Wheat rotation systems: Experimental data showing the amounts of mineral *N* present in soil and crop at various stages of crop growth. *R* crop residue decomposition, *M* contribution from mineralisation of previous years' residues, *SNF* symbiotic N fixation, *L* denitrification losses, *NSNF* non-symbiotic N fixation. (Redrawn from Ralph 1986 based on research conducted by Ladd and Amato, CSIRO, Adelaide)

Australia, up to 50 kg N per ha per year can be leached below the effective crop rooting zone following spells of summer rainfall (Roget and Gupta 2004). Stubble retention and reduced tillage may reduce these losses because increased microbial biomass immobilises N mineralised following summer rainfall events. In addition, asynchrony between N supply and crop demand is likely to be greatest in legume-based systems when a fallow period follows a legume, as can occur in the traditional low-input pasture–crop rotations in the Mediterranean regions of southern Australia.

Mid infrared (MIR) technology allows rapid chemical and physical analysis of soil samples and mapping of large-scale field variability in soil fertility, using the close correlation between soil N, total carbon and clay content (Dan Murphy, University of WA, personal comm.). This MIR technique can be used to correlate measured biological soil N with MIR-predicted biological soil N supply. MIR measurements could be thus used to set fertiliser rates to optimise production and reduce input costs.

In legume crops (pulses), most of the fixed nitrogen is removed by the grain, leaving plant residues relatively low in nitrogen. However, soil mineral-N not used during the growth of the grain legume and mineral N from legume residues in the surface soil become available for following non-legume crops – unless lost through leaching. Decomposition of relatively N-rich (low C:N ratio) legume residues readily releases mineral nitrogen to become part of the soil N pool available for future crops (Ladd et al. 1986; Crews and Peoples 2005).

Herbicide use is an integral component of conservation cropping systems, and selective herbicides are routinely used in legume crop production. However, some herbicides can affect the legume–Rhizobium symbiosis (Eberbach 1993). Applications of in-crop herbicides in grain legume crops such as peas, vetch and faba beans can result in crop yellowing (Gupta et al. 2002; Gupta and Roberts 2000) and may reduce the proportion of N derived from N fixation by 35–60% in southern Australia (Drew et al. 2007).

In the generally low fertility soils of Mediterranean-type regions, application of a number of other nutrients such as phosphorus, sulfur, potassium and micronutrients may be needed to reduce the impact of soil-borne diseases, improve nitrogen fixation and achieve targeted yields and higher water use efficiencies (Riffkin et al. 1999; Wilhelm and White 2004; Reuter 2007). P availability in many alkaline and alkaline-calcareous soils can be improved through increased biological activity. Soil-application of liquid fertilisers alters chemical and biological transformations of P and can increase P uptake in plants compared with granular applications (Holloway et al. 2001). Adequate trace element nutrition may be critical for crops to withstand soil-borne plant diseases through increased root growth and improved host plant tolerance. Application of trace elements such as Mn, Zn and Mo can reduce the impact of soil-borne diseases such as Take-all and *Rhizoctonia* bare patch in wheat and medics (Wilhelm et al. 1988; Neate 1994; Streeter et al. 2001).

6.4.3 Soil Structure

In clay soils, structure is important for aeration, water penetration, biological activity and root growth. Good structure with stable aggregates and pores can be achieved through both physical and biological aggregation (Degens 1997; Six et al. 2004). The fine mycelia of fungi, along with gums produced by bacteria, hold aggregates together, resulting in stable aggregate formation (Tisdall and Oades 1982; Gupta and Germida 1988). The movement of larger organisms such as earthworms, termites and arthropods creates channels through which water and air can penetrate. No-till farming improves organic matter content and structure of soils (Kay and Munkholm 2004; Weisskopf and Anken 2006) while decomposing roots encourage high microbial populations. Increased levels of water-stable aggregates and higher populations of earthworms are found in soils under no-till (Rovira et al. 1987; Smettem et al. 1992).

In the coarse-textured soils in the semi-arid region of southern Australia, reduced tillage and stubble retention promote microbially-mediated increases in dry aggregation (>2 mm diameter) in surface soils and reduction in wind erosion (Leys et al. 1996; Eldridge and Leys 2003).

6.4.4 Plant Growth and Root Growth Promoting Rhizobacteria (PGPR)

When soil physical, chemical or biological constraints slow the development of roots, efficient use of water and nutrients from the restricted root zone then becomes of great importance for achieving high yields. Soil microorganisms can promote root growth either by producing plant hormones or by modifying the soil physical and chemical conditions.

During the last 20 years, research in Australia on plant growth-promoting rhizobacteria has concentrated more on biological control of plant diseases (Ryder et al. 2005) than on other beneficial microbial inoculants that promote plant growth. However, North American research indicates that single or multiple species of microbial inoculants can promote root and shoot growth and deliver production benefits in wide-ranging environments, particularly in intensive farm systems (Kloepper et al. 1999, 2004). These beneficial effects may reduce the constraints and also increase access to water and nutrients. For example, changes in root architecture can profoundly affect the capacity of plants to access and absorb water and nutrients (Lopez-Bucio et al. 2003) as well as influence rhizosphere biotic interactions involving pathogens and beneficial organisms. On cropping soils poor in carbon and nutrients, microbial inoculants that promote plant growth through hormonal and other biochemical mechanisms could benefit crop productivity.

Microbial inoculants produced under optimal conditions may require physiological adaptation in order to be effective in difficult soil environments. Therefore a better option for cropping systems in such situations may be to develop management practices that enhance the native microbial communities which contain beneficial microbes (Cook 2007).

As microbially-mediated root growth responses probably occur during the early periods of seedling establishment, an inoculant has only to perform effectively for short periods, probably under optimal soil conditions. However, such benefits may not directly help to combat subsoil constraints. Further, as plants differ in their root growth response to specific microorganisms, biocontrol inoculants may be plant species specific. For example, some bacteria that demonstrate PGPR benefits for wheat may be deleterious for some legume crops (de Freitas et al. 1993).

6.4.5 Biological Control of Root Diseases

Bacteria, fungi and actinomycetes can act as biocontrol agents against root diseases (Whipps 2001[4]). However, no single microbial inoculant has yet been consistently

[4] See also http://www.biocontrol.co.za/; http://www.oardc.ohio-state.edu/apsbcc/

Table 6.2 A summary of field trial evaluation of biological control of Take-all in the South Australian rainfed region (Rovira et al. 1992; Tang et al. 2001)

Treatment	Average (% control)	Range of yield response
Trials during 1987–1991[a]		
Trichoderma koningii (Tk7a – in furrow)	7.9	−9 to +33
Pseudomonas corrugata 2,140 (seed coating)	+2.5	−15 to +23
Chemical fungicide (Triadimefon – DMI group)	+3.5	−7 to +13
Trials during 1999–2001[b]		
Trichoderma koningii (Tk7a – in furrow)	+3.6	−8 to +18
Pseudomonas sp. P32 (seed coating; 3 trials)	+2.9	−7 to +22
Chemical fungicide (Triazole group)	+6.2	−10 to +24

Note: Pathogen inoculum was either the natural inoculum present in the soil at the site or added pathogen inoculum

[a]Mean of 13 treatments from 7 trials; mean wheat yields were 2 to 3.5 t/ha

[b]Means of 6 treatments from 5 field trials; mean wheat yields were 1 to 6 t/ha

successful under Australian broadacre rainfed agriculture systems (Ryder et al. 1999). Biocontrol of Take-all using a bacterial and a fungal inoculant has shown a wide range of responses (Table 6.2).

Challenges with the introduction of biocontrol organisms to control soil-borne plant pathogens (Weller and Thomashow 1994) include their poor survival in the natural environment and variable root colonisation. The success of biocontrol inoculants depends upon our ability to: (1) maintain the density of introduced bacteria needed to provide effective biological control; (2) lengthen the period during which a threshold population density is sustained in the rhizosphere; and (3) increase the magnitude of disease control provided by introduced rhizobacteria.

A number of inoculant formulations with the fungus *Trichoderma* spp. are available commercially to control several soil-borne pathogens, e.g. *Gauemannomyces* sp., *Rhizoctonia solani, Fusarium* sp., in broadacre crops in Australia, China and India (Simon 1989; Ryder et al. 2005; Harman 2006; Vinale et al. 2008). Biocontrol organisms can be more effective where there is significant concentration of disease organisms (Ryder et al. 2005; Franco et al. 2007) but the level of success is unpredictable.

Endophytes are microorganisms living inside plants without causing any pathogenic symptoms to the host plant. Unlike rhizosphere-based inoculants, they escape problems associated with survival in harsh and carbon-poor soils and avoid competition with the soil microflora in the rhizosphere. Actinobacterial endophytes can colonise plants without disrupting the 'normal' endophytic populations, can produce antifungal antibiotics and plant growth hormones, and can also induce systemic disease resistance in plants (Conn et al. 2008). Significant benefits in disease control by inoculating with bacterial and actinobacterial endophytes have been shown with a variety of crops, in both broadacre rainfed agriculture and intensive production systems (Hallmann et al. 1997; Franco et al. 2007); however, the success has not yet been consistent under field conditions. As with inoculants in general, endophyte inoculants that help plant health through more than one mechanism such as biocontrol and plant growth promotion have the best chance of performing consistently. While some endophytes are seed-borne, plants are also colonised by a succession of microbial endophytes which are recruited from the large pool of rhizosphere species (Rosenblueth and Martinez-Romero 2006). This succession of different microfloral partners could have a strong impact on plant performance and crop yields and also on the microbial community associated with the following crop. Plant–microbe specificity may restrict the use of a single endophyte inoculant across a range of plant types, suggesting the need for the development of plant or cultivar specific inoculants (Bowen and Rovira 1999).

The search for biocontrol organisms has shifted to multiple inoculants that can complement each other, in particular with the multiple mechanisms involved in the control of some diseases such as *Rhizoctonia* bare patch and Take-all (Jetiyanon et al. 2003; Duffy et al. 1996; Barnett et al. 2006). In addition, observations from field-based experiments show the potential for manipulating rhizosphere microbial communities and plant–microbe interactions *in situ* for developing ecologically robust strategies for disease control.

Biocontrol inoculants that induce a systemic resistance to diseases and pests have the greatest potential to succeed in field conditions (Kloepper et al. 2004) because they can evade the influence of edaphic factors on inoculants. Variable soil conditions within a field and between fields are another reason for the overall low-level effectiveness of biocontrol agents in the large-scale farming systems (1,000–5,000 ha per farm) in Australia.

6.4.6 Suppression of Root Disease

Some soils can reduce the severity of disease even in the presence of a pathogen, host plant and favourable climatic conditions for the disease. Levels of disease suppression that can result in minimal or no disease constraints to plant growth and productivity have been reported from a variety of cropping systems worldwide (Simon and Sivasithamparam 1989; Roget 1995; Alabouvette et al. 1996; Mazzola 2004).

The successful control of many soil-borne plant pathogens involves management of the pathogen at a combination of different soil microsites (e.g. inoculum source or rhizosphere) at different time periods (pre-season or in the presence of the susceptible plant). Therefore *in situ* enhancement of natural disease suppression may be more effective than adding inoculants (Cook 2007). Suppressive ability is a continuum, and all soils have some potential for disease suppression (Roget et al. 1999). In ‘general’ disease suppression, the inhibition of pathogenic populations is related to either the activity of the total microflora or diverse microbial-faunal interactions. In contrast, ‘specific’ suppression has been attributed to the activity of specific groups of microorganisms (antagonists) (Cook 2007). Two complementary mechanisms have been suggested to be involved in the natural disease suppression of soil-borne pathogens i.e. competition between pathogen and general microbial community and the activity of antagonists.

Some abiotic factors of soil such as pH and clay minerals have been associated with certain types of disease suppression, for example, *Fusarium* wilts, Take-all and *Rhizoctonia* root rot (Hoper et al. 1995; Duffy et al. 1997; Ghini and Morandi 2006; Janvier et al. 2007). Some of the management and biotic factors that have been suggested over the years for the development of disease suppression are: (1) monoculture of host crops over a number of years, resulting in increased populations of specific biocontrol agents (Simon and Sivasithamparam 1989; Cook 2006); (2) addition of antibiotic producing/antagonistic microflora and non-pathogenic variants of these organisms (Weller et al. 2002; Cook 2006); (3) modification of physico-chemical properties of soil; (4) addition of composts or other organic manures (Hoitink and Fahy 1986); (5) crop rotations using crop types that promote specific microbial communities; (6) crop residue retention and appropriate tillage treatments; (7) addition of large amounts of simple substrates; and (8) continued addition of carbon materials to support higher levels of C turnover over a long period or multiple seasons.

It is becoming increasingly clear that the presence of microbial genotype(s) capable of biocontrol is only one of the means of effective disease suppression. The expression of disease suppression may also be regulated by crop management practices.

Development of broad-based suppression against *Rhizoctonia* bare patch and Take-all is illustrated in Figs. 6.8 and 6.9 for a long-term trial at Avon, South Australia.

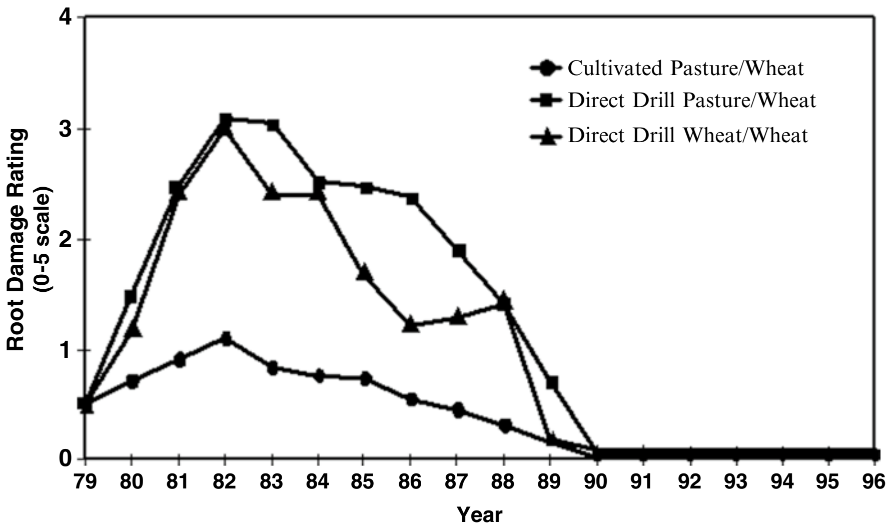

Fig. 6.8 Build up and decline in *Rhizoctonia* root damage of wheat in the long-term farming system trial at Avon, South Australia over the period 1979–1996 (adapted from the data in Roget 1995)

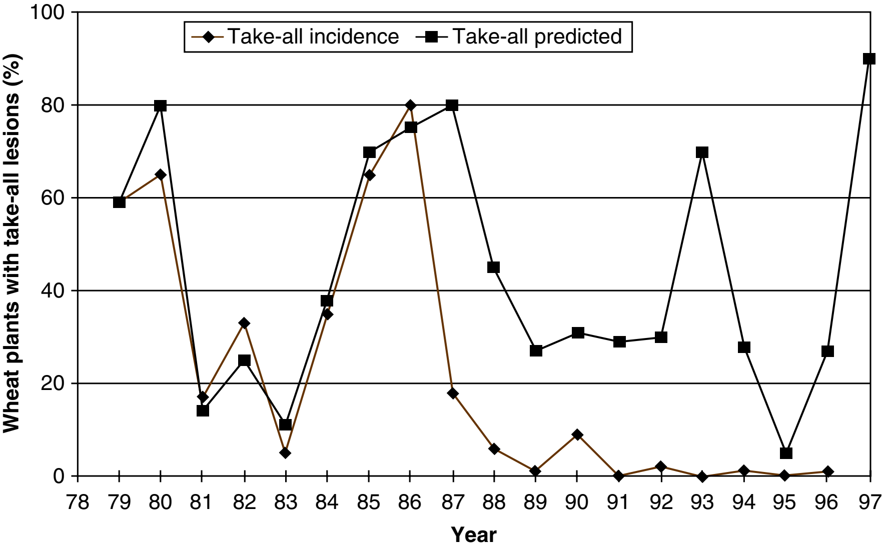

Fig. 6.9 Build up and decline of Take-all disease in continuous, direct-drilled wheat in a long-term farming system trial at Avon, South Australia over the period 1979–1997 (Roget 2003). Incidence of Take-all agreed closely with incidence predicted from previous season's rainfall until 1986, after which Take-all incidence declined due to suppression. By contrast (Fig. 6.8), *Rhizoctonia* root disease was not influenced by rainfall

The decline in disease incidence occurred under a range of rotations (i.e. continuous cereal, cereal–grain legume and cereal–medic pasture) and tillage systems (Roget 1995, 2003). Wiseman et al. (1996) demonstrated the biological nature of this phenomenon and Gupta and Neate (1999) described the complex biotic interactions that are involved in such disease suppression. The exact causes of the decline of different soil-borne diseases are more likely to be different from the specific suppression reported for the classic 'Take-all decline[5]' in cereal monoculture (Simon and Sivasithamparam 1989; Cook 2006).

It was initially considered that soils low in fertility in lower rainfall regions with Mediterranean climates may not have the potential or environmental conditions to support microbial communities that can lead to general suppression against a broad pathogen range. However, in the above mentioned long-term trial, disease suppression increased from a low to a high level over a period of 5–10 years following the change from pre-trial management practices of stubble burning and cultivation to full stubble retention, limited grazing and higher nutrient inputs to meet crop demand (Roget 1995). The increase in suppression provided complete control of the soil-borne diseases *Rhizoctonia* bare patch (Roget 1995) and Take-all (Roget 2003) within 10 years. The increased suppression over time was associated with a

[5] See Glossary.

lack of agreement between the actual incidence of Take-all disease after 8 years (Fig. 6.9), and that predicted by a model based on pathogen response to the previous season's rainfall alone (Roget 2001).

Soils with high levels of disease suppression have been identified in commercial farms across southern Australia (Roget et al. 1999). It has been found that management practices which supply higher levels of biologically-available carbon inputs over long periods (greater than 5–7 years) can result in changes to the composition and activity of the soil microbial community and consequently support higher levels of suppression (Gupta and Neate 1999; Roget and Gupta 2006).

Although the expression of this broad-based suppression was initially considered to be stable, it has been found to be modified by changes in amount of C and N turnover during summer and autumn (Roget and Gupta 2006). Similarly, suppression against specific pathogens, developed through monoculture or addition of composts or manures, may be lost following a change in crop rotations or cessation of amendment addition (Cocking 2003).

The evidence therefore suggests that suppressive ability is not a fixed property of a soil, but it can be acquired and maintained at a level beneficial to rainfed crops. This leads to the attractive proposition that productivity losses from root diseases can be reduced and high WUE attained without expensive chemical control. Such methodology needs to be developed for subsistence and other poorer farmers who cannot afford costly inputs (See Chap. 38).

The development of disease-suppressive soils in response to specific cropping sequences or above-ground plant species diversity has also been demonstrated for some plant–pathogen combinations (Garbeva et al. 2006; Janvier et al. 2007). Genetic variation within the host can be employed to enhance the positive interactions with plant-beneficial microorganisms – in addition to those of mycorrhizae or rhizobia. In the longer term, identified plant characteristics (e.g. rhizodeposition, root growth structure) that drive the selection of beneficial microbes, or molecular markers associated with these characteristics, can be incorporated into breeding programs to introduce or retain traits of value. Although the majority of the discussion in this section deals with soil microflora, the role of soil-fauna (in particular micro-fauna and mesofauna) in the suppression of soil-borne pathogens has also been recognised (Curl 1988; Gupta et al. 1999a).

6.4.7 Influence of Break Crops on Soil Biota

The benefits of 'break' crops in cropping systems have been known for many years. As components of crop rotations they are integral to the management of crop-specific soil-borne pathogens, weeds and plant nutrients. They can be major contributors to the control of root diseases such as Take-all and cereal cyst nematode (Rovira 1990, 1994; Kirkegaard et al. 2008). Cereal crops benefit from the N addition and mineralisation from a prior legume crop or forage (McDonald 1989; Khan et al. 2003).

The control of crop-specific diseases can be attributed to the removal of a host and hence of pathogen inoculum, while pathogens with a broad host range may also be controlled through effects on the populations and activity of disease-suppressing microbial communities. In addition to non-hosting, the effect of 'break crops' on disease reduction is a product of a number of pathogen–host–microorganism interactions. For example, crop species and varieties differ in their influence on populations of microbial communities in the rhizosphere and near-decomposing residues, which can then affect the growth and nutrition of the following crop.

Traditionally, the impact of soil-borne disease incidence on productivity was looked at only in terms of pathogen inoculum dynamics, but the effect of diseases on yield and economic returns also depends on the interaction between pathogen, host, cultural practices and seasonal conditions (Rovira et al. 2007; Kirkegaard et al. 2008).

Brassicas have been found to be superior to other break crops for reducing Take-all of wheat (Angus et al. 1994; Kirkegaard et al. 1994). The initial explanation was that Brassicas 'biofumigate' the soil and kill the Take-all fungus through isothiocyanates (ITC) released from canola and mustard roots, but these plants (residues or rhizosphere) could be stimulating specific soil fungi such as *Trichoderma* spp. active in the biological control of root diseases (Gupta VVSR and Roget DK, unpublished).

The role of reduced inoculum levels has been emphasised as the major reason for the 'break crop' effect. However, there are many world-wide reports under new farming systems that include reduced tillage, stubble retention and chemical weed control of significant 'break crop' effects that cannot be attributed to disease benefits alone (Cook et al. 2002; Sieling et al. 2005).

6.4.8 Arbuscular Mycorrhizal Fungi (AMF)

The symbiotic association of plants with AMF has long been recognised; however, there is considerable uncertainty about the functional and ecological benefits of the association in rainfed crops (Smith et al. 2009). 'Long fallow disorder' in the vertosols of southern Queensland is seen as poor growth in crops such as corn, wheat, sorghum and linseed following a long (18-month) weed-free fallow. It is associated with a decline in viable propagules of arbuscular mycorrhizal fungi (AMF) leading to its poor colonisation of the roots of the following crop (Thompson 1987, 1994) and subsequent deficiencies of phosphorus and zinc. The movement of these nutrients in soil is limited and their uptake depends on the roots, root hairs or AMF making contact with soil P and Zn.

AMFs are thought to be less important for wheat in southern Australia with different soil types (Ryan and Angus 2003) and the application of in-furrow phosphate fertiliser which suppresses the growth of AMF from roots. However, AMFs probably play a role in supplying nutrients to pasture legumes and grasses. Using ^{32}P methods, Li et al. (2006) showed that, in a highly calcareous soil with strong phosphate fixation, up to 50% of the P in the wheat was taken up via the AMF although this was not reflected in grain yield which did not respond to the introduction of AMFs. Smith et al. (2009) suggested that, depending upon the individual AM fungi present in specific plants, the role of AMF in the field may be much more subtle than previously envisaged. However, the extensive hyphal networks of AMFs help in the formation of stable aggregates and are associated with improved soil structure (Tisdall et al. 1997; Rillig and Mummey 2006).

6.5 Soil Fauna in Rainfed Agriculture

Different types of soil microfauna (protozoa and free-living nematodes), mesofauna (collembola and mites) and macrofauna (earthworms and termites) play a significant role in some essential plant biological processes (Coleman et al. 2004). Their effects on essential biological processes are generally less specific than those of microflora, except for pathogenic fauna such as plant parasitic nematodes and mites. It is the interactions between microflora and various groups of soil fauna that are critical for a number of biological functions, such as nutrient mineralisation, disease suppression and survival of introduced microflora (Gupta and Yeates 1997; Coleman et al. 2004).

Macrofauna such as earthworms have been identified as 'ecosystem engineers' that play an important role in the formation of stable soil macroaggregates through bioturbation[6] and other mechanical activities (Lavelle et al. 2006). The benefits may not be so evident in light-textured soils and where environmental conditions such as moisture are inadequate for their activity.

In most Australian environments supporting rainfed agriculture, it is the organic matter level that controls macrofaunal (earthworm) activity rather than vice versa, and this may also be true for many low-fertility agricultural soils in other rainfed Mediterranean regions. Managing organic matter through macrofaunal activity has limited potential in most rainfed cropping regions. It has greater application in (1) high-rainfall, heavy-textured soils and (2) accelerated crop residue decomposition in irrigated environments. Introducing earthworms to pastures in higher rainfall regions of south-eastern Australia has resulted in increased pasture production, as well as improvements in plant nutrition and associated aspects of soil quality (Baker et al. 1993, 1999, 2003). Macrofaunal activity can accelerate the decomposition of residues of high-yielding crops particularly when moisture is not limiting. Suitable microflora, the primary decomposers of plant residues, must be present to gain benefits from macrofaunal activity, and thus to maximise benefits in rainfed farming systems.

Macrofauna have been shown to reduce pathogen inocula (*Rhizoctonia solani, Fusarium* spp.), disperse beneficial organisms (e.g. *Rhizobium*, biocontrol bacteria)

[6] See Glossary for explanation.

and release nutrients from crop residues (Stephens et al. 1993; Doube et al. 1994; Baker et al. 2003; Baker 2007). Large numbers of macrofauna would be needed for significant benefits to farm systems but earthworm population densities are variable across the landscape in broadacre systems. In southern Australia, this is particularly true in sandy soils with annual rainfall below 400 mm.

6.6 Detrimental Effects of Soil Biota on Productivity and Sustainability

6.6.1 Soil-Borne Root Pathogens

One of the major constraints on productivity in rainfed farming systems is root disease caused by soil-borne root pathogens. The roots of cereals and pasture plants are prone to attack by pathogenic fungi including *Rhizoctonia solani*, *Gaeumannomyces graminis* var. *tritici*, *Fusarium pseudograminearum*, *Pythium* spp. and nematodes (e.g. CCN, root lesion nematode) which, in climates with limited rainfall, can markedly reduce yield. A description of these soil-borne pathogens and their control is given in Wallwork (2000).

The adoption of minimum tillage and no-till practices in broadacre agriculture has resulted in an increase in the incidence of important fungal diseases. In the case of *Rhizoctonia,* tillage is believed to destroy pathogen propagules. This disease is more of a problem in lower rainfall regions (less than 350 mm) and lighter soils and occurs across the entire Australian wheat belt. Root disease caused by *Rhizoctonia solani* AG8 is widespread throughout the sandy soils of southern Australia (MacNish and Neate 1996) and can cause severe root damage in direct-drilled wheat. *R. solani* AG8 has been associated with particulate plant debris concentrated in the top 5 cm of the soil profile (Neate 1987). Soil disturbance below seeding depth by direct drilling with narrow sowing points can reduce root damage by *Rhizoctonia* root rot in wheat and barley (Roget et al. 1996).

The retention of stubble, particularly cereal residues, has been associated with increased incidence of crown rot of cereals caused by *Fusarium* spp. (*F. pseudograminearum*, *F. graminearum* and *F. culmorum*). This is because decomposing stubble can act as a medium for the build-up of pathogenic fungi (Burgess et al. 2001).

Cultivation reduces the incidence of Take-all on the developing wheat roots, this being attributed to breaking up the dead crowns and roots of host plants. More severe Take-all in no-till wheat than in wheat sown following cultivation (Moore and Cook 1984) has been linked to larger propagule size which has helped the fungus grow a greater distance to reach developing roots (Wilkinson et al. 1985a, b). Thus farmers changing their cropping system from conventional cultivation to no-till must have already adopted rotations which reduce the levels of root pathogens in soil, or there could be significant yield penalties.

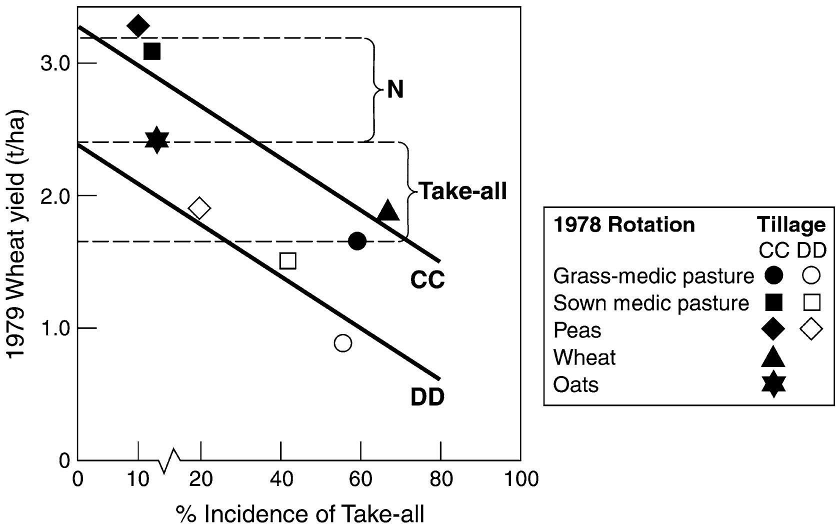

Fig. 6.10 Effect of rotation and tillage treatment on the incidence of Take-all disease and grain yield of wheat during 1979 at Avon, South Australia. Values are averages of four replicate plots (Rovira, unpublished). *DD* direct drilling, no cultivation before seeding; *CC* three cultivations before seeding. Regression values (R^2) for CC and DD were 0.79 and 0.91, respectively

Soil-borne, necrotrophic fungal pathogens vary in their saprophytic competency. For example, the Take-all fungus (*Gaeumannomyces graminis* var. *tritici* or Ggt), a pathogen considered to have relatively low competitive saprophytic ability (Garrett 1972) depends heavily, for persistence, on its survival in the residues of cereal roots and crowns colonised during its pathogenic phase in the previous winter and spring.

Data related to these principles are shown in Fig. 6.10. Preceding the wheat crop with a non-host crop such as peas, oats, or a pure medic (grass-free) pasture reduced the incidence of Take-all to less than 20%. In contrast, when a host crop such as wheat or a self-sown grass–medic pasture preceded the wheat crop, the incidence of Take-all on the roots of the wheat ranged between 40% and 70%. The two highest yields in Fig. 6.10 illustrate the benefits of both the reduction in Take-all and the increase in soil nitrogen from the legumes. While direct-drilling (no-till) gave lower yields in this experiment, in the long term, conservation farming systems with increased crop residues can promote disease suppression and result in reduced disease incidence, with increased yields (Roget 1995).

Due to the poor saprophytic ability of the Ggt fungus, sources of Take-all inoculum can be lower following summer rainfall events in southern Australia. This is because rainfall at this time (1–2 months before sowing) promotes microbial activity and increases competition against Ggt from general microbial community. It would also result in lower C availability for the Ggt fungus after sowing

(Gupta and Roget 2002). In Fig. 6.10 the level of Take-all disease is lower in rotations in which wheat followed non-host crops (peas, oats) and grass-free medic pasture and there are about equal yield responses to the nitrogen fixed by legumes and to the control of Take-all.

Increased wheat yields in southern Australia have been obtained through rotations to control Take-all, the use of narrow sowing points to reduce Rhizoctonia damage to roots and use of new cereal cultivars resistant to cereal cyst nematode.

In lower fertility soils common in many Mediterranean environments, both biological and chemical constraints to production (e.g. soil-borne pathogens, N, P deficiencies) can be interlinked and would need to be corrected. For instance, in a trial on highly calcareous soil with low P availability, fumigation to destroy pathogens and applications of liquid phosphatic fertiliser with the seed were both needed to improve root health and grain yield (Fig. 6.11 Roget, personal comm.). This is an excellent example of the benefits from considering soil biology as part of a systems approach and not just as an isolated factor.

Soil-borne diseases of pasture legumes: Crop and animal production in southern Australian rainfed agriculture has depended greatly on nitrogen fixation by pasture legumes to build up and maintain soil nitrogen, but a number of soil-borne pathogens cause serious disease to roots of clovers and medics (Barbetti et al. 1987, 2006). Sources of resistance to two pathogens, *Fusarium avenaceum* and *Pythium irregulare*, have been found in subterranean clover and it is hoped to incorporate this resistance into commercial varieties.

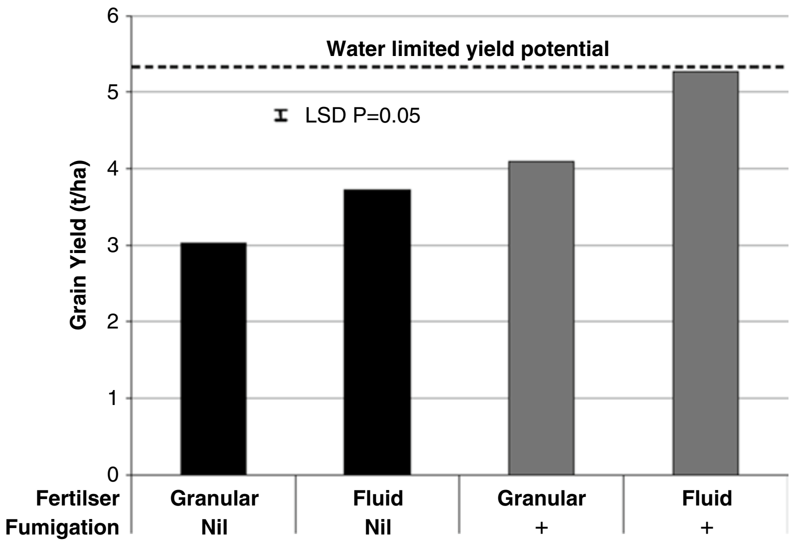

Fig. 6.11 Linkage between chemical and biological constraints to productivity – yield of barley with and without soil fumigation and two forms of *P* fertilisers on a grey calcareous soil in the Eyre Peninsula region in South Australia

6.6.2 *Detrimental Soil Bacteria*

The classical thinking on plant–microbe interactions has concentrated on plant pathogens and a variety of beneficial organisms. However, a group of rhizobacteria which are not necessarily plant pathogens can inhibit plant growth; these are called 'deleterious rhizobacteria' (DRB) (Suslow and Schroth 1982). Deleterious rhizobacteria have been proposed as biocontrol agents to control unwanted plant species, especially as part of integrated weed management (Kremer 2006). The nature of the effect of individual bacterial species on specific plants may fluctuate between DRB and PGPR depending upon interactions between environmental conditions, host genotype and other factors, and the microbial community (Nehl et al. 1996).

Crop type in one season is the major driver of change in microbial communities that can influence growth and yield performance of following crops. Specific microbial communities, both beneficial and deleterious, have been found both in the rhizosphere and on residues of crops or particular varieties of crops including wheat, legumes and cotton (Cochran et al. 1994; Edel et al. 1997; Grayston et al. 1998; Smith et al. 1999; Germida and Siciliano 2001; Miethling et al. 2003; Nicolardot et al. 2007). This genotype specificity is due mainly to root exudates/rhizodeposits (Mazzola and Gu 2002; Bias et al. 2006). Thus wheat cultivars may differentially select for microbial communities that can affect the growth and productivity of the following wheat crop (Gupta et al. 2004). Identification of appropriate variety sequences may make it possible to overcome this type of yield constraint to succeeding wheat crops. Higher populations of fast-growing bacteria (copiotrophic) are associated with varieties that perform poorly as second or subsequent wheat crops, whereas higher populations of slow-growing bacteria (oligotrophic) are associated with better performing varieties (Gupta et al. 2004).

6.7 Conservation Farming and Soil Biota

Stubble retention and direct drilling can increase microbial biomass, populations of specific functional groups of microflora (e.g. cellulolytic microorganisms and non-symbiotic N-fixing bacteria) and soil fauna including earthworms (Roper and Gupta 1995; Young and Ritz 2000; Kladivko 2001). However, the improvements seen in soil physical, chemical and biological properties may not always result in higher yields (Kirkegaard et al. 1995). A temporary increase in the incidence of soil-borne fungal diseases during the early phases of no-till adoption has been widely reported (Neate 1994). Such an increase has sometimes been attributed to the development of extensive fungal hyphal networks and, in the case of Take-all, larger propagules of the pathogen under no-till systems. Although there may be no difference in occurrence of root pathogens, total fungi, total bacteria or total pseudomonads, there can be an increase in specific pseudomonads which inhibit root growth in no-till soils (Simpfendorfer et al. 2002).

Increased spatial heterogeneity is one of the key characteristics of soil structure in no-till systems influencing biota populations and transformation processes (Young and Ritz 2000). Such results highlight the complex nature of the soil biota and the difficulty of obtaining meaningful and consistent results on biota populations across different agroclimatic zones and soil types. Unlike the conventional plate culture methods of studying soil microflora which mostly provide information about a small portion (<10%) of the total microbial community, molecular identification techniques can help to better unravel the dynamics of the entire community. Hence they could be used to detect shifts in population structure (both phenotypic and functional aspects) in different farming systems. This may lead to the development of innovative farming practices that harness biological functions better (Tiedje et al. 1999; Roper and Gupta 2007).

In a review of 27 long- and medium-term trials in eastern, southern and western Australia, reduced tillage and stubble retention had little overall effect on yield despite improved soil structure at many sites (Kirkegaard 1995). Reduced early seedling growth at some sites was attributed to pseudomonad bacteria which colonised roots and inhibited root growth. Exudation of sugars and amino acids from roots increases when root elongation is impeded (Barber and Gunn 1974), thus the impeded root growth in direct-drilled crops could give greater exudation and hence higher microbial populations including pseudomonads. No-till plus stubble retention can result in reduced early seedling growth, but rarely adversely affects final grain yield. This reduction in early seedling growth could be overcome by modifying seeding equipment to disturb the soil below seeding depth and to better place fertiliser N application to compensate for microbial immobilisation (see also Chap. 39).

The widespread adoption of no-till farming indicates that farmers' crop yields are not reduced as they appear to be in the field experiments reported by Kirkegaard et al. (1995). Farmers adopting no-till may, on the whole, be better qualified to handle the greater knowledge necessary for no-till farming than those farmers still cultivating before sowing (Walters and Rovira 1994).

6.8 Conclusions

In this chapter we have presented concepts on the importance of life in the soil for the development of productive and sustainable rainfed agricultural systems across the Mediterranean region of Australia and around the world. We have mainly drawn upon a considerable body of research done across southern Australia over the past 30 years and relevant research from other parts of the world. Every continent has large areas of rainfed farming in climates similar to that of southern Australia; hence the concepts and principles presented in this chapter can be applied to these areas in other continents.

In summary, some of these principles are:

- In the lower fertility agricultural soils, under rainfed conditions, activities of all organisms and key biological processes are affected by the levels of biologically available carbon, soil moisture and temperature.

- The contributions of biological functions to plant and root health, crop productivity and overall soil health are dictated by seasonal variability in soil and environmental conditions in the Mediterranean-type environments of southern Australia.
- The impact of a soil biological process within a farming system depends on when it occurs in relation to the crop growing season, and thus varies between agro-ecological zones. Moisture, temperature and carbon availability need to be synchronised for optimal performance of a range of key biological functions.
- Nitrogen fixation by legume–rhizobium symbiosis dominates global inputs of biologically fixed N. A greater level of synchrony between N release from legume residues and crop uptake will increase crop production.
- Availability of energy sources, soil moisture and temperature are the main regulating factors for non-symbiotic N fixation (NSNF) by free-living bacteria. Rhizosphere and fresh decomposing crop residues have the potential to support significant levels of NSNF.
- In the generally low fertility soils of the Mediterranean-type regions, phosphorus, sulfur, potassium and micronutrients may need to be applied to reduce the impact of soil-borne diseases, to improve nitrogen fixation and to achieve higher water use efficiencies.
- *In situ* management of natural disease suppression against soil-borne diseases is more productive than adding inoculants. Such natural disease suppression is a function of the population level, activity and composition of the total microbial community.

In addition, we believe that for soil biological research to be effective in variable seasonal climate and soil conditions, it must be evaluated in the field and within a farming systems context. Also, as farming systems are constantly changing due to economic and technical drivers, soil biological functions need to be re-evaluated along with these changes. The move to no-till has been a good example of this, while precision guidance systems, use of genetically modified plants and associated farming system changes will also impact on the life in the soil and require further research. For example, using precision guidance technology, it is now possible to sow precisely in between the previous season's crop rows but we do not know "how long the microbial footprint from previous crops remains effective within and between the previous year's crop rows."

Traditionally, soil biology research has been discipline-based and, in this chapter, we emphasise the need to integrate soil biology with chemistry, physics, agronomy and plant science in order to successfully extend the basic knowledge to field situations. Recent developments in DNA and biochemical methods can help unravel the complexity of life in soil to provide new insights into the diversity and functional capability of soil biota. New knowledge of soil biology will greatly help to drive the development of innovative farming systems that are economically and environmentally sustainable, whilst protecting the soil resource.

Acknowledgements Financial support for most of the research reported in this chapter was provided by the Grains Development Research Corporation, CSIRO Divisions of Soils, Land and Water, Entomology, Ecosystem Sciences and Sustainable Ecosystems and Mallee Sustainable Farming Inc. Authors wish to thank all the technical officers involved in the various experiments for their efforts with field work and laboratory analysis.

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Chapter 7
Technological Change in Rainfed Farming Systems

Implications for Their, Function, Productivity, Stability and Sustainability

Colin Birch and Ian Cooper

Abstract This chapter examines technological change in agriculture and its implications for the functioning, productivity, stability and sustainability of rainfed farming systems. The need for a systems approach to avoid unintended consequences is considered along with the contribution of plant breeding, changes in tillage practice, crop residue management, use of cover crops, weed, insect and disease management, plant nutrition and fertiliser use, biotechnology, precision farming and automation, modeling and decision support methodologies. The chapter also examines the impacts of past technological change, and current technology and the potential for future innovation.

Keywords Technological change • Rainfed farming systems • Stability • Sustainability • Sustainable agriculture • Adaptation • Biotechnology • Precision agriculture • Decision support • Modeling • Automation • Plant breeding • Fertiliser • Crop nutrition • Plant nutrition

7.1 Introduction

Technological change influences the functioning, productivity, efficiency, stability and sustainability of rainfed agricultural production systems. It has always been an integral feature of agricultural systems, usually occurring in response to 'problems' related to biophysical, economic, social, political or personal issues (see Chap. 12

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_7,

for a detailed discussion of factors influencing the management of a farm system). Technological changes are intended to improve the wellbeing of farmers and their families through higher levels of production, efficiency and profitability of their farm systems. However; they may sometimes have unintended or even negative impacts. For instance, the rate, frequency and extent of change may cause social disruption. Small farmers may be displaced by large farmers, tenants by owners, workers by labour-saving innovations, and producers in marginal areas by those in better-endowed environments (Scobie and Posada 1978).

Technological change in agriculture has occurred in conjunction with economic and social change in the wider economy, for example, in association with industrial development. This has often seen the transfer of labour from farms to the new industrial jobs, sometimes at a disadvantage to farming.

As indicated in Chap. 1 and throughout this book, a particular technology does not operate in isolation from others used in a farm system. It is indeed part of the system, interacting with other parts of it and having consequences for the system as a whole.

This chapter reviews the contribution of technology to agriculture and considers how technology can be best applied to ensure improved performance of farm systems. It also examines anticipated future directions of technological change and consequent impacts on farming in the light of expected changes in world agriculture.

7.1.1 Effects of Technological Change

Technological innovation has driven the improvements in the yield and quality as well as the storage, preservation and transport of agricultural products; it has supported the rapid expansion of human populations and urbanisation of societies. Most industrialised countries had achieved sustained food surpluses by the second half of the twentieth century (IFPRI 2002). In the 37 years from 1961 to 1997, growth of world agricultural production averaged 2.25% per year; it more than doubled during that period and food prices fell by 40% (Alston 2000). Alston also estimates that without the productivity gains flowing from new technology, grain prices might be 42% higher and production 8% lower.

While advanced technology has been applied more widely, and for longer, in developed countries and economies, less developed countries are now adopting new technologies such as small-scale mechanisation, new varieties of crops (including genetically modified (GM) plants), inorganic fertilisers and no-till planting. Such changes are generally regarded as essential to raise productivity with sustainability and provide food security. It would be expected that the emphases of technological changes will themselves change as agriculture becomes more productive and intensive. There will be changes in technology in response to new challenges such as climate change with global warming and possibly reduced rainfall, increasing cost of fossil fuels, and the concurrent needs for greater food supply for an increasing world population. This will be accompanied by the need for improved food quality and functionality[1] and increasing demands for environmental responsibility and sustainability.

A well known example of the effect of technological change is that of the 'Green Revolution'. While the term 'Green Revolution' was first used in 1968 by USAID director William Gaud, it began in Mexico in 1945 when the Rockefeller Foundation and the Mexican government established what later became the International Maize and Wheat Improvement Centre (CIMMYT). Within 15 years, Mexico went from importing half of its wheat to being self-sufficient in wheat production.[2] With the help of aid agencies, the movement spread to many developing countries. There was a rapid uptake of the use of high-yielding crop varieties leading to increased production; for example, increases in yields and areas grown resulted in a near doubling of cereal production in Asia between 1970 and 1995 (IFPRI 2002).

7.2 Technology Use in Rainfed Farming Systems

The usefulness of a particular technology to a specific farm system will depend on a number of factors working together:

- The results of the technology must be consistent with the goals of the farm system and its component structure and adapted to the environment of the system.
- The technology must be based on a good understanding of scientific and management principles, as well as being technically sound.
- Its effect on, and consequences for, the whole system must be understood and be beneficial for the whole system (not just a part of it). 'Whole System' may include the farm family and a wider community.
- Its operation should have been thoroughly tested and evaluated.
- Its implementation should be monitored to detect, prevent or solve problems associated with its use.

An example of an innovation that appears to fulfill these criteria is 'No-till' technology, which is widely cited in this book, and is being rapidly adopted worldwide. The case studies in part of this book, particularly Chaps. 41, 43–45 demonstrate how the no-till technology aligns with the farmer's goals. Chapters 19, 20, 31, 39 and 40 provide details of the scientific principles and system effects, along with the testing and evaluation of the technology. These chapters also indicate how it has been monitored and improved as it has been implemented in both developed and developing economies.

[1] 'Functional Foods' are foods or dietary components that may provide a health benefit beyond basic nutrition.

[2] CIMMYT http://www.cimmyt.org/english/wps/about/index.htm.

A technological innovation may be appropriate to a particular farming system and yet not be adopted. This may be due to various ‘social’ or cultural reasons. Some of these are discussed in Chap. 38 for agronomic improvements in a developing country. There may also be social impediments to technological innovation in developed economies – for example consumer resistance to products of genetically modified (GM) crops. Adoption may be assisted if the innovation is supported by a range of groups that may include government and research institutions, commercial companies, peer (e.g. farmer) groups and consultants. On the other hand, there have been some innovations that have gained acceptance by some farmers before validation by scientists. For example ‘natural sequence farming’ – a farming system devised in Australia by Peter Andrews – is based on restoring natural hydrological features in the landscape that existed before European settlement. This system has a number of farmer adherents but has been met with skepticism by scientists (Smith et al. 2007).

New technology will usually be adopted only if it ‘pays’ a farmer to do so. For instance, widespread use of pasture legumes (particularly subterranean clover) led to increased acidification of a number of Australian soils. While liming could have readily countered this, it was not widely adopted until farmers saw the profitability of introducing ‘acid-sensitive’ crops such as canola and lucerne into their system (see Chap. 26).

A new technology must also be within the capability of the farmer. A complex new technology may be adopted widely only when assistance is given to the farmer in the form of mentoring, training and practice under supervision, as was undertaken, for example in Canada, for the introduction of no-till technology (Lafond et al. 1997, Chap. 19). It is also becoming apparent that a new technology will be better adopted by farmers if they have been involved in researching and developing it. Chapter 33 outlines how this was done with conservation agriculture. Chapter 37 has a case study of involving farmers in the planning and use of Decision Support Systems.

A new technology often wins support by being a way of overcoming very difficult problems (as well as saving or making money). Some of the biotechnology and GM technologies described below (e.g. herbicide tolerance in crops) have the potential to overcome otherwise intractable problems of farming systems. However, farmers, governments and the public must be convinced that these solutions are safe to the environment and to people, and are sustainable. For example, the use GM crops has been limited in Australia due to fears about the safety of their products.

For new technologies to be widely adopted, they require supporting infrastructure of scientific research in the development, testing, commercial support and, as mentioned above, technical advice to farmers and monitoring of results. An example of this is the introduction of new crop and pasture varieties with superior yielding ability, quality, resistance to diseases and pests and adaptation to climate and soils. Such varieties require initial breeding and selection, testing in a range of field environments, commercial multiplication and distribution and continued monitoring for qualities such as disease resistance and environmental adaptation.

Decisions on the introduction of new technology need to take into account the goals of farmers. For example, research on the Eyre Peninsula of South Australia determined, from a long-term trial, that continuous cropping with a peas–wheat–barley rotation was environmentally suited to the area and gave the highest average economic returns. However, the local farmers did not adopt the rotation; the researchers had failed to recognise the farmers' risk preference. Although the promoted rotation had the highest average return, it also had the highest costs and greatest variability of return. Farmers were prepared to forgo higher return for stability of income (Cooper et al. 2003).

The benefits of new technology should also be equitable. Concern has been expressed (IAASTD 2009) that "while agricultural science and technology have made it possible to greatly increase productivity in the last 50 years, the sharing of the benefits has been far from equitable. Furthermore, progress has been achieved in many cases by high social and environmental cost"; for example, loss of population and thus political power from rural areas (social cost), loss of soil health and loss of water quality (both environmental). These and other examples are discussed at length in IAASTD (2009). Further, technological advances in developed economies have lowered the price of some farm products with adverse impacts on the incomes of farmers in less developed economies who can not afford new technology. Moreover, some technology has been introduced without taking into account a whole system view, with consequent impact on the environment such as loss of biodiversity, soil degradation or pollution of water resources. Correction of these effects requires considerable research and financial costs (see also Chap. 20).

The IAASTD report (an International Assessment of Agricultural Knowledge, Science and Technology for Development) also notes the following difficulties associated with new technology:

1. In North America and Europe, the amount of agricultural research funded by the private sector has greatly increased, and this has largely determined the direction of the research. Large transnational corporations thus wield considerable influence on agricultural science and its priorities. This may not comply with the need to have farmers involved in initiation of new technology, and they may be involved only in later stages as already discussed.
2. Central and West Asia and North Africa retain a unique agricultural biodiversity, (wild races of agricultural plants and related species, as well as local varieties in use by farmers) but these are starting to disappear. While the loss of these genes is being addressed by the creation of gene banks (or seed banks) by international agricultural research organisations and national government institutions, more needs to be done to preserve the biodiversity. These regions are particularly at risk from climate change and are likely in coming years to suffer the negative consequences of limited water resources. Already nearly half of their renewable water resources are below the minimum level necessary for development (for irrigation and for human and livestock consumption).
3. In East and South Asia, the current agricultural development path is leading to increased water pollution, notably from nitrogen. At the same time, climate

change is likely to produce large-scale people migration. Between 2008 and 2020, the amount of water available per person will decrease to approximately a third of what it was in 1950 or even less. This will affect farming systems in the area with pressure on farmers to use water more efficiently, for example using Conservation Agriculture (CA) and water harvesting.

4. In Latin America, greatly increased agricultural production has not led to a significant decrease in poverty, which still affects 37% of the population, (the benefits of new technology have not been spread equitably).
5. In Sub-Saharan Africa, agriculture accounts for an average of 32% of the region's GDP.[3] Water scarcity, however, affects nearly 80% of agricultural land. This will lead to further changes in farming systems such as adoption of Conservation Agriculture (CA). Adopting CA will mean less crop residues available for animal consumption – a major system change in this part of the world.

The 'Green Revolution' has been a major source of the improved productivity which has occurred – but it has had some criticism. The critics point to environmental degradation (including loss of biodiversity), inequitable asset distribution, and worsened absolute poverty. IFPRI believe that, while some of these criticisms are valid, there is a tendency to overstate them and ignore the possible hunger and poverty without the Green Revolution (IFPRI 2002). This is an example of how *all* consequences of new technology must be taken into account to avoid or minimise adverse effects.

Governments that encourage technological change in agriculture must consider the economic impacts of their policies. In particular, there are questions of who benefits from the technology. The problem arises principally from the 'relatively inelastic[4]' demand for most agricultural products. This means that an increase in production usually results in a decrease in price. Early adopters of technology may benefit for a while but, in the long run, there may be little benefit to producers; later adopters may need to take up the technology simply to maintain income (Gabre-Madhin et al. 2003). The problem is less important in developing economies where a major portion of production is consumed by the farm family and less is sold.

In order to foster technology change, governments have to consider the price-setting mechanism – whether it is free market, government controlled or a form of price stabilisation. Gabre-Mahadin et al. (2003) suggest that, for developing countries, a market-based stabilisation policy (as opposed to a free-market policy or government price regulation) places the burden of stability on governments not markets, thus transferring risk away from producers, who are least able to bear it. Dampening large fluctuations in market price leads to more stable crop choice (for instance growers do not change crops constantly to gain maximum return) and promotes investment in the farm which, in turn, leads to greater system stability and sustainability.

[3] See Glossary for explanation.

[4] See elasticity of demand in Glossary.

Morris et al. (1999) advocate the use of systems methodology to manage technological change in agriculture. Their study has raised a number of points:

1. It is important that the benefits and costs of technologies are quantified. A systems perspective enables a more complete evaluation of the strengths and weaknesses of technologies, including technical, social, environmental and political outcomes.
2. System information and ideas can usefully inform the implementation of new technology. As a tool, technology has a basic requirement of skill for its operation but, in order to be useful, it must fit into particular farming systems, with consequences of its use understood and optimised.
3. Many technical professionals (e.g. agronomists, soil scientists) have difficulty in understanding and including social dimensions in their thinking. Training in systems methodology provides an opportunity for them to remedy this and improve their communication with farmers and others involved in technology adoption.

Successful use of innovative technology in rainfed farming systems thus depends on a variety of factors. For the farmer it must be profitable, not too risky, within the manager's capability and capable of overcoming a real problem. For innovations to be generally adopted, they must be seen to be safe for human health and the environment, have supporting infrastructure, be equitable to all participants and be supported by appropriate government policy. Systems methodology has a role in ensuring all these prerequisites are met.

7.3 How Rainfed Farming Systems Have Benefited from Technological Innovation

7.3.1 Plant Improvement

Much plant breeding has been focused on 'defect elimination' (such as susceptibility to disease) and 'adaptive breeding' (to increase the range of environments in which a particular crop can be effectively grown) using classical plant breeding techniques. However, in recent years the advent of biotechnology and consequently genetic modification of plants means that the rate of progress in plant breeding can be increased substantially (Sadras and Calderini 2009). Throughout the world, there are international and domestic organisations involved in plant breeding, including the Cooperative Groups for International Agricultural Research[5] (e.g. International Centre for Agricultural Research in the Semi-Arid Tropics; ICRISAT, International Centre for Maize and Wheat Improvement; CIMMYT and International Centre for Agricultural Research in Dry Areas ICARDA), national government agencies,

[5] See CGIAR website http://www.cgiar.org/ for links to partner organisations.

universities, and corporations which are often transnational. These organisations have access to a large store of germplasm collected from their locality and from breeding programs.

Key objectives of plant breeding have traditionally been to improve crop yield and resistance to pathogens (viruses, bacteria, fungi), insects and nematodes. More recently, attention has been focused on breeding for efficiency of nutrient and water use, drought tolerance and resistance to biocidal agents (principally herbicides) (Sadras and Calderini 2009).

Adaptive plant breeding for the range of desirable features has contributed to improved crop yield and reduced costs, and to an improvement in the productivity of rainfed farming systems over a long period (see also Chap. 28). New genotypes must be tested and selected over a range of environments which vary in climate, soil and 'pest' challenges.

An early example of wheat breeding from Australia was William J Farrer's variety 'Federation' which was released in 1901 (Wrigley 1981). This pioneering work laid the foundation for breeding many improved varieties over a period of decades. It was the forerunner to many new wheat varieties produced by recurrent selection procedures, now supported by selection using marker genes (Chapman et al. 2006). Hybridisation within several crops (principally maize, sorghum and sunflowers) has contributed to rapid improvement in productivity through hybrid vigour, initially in developed countries and then in many developing countries (Fehr and Hadley 1980). Table 7.1 provides examples of improvement in maize yield since 1961 for various countries.

The principal contributors to increases in maize yield have been hybrid vigour, improved cultural practices, (principally the application of nitrogen fertilisers and increased plant populations in areas of favourable climate), and breeding for improved physiological adaptation and resistance to diseases and insect pests (Duvick 2005). However, local landraces (open pollinated varieties) are still widely

Table 7.1 Improvement in maize average yield (1961–2004) in selected countries and regions. (Source: FAO Stat 2006)

Country/region	Average yield (t/ha) 1961	Average yield (t/ha) 2004	Gain/yr (kg/ha)	R^2
European union (15 states)	2.5	9.3	163	0.97
Eastern Europe	1.8	4.9	42	0.39
USA	3.9	10.1	114	0.85
Canada	4.6	8.2	71	0.79
China	1.2	5.1	100	0.96
India	0.9	1.9	22	0.81
Australia	2.1	5.5	93	0.87
Southern Asia	1.0	2.0	24	0.82
Argentina	1.8	6.4	100	0.87
Brazil	1.3	3.4	47	0.83
South America	1.4	3.7	52	0.87
South Africa	1.3	3.1	31	0.37
Southern Africa	0.7	0.8	5	0.17

used in developing countries; consequently the benefits of hybridisation and hybrid vigour are not available. Further, from a systems viewpoint, the adoption of hybrids implies that adoption of other technologies e.g. increased fertiliser input to support the higher yield potential, and financial and input availability constraints can limit the capacity of farmers to use hybrids.

There are, though, areas where improvement has not occurred, for example in Zimbabwe, where yield has declined from an average 1.2 t/ha in 1961 to less than 0.5 t/ha in 2004. Similarly, it has increased only marginally in southern Africa, for non-technological reasons (see Chap. 38). In southern Africa, yield has been extremely variable from 1 year to the next, indicating that improvements in agronomy are likely to produce substantial gains.

More recently, plant breeding programs have targeted specific characteristics such as ‘stay green’ in sorghum (Borrell et al. 2004), water and nutrient use efficiency in a range of crops (Condon et al. 2004; Fageria et al. 2008), drought tolerance (Ribaut et al. 2002), resistance to insect attack (Clement and Quisenberry 1998) and resistance to herbicides in a range of crops (van Deynze et al. 2004; Crosby et al. 2006). Biotechnological techniques such as gene mapping and molecular markers that permit genetic modification of plants are being used to enhance the rate of progress in plant breeding programs (Ribaut et al. 2002; Lorz and Wenzel 2004). An interesting extension of these techniques could lead to enhanced efficiency of symbiotic N fixing associations of legumes with *Rhizobium* species and of cereals with other nitrogen-fixing organisms (Hardarson and Broughton 2001). In addition, modelling techniques are being used to assist plant breeders by assessing probable adaptation and performance of genotypes and phenotypes in particular environments, as described in Hammer et al. (2006).

However, particular genotypes may affect other aspects of the production system. For example, different temperature or vernalisation requirements or photoperiod sensitivity of a genotype may increase the opportunities for planting earlier or later in the planting ‘window’ when soil water conditions are favourable or to avoid temperature extremes. The use of lower or higher plant populations may follow from use of varieties with differing tillering behaviour (as in cereals) or branching (as in many legumes) or even change in plant habit (bunch habit to running habit in peanuts), or decrease in angle between the leaf and stem (leaves more erect) in maize and sorghum. These plant morphological changes affect canopy structure and thus processes such as light interception (a physical process) and gas exchange (a diffusion process). They may even lead to increased susceptibility to diseases and insects; for example, high humidity in a dense canopy may increase susceptibility to disease. However, in areas where substantial rain falls during the growing season, early canopy closure by rapid leaf area production may reduce soil evaporation. Also, where the growing season is short due to temperature limitations, rapid early growth is needed for achieving satisfactory yields from short-season cultivars used in these circumstances. Conversely, a cultivar that has slow initial production of leaf area – and hence reduced water consumption – followed by more rapid canopy development before flowering can improve water use efficiency and thus final yield in environments where water supply is a major constraint, for example in north-eastern Australia (see also Chap. 25). This is particularly so in areas where crops are grown on stored moisture and the soil surface is dry for much of the crop life, thus avoiding high levels of soil surface evaporation. This concept has been explored elegantly by Hammer (2006) for grain sorghum using modelling techniques based on numerous experimental studies in water-limited environments.

A new genotype, by raising crop productivity, may also need greater nutrient input to sustain higher yields; which illustrates how new technology usually requires the adjustment or improvement of other inputs or features of the farm system. Furthermore, as some improvements in genotypes are not stable over the long term, there will also be a need for continued genotype improvement. For instance, resistance to diseases, such as leaf and stem rust in wheat, needs to be maintained by continuous plant breeding programs. Such breakdown in desirable characteristics in plants bred by standard procedures implies that breakdown will also occur in genetically modified plants.

The productivity and sustainability of present-day farming systems is continually reliant on the maintenance of effective crop (and pasture) genotypes, as well as of other components of farm systems on which their value relies.

7.3.2 Agronomic Practices

In rainfed systems, agronomic practices should be designed to conserve water and use it efficiently, with a measure of the success being the amount of output produced per unit of water consumed. Water use efficiency (WUE) is defined and discussed in detail in Chap. 1. Best practice in Australia produces around 20 kg of grain per mm of water transpired by wheat (French and Schultz 1984a, b) and maize (Goyne and McIntyre 2002). Agronomic practices relevant to WUE include tillage, use of cover crops, weed control and fertiliser use: these are discussed below.

7.3.2.1 Tillage, No-Till and Residue Management

Many diverse soil tillage practices are used in rainfed agricultural systems – from hand tools and animal power to highly sophisticated mechanisation. During the twentieth century, there was a general tendency towards increased mechanisation of tillage, although its intensity – amount, depth, force and frequency – has decreased in many areas since the mid-1970s.[6] This apparently paradoxical situation arises from the increased use of small-scale mechanisation of tillage and other production

[6] Buckingham (1976), *Fundamentals of Machine Operation,* John Deere, illustrates the multiplicity of tillage methods and machinery of that time.

practices in developing countries with widespread reduction in tillage, even as far as no tillage at all, in developed and some developing countries (Aboudrare et al. 2003, Chaps. 39 and 40). Principal factors contributing to the reduction in tillage are:

- energy costs of tillage
- need to control soil erosion and maintain soil fertility, usually in conjunction with stubble retention (See also Chaps. 4–6 and 14). The optimum combination of agronomic practices – of which tillage is one – varies according to soil type and climate;
- availability of low-cost and effective herbicides to replace tillage for weed control. While initially more relevant to highly-developed mechanised agriculture, the use of herbicides is expanding in developing economies, using small-scale equipment.
- improved yield, usually in the range 5–20%, widely reported for reduced and zero tillage (no-till) practices. (See also Chaps. 34, 39, 40 and 45 for the practice of this technology, and various other chapters, in Parts II and IV, for its development and benefits.)

Examples of technology changes involved in the adoption of no-till can be seen in Chaps. 19, 20, 25, 26, 31, 33, 34, 39 and Part V. These include changes in (1) planting equipment to ensure accurate seed placement in the absence of cultivation and the presence of large amounts of crop residues; (2) the system of weed management, also in the absence of cultivation; and (3) the calculation and application of nitrogen fertiliser requirements.

Planting into well-tilled soil with a fine, firm seedbed 'free' of residue of previous crops has now been widely replaced by planting into soil less thoroughly tilled, or not tilled at all, and with substantial amounts of crop residue on or near the soil surface. As the objectives of planting are still to establish a consistent population of plants that emerge uniformly (i.e. on the same day), minimum or no-till planting practice must be substantially changed to achieve satisfactory soil–seed contact, and is achieved through changes in machinery design and operation (see Chap. 39 and Part V).

The impact of tillage on the availability of plant nutrients (particularly available N) is variable, depending on soil moisture, temperature and organic matter content, as discussed in Chaps. 4–6 and 14.

In the case of no-till systems, continued reliance on herbicides in place of tillage for weed control has led to the development of herbicide-resistance in target weeds, for example in wild oats, annual ryegrass[7] and barnyard grass (Storrie 2007; Preston 2005). Strategies are required to minimise the risk of further development of herbicide resistance. The response may be 'short-term and directly interventionist', for example by use of alternative herbicides to control weeds. Alternatively, the response may be longer term, such as modifications to crop–crop or crop–pasture rotations, allowing the use of a range of herbicides in different crops of the rotation.

[7] See Glossary for botanical names.

Planting operations for no-till practice require modified technologies for concurrent application of fertilisers, herbicides and insecticides. These topics are integrated into other chapters of this volume. Changing one major technology such as tillage practice can therefore have substantial implications for other technologies, practices, and the design of equipment for planting; and consequently for other aspects of the farm system. The changes need to 'fit together' to ensure sustained productivity, stability and other desirable features of the system.

7.3.2.2 Use of Cover Crops

Cover crops have long been an integral part of many agricultural systems. They may be grown as 'green manure' crops which may be cultivated into the soil, killed *in situ* to maintain soil cover, or harvested for animal feedstuff. In all cases, they provide a period of vegetative cover prior to planting of a crop. This approach is compatible with areas where year-round rainfall is adequate for two crops per year, each crop relying on rainfall during its growing season, without the need for accumulation of moisture under fallow (see Chap. 39 concerning cover crops in South American farming systems).

Thus, cover crops have not been widely used in rainfed farming systems where a period of bare fallow is used to accumulate soil water (see Chaps. 4, 20 and 25). However, it has been shown that a brief period of cover cropping can be used, without detriment to the following crop, provided that there is still sufficient time for water accumulation in the fallow soil before the crop is planted. For example, in the Eastern Farming Systems Project in Queensland (Australia), 60 days of millet[8] cover crop growth in the spring provided a range of benefits to both soil and the following winter crop. Benefits included improvements in water infiltration, ground cover during the fallow period, establishment and yield of the winter crop, water use efficiency and in mycorrhizal colonisation of roots of wheat (Price 2006, 2009). The millet crop was grown on residual stored water and spring rainfall but, as its duration was restricted, sufficient time remained for accumulation of soil water for the subsequent winter crop. Thus cover crops may have a place in improving the sustainability of some rainfed farming systems, even in semi-arid–sub-humid areas.

7.3.2.3 Pest Control

In most rainfed systems, weed control to minimise competition for water is the predominant pest management challenge, but reduced production from disease and insect pest damage is also important in many situations. Some important control and management technologies are common to all pests. These include the use of

[8] Se Glossary for botanical names of crops.

chemical sprays, integrated management technologies and, more recently, GM technology. There are also differences, such as the possibility of breeding for resistance to diseases and insect pests, although this is also fraught with problems of the development of races of the pest to which the plants are not resistant (see Chaps. 8–10).

Weed Control

The conventional use of mechanical tillage without stubble retention for weed control is unsustainable, at least on sites where soils are prone to erosion. The increasing development and use of herbicide technology has occurred in parallel with the reduction in tillage for weed control in both developed and developing countries. However, this in turn has resulted in the development of herbicide resistance in weeds (Powles 2007).

Herbicide resistance is increasing and is a further impediment to system sustainability, even though use of herbicides has become widespread only since the end of World War II (see Chap. 8). Herbicide resistance by weeds thus represents flaws in the technology, and these are now being addressed through the combination of technologies known as Integrated Weed Management (IWM) (see Chap. 8). While IWM represents the future direction in weed control, it also needs to be a flexible group of technologies as it must adapt to changes in weed population density and the range of species present (Sandow and Rainbow 2007), along with changes in farming due to climate change and economic challenges.

Herbicide resistance has been detected in a range of weeds (e.g. ryegrass, barnyard grass) and to a range of individual herbicides (e.g. glyphosate and trifluralin (GRDC 2009)), or groups of herbicides (Preston 2007). Even more concerning is that cross-group resistance has emerged, meaning several herbicides in different chemical groups all lose their effectiveness against at a particular weed species (Preston 2007). Consequently, new herbicides and new strategies of use of new and existing herbicides must be developed. Alternatively, there may be some opportunity to develop crop and pasture plants that produce allelotoxins (materials produced by plants or their residues) that kill or prevent establishment of other plants. These may offer promise for control of a limited range of weeds (see Chap. 8).

A further step in use of herbicides has been the development, through use of GM biotechnology, crop plants that are resistant to the herbicides that previously damaged or killed them. The best examples here are GM maize, cotton, canola and soybeans that are unaffected by the herbicide glyphosate (the RoundUp Ready® suite of crops). This technology relies on the insertion of a gene or group of genes that renders the crop unaffected by the herbicide or enables the crop to detoxify it (see also Chaps. 8, 31 and 49).

The increased use of herbicides has had some other negative effects on rainfed farming systems. These include adverse health impacts from carcinogenic and teratogenic effects of the bioactive agent, breakdown products (residues) entering the food chain, leaching of chemicals into underground water supplies that are subsequently used for drinking, and escape into surface water bodies, leading to damage to aquatic plants and ecosystems. These concerns foster community disquiet over the use of herbicides, which is another aspect of agricultural technology which must be taken into account (see Chap. 8).

Therefore the challenge for the future is to both maintain crop and pasture production and control weeds through further adjustment of the farming system, IWM being an important adaptive strategy (Sandow and Rainbow 2007). Development of Controlled Traffic Farming Systems and Precision Agriculture as enabling technologies is expected to lead to the adaptation of mechanised systems which can more effectively target weeds separately from crops. These approaches are expected to include the use of information and communication technologies to sense positional relationships of crops, weeds and machinery, identify weed species present and guide the application of chemicals (Loghave 2008) (see Chaps. 8 and 34).

Insect, Disease and Nematode Control

The chemical control of these organisms has adverse effects similar to those from the chemical control of weeds. Examples are: development of resistance in the pests, public perception of the adverse effects of chemicals on health and some adverse effects from application such as spray drift and chemical persistence in the environment. However, the chemicals used for insect and nematode control in particular are usually more toxic to humans and animals (including fish) than herbicides, raising public pressure for alternative practices and for food sources not treated with chemicals. Fortunately, selection and breeding of plants resistant to disease and pest organisms and use of appropriate crop rotations continue to provide opportunities for their control. Indeed, many major plant diseases are controlled by plant resistance, including such widespread and damaging diseases as leaf and stem rust of wheat, leaf blight of maize, various powdery and downy mildews and root rots that affect a range of crops, The 'genetic' opportunity for control is greater than that provided by application of chemicals, as plants themselves produce a bewildering array of chemicals (including alkaloids, cyanogenic glycosides, glucosinolates, terpenoids, phenolics, condensed tannins, silica, lignins, fatty acid derivates, amino acids and peptides) and have other strategies such as thick waxy cuticles to resist attack by insects and disease organisms.

The use of genetically modified organisms (GMO) relies on transfer of genetic characteristics from one organism to another. This approach may be used to transfer disease or insect resistance or, in the case of cotton, the ability to kill an insect by producing a specific toxin transferred from the bacterium *Bacillus thuringiensis* (*BT*) which is toxic to *Heliocoverpa* species. This capacity has been incorporated, using biotechnological techniques, into BT cotton.[9] The plant then produces a toxin specific to *Heliocoverpa* species (common names for which include bollworms (of cotton),

[9] See Glossary.

budworms and pod borers (of a range of other crops); see also Chaps. 9 and 10). Technological advances in the management of pests and diseases are likely to continue to improve the productivity of farming systems, but their use raises concerns about adverse effects on health and the environment, and these need to be addressed continually (see also Chap. 10).

7.3.2.4 Plant Nutrition and Fertiliser Use

In most rainfed farming systems, nutrient deficiency is second only to water supply as a production limitation. Unfortunately, many agricultural production systems remain in an exploitive feature of land use – a simple nutrient balance assessment often reveals that more nutrients are exported in harvested products than are returned as fertilisers or animal manures – (see an Australian example in Chap. 25, Sect. 25.5). As discussed in several chapters, there is a need to match nutrient input with nutrient need, thereby optimising nutrient utilisation efficiency and avoiding both a negative nutrient balance and surpluses with losses to the environment (see also other chapters, including Chaps. 5, 19 and 20).

The identification and correction of plant nutrient deficiencies is integral to the successful operation of farming systems. The technologies for determining nutrient deficiencies and the efficient supply of crop nutrient needs are well developed, although still the subject of ongoing research (Ryan 2004, Chap. 5).

Fertilisers, though, represent a major cost input to agricultural production systems. Nitrogen fertilisers require energy for manufacture from hydrocarbons and for their transport. This energy should be taken into account in assessing their efficiency and energy cost. Currently, the only realistic alternative to N manufactured from hydrocarbons is N from legume–rhizobium symbiotic fixation, implying the need for changes to production systems (e.g. rotations, pest control and mechanisation) to accommodate greater use of crop and pasture legumes. Research into improving nitrogen fixation is discussed in Chap. 6.

Application of fertiliser can have negative as well as positive impacts. For example, it can change the chemistry of soils – the best example being a reduction in soil pH after prolonged use of nitrogen fertilisers – which then causes reduced solubility/availability of some plant nutrient elements and increased solubility of others. The latter may result in toxic concentrations of, for example, manganese and aluminium (Bouman et al. 1995). Nitrogen supplied from legumes can have similar effects on pH. For example, in Australia, 40–50 years of subterranean clover-based pasture grown in rotation with crops has resulted in significant soil acidification over large areas in southern Australia (Black and Batten 2003). This is an example of a technological change having unintended adverse consequences that need to be corrected to maintain sustainability in the system.

New technologies and practices that are likely to become commonplace in agricultural production systems are those which enable production inputs to be precisely monitored and applied. These technologies include yield mapping, crop monitoring, site-specific application of fertilisers, 'on-the-run' sensing of plant nutrient status, and remote sensing for early warning of emerging nutrient stress in crops. These technologies would be used on farms with simulation modelling and decision support systems in planning fertiliser use. Regionally they could assist in managing inputs and losses of nutrients; for example, the model APEX (Agricultural Policy Environment Extender) (Williams et al. 2006) has been developed by the United States Department of Agriculture to assess catchment impacts of agricultural production and other land use practices (Gassman et al. 2009). New and advanced technologies are also in use for such applications as variable-rate technology for fertiliser application, guidance systems for sprayers and tractors, and weed-tracking sensors, as discussed in Kelly and Jensen (2006). Some of these technologies are examined in more detail in Chap. 34.

7.3.2.5 Agricultural Mechanisation and Automation

In developed countries, the use of high-capacity equipment for tillage, planting, harvesting, storage and transport has led to improved land and labour productivity and improved timeliness of many operations. However, in developing countries, smaller-scale, high-reliability mechanisation is most likely to be needed because holdings are small and labour availability remains comparatively high (FAO 2008; IAASTD 2009). In technologically advanced countries, automation is becoming accepted as part of agricultural practice. For instance, automatic data collection during field operations for yield monitoring while harvesting, (Kelly and Jensen 2006) is increasingly accepted as part of efficient farming, with automation potentially extending to driverless tractors (Katupitiya 2007). When integrated into modern farming systems, these technologies have the potential to reduce costs.

7.3.2.6 Precision of Field Operations

Improved precision of farming operations is needed because of the drive for efficiency to cut costs and increase profitably. It is assisted by greater knowledge of how agricultural inputs affect resources (soil, water) and plants (Boydell and Boydell 2003; Blackwell et al. 2003).

Technologies such as air stream or vacuum planting and seed delivery monitoring equipment contribute to improved control of the planting operation and plant population, and thus crop canopy growth and structure (see also Chaps. 34 and 39). Precise technologies are being developed for monitoring crop condition and managing inputs, including fertiliser application (Kelly and Jensen 2006), weed control (see Chap. 8) and harvesting (Kelly and Jensen 2006).

Precision guidance systems for machinery are available to improve field efficiency[10] and fuel economy (Blackwell et al. 2003; Tullberg 2001), on-the-run weed

[10] See Glossary.

identification using colour and shape discrimination to achieve targeted application of herbicides (Aitkenhead et al. 2003; Brown and Noble 2005), and rapid in-field tests of plant nutrient status (Bierman et al. 1995; Barker and Pilbeam 2007). Other technologies available are weather monitoring, remote sensing of crop condition and crop growth, using ground equipment, and manned and potentially unmanned aircraft and satellites fitted with equipment to sense biotic and abiotic stresses in crops (Pinter et al. 2003; Heap 2007; Zarco-Tejada et al. 2008). These methods may be applied to specific purposes such as identifying weeds during field operations or more general identification of crop water stress or reduced growth rate (Cook 2000, Chaps. 34 and 39).

On the output side, precision technologies are being increasingly used to monitor crop yield and crop quality (e.g. protein concentration of cereal grains during harvest). This can be used to inform decisions on inputs (e.g. fertiliser) to subsequent crops. These concepts have been explored extensively in literature on precision agriculture (for example, Boydell and Boydell 2003) (see also Chaps. 34 and 39).

Precision technologies in agriculture fundamentally rely on detailed information and its interpretation and communication in useful forms – an application of information and communication technology (Boydell and Boydell 2003). The information gathered can be incorporated with other information – for example weather records for a season or sequence of seasons – to enhance understanding of reasons for variation in crop yield and/or quality or the effectiveness of inputs such as pest management or fertilisers. Alternatively, it may be combined with forecasts of weather conditions in the next cropping season to assist with operational and budget preparation and for assessment of risk of crop failure (see Chap. 34).

These technologies are useful in that they provide objectivity in decision making (Cook 2000; Boydell and Boydell 2003), and therefore have the capacity to enhance functioning, stability and sustainability of agricultural systems. Importantly, they can provide early warnings of system perturbations – that is, departures from expected performance – so that corrective action can be taken. For example, sub-optimal nitrogen can be detected and remedied before it becomes serious.

7.3.3 Modelling – A Tool for Improved Efficiency in Agriculture

The capacity of simulation and decision support modelling to address practical issues has been developed since computers and programs became more 'user friendly' – essentially since the advent of personal computers in the late 1980s. Initially, modelling was a research tool, but it has been developed for assessing likely outcomes from alternative production scenarios such as combinations of options for time of planting, cultivar choice and soil water supply at planting. Thus the probability of a range of outcomes can be determined (see, for example, Birch et al. 2006; Howden and Jones 2004).

There are many applications of models including assessment of: (1) weed management options (Pannell et al. 2004; Buckley et al. 2004); (2) risks of frost

(WHEATMAN, Cahill et al. 1998) and heat stress; (3) nutrient requirements of a range of crops (APSIM, Keating et al. 2003); (4) management of pests and fertiliser use in cotton (Cotton LOGIC, Larsen 2005); (5) other management options (Asseng and Turner 2006); (6) selection of cultivar type; and (7) retrospective analysis of system function to identify where changes might be made to improve future system performance (Birch et al. 2006). Use of models to examine alternative production practices and improve plant performance is discussed in Chap. 25.

Large-scale catchment and cropping system models include the APSIM models previously mentioned and the Soil and Water Assessment Tool – SWAT. SWAT is a river-basin scale model developed to quantify the impact (e.g. on water pollution) of land management practices in large, complex watersheds. It is publically available and used internationally (Arnold et al. 2009) with the active support of the USDA Agricultural Research Service. A similarly complex model for environmental analyses of landscapes and watersheds is Agricultural Policy Environmental Extender (APEX). APEX is a dynamic tool for simulating a wide range of management practices, cropping systems, and other land use across whole farms and small watersheds. It can also be used to examine the effect of pesticides, forestry, buffer strips, and conservation practices at plot, field, watershed, or regional scale (Gassman et al. 2009). Though such models are principally used in developed countries, SWAT is increasingly used in developing countries with the support of International Agencies (Arnold et al. 2009).

Aside from these large, complex models, there are many others developed for specific areas or objectives. With the current emphasis on adaptation to, and mitigation of effects of climate change surveys and assessments of a range of models that may be used for this have been completed (Dickinson 2007; UNFCCC and Stratus Consulting 2005). These list many of the models and modeling activities that have been developed for agricultural application including APSIM (Agricultural Production Systems Simulator), ORYZA 2000 and RICEMOD (both rice models), International Consortium for Application of Systems Approaches to Agriculture (ICASA), the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) family of models, AFRC-Wheat, Alfalfa 1.4 (an alfalfa model), GOSSYM/COMAX (Cotton models) and CROPWAT (an irrigation model) as well as a series of economic, climate and water management models.

More recently, it has become possible to model the structure and function of individual plants or communities of plants as a crop or a pasture (de Reffye and Hu 2003). Included among these models are the ADEL models: ADEL-Maize (Fournier and Andrieu 1999), ADEL-Wheat (Fournier et al. 2003), AMAP and Greenlab (de Reffye and Hu 2003). They are still essentially research tools, though developing rapidly and being used to enhance understanding of plant canopies, how they respond to environmental stimuli and how they can be managed (Evers 2006; Evers et al. 2006).

Analysis of climatic data for providing seasonal outlook forecasts as input into farming decisions is of increasing importance as global warming brings increased climate variability (Howden 1999a; b; Sultan et al. 2005). Both historical scenario analysis (Birch et al. 2006), and prospective seasonal scenarios (Potgieter et al. 2004) can be examined to provide guidance to crop performance under a range of seasonal conditions. Of particular interest to rainfed systems of agriculture is the developing ability to model the impact of water stress on crop development and to examine options for management of canopies to maximise water availability for the grain-filling stage (Hammer 2006). A related issue is the accumulation of water in soil profiles, which can be modelled from rainfall data using programs such as HowLeaky (McClymont et al. 2006).

Models have been developed into Decision Support Systems (DSS) for farmers; for example, Yield Prophet® has been developed from APSIM (see Chap. 37 for details).

In future, simulation modelling, decision support systems and ultimately functional structural modelling will be focused on enhancing existing capacity to improve predictability of system performance, and so as to more comprehensively explore system flexibility, efficiency, stability and sustainability. Enhancements to models will provide more sophisticated approaches to nutrient transformation in soils and uptake by plants, greater capacity to predict pest incidence and severity in crops. This will improve the capacity to guide system sustainability and productivity. Modelling will be able to provide 'early warnings' of impending system instability (e.g. for example pest outbreak, changes to soil fertility) and thus alert agricultural producers and policy makers to take action to modify production practices in the interest of system sustainability. The predictions of modelling will, of course, need to be combined with 'ground truthing' (field observations) to ensure the appropriateness and timeliness of decisions and interventions that affect system sustainability (see Chap. 37 for an example using Yield Prophet®).

The use of modelling is not confined to highly developed countries; it is widely used by advisers and consultants in developing countries as a research tool and for providing advice to farmers, consultants and governments on appropriate agricultural policies and practices. The uses are essentially the same as those outlined above, with an emphasis on support of development and mitigation of the consequences of such processes as climate change and desertification. These activities rely on research supported by organisations such as CIRAD, Kenya Agricultural Research Institute (KARI) and the Cooperatives Groups for International Agricultural Research (CGIAR), e.g. ICRISAT, ICARDA, CIMMYT. Through modelling, it should be possible to enhance adoption of strategies that both improve production and reduce environmental damage, especially in areas where resource degradation is occurring rapidly because of population and economic pressures. Thus, modelling should contribute to improved short-term stability and ultimately long-term sustainability of systems in both developed and developing countries. In both, the power of modelling lies in the capacity to assess and compare many scenarios (Lambin et al. 2000; Thornton and Herrero 2001; Parry et al. 2004). The weakness that remains is the capacity to undertake the necessary 'on-ground' demonstration of outcomes and education, and to gain acceptance of indicated practices in situations where the primary concern of individuals is food security (Parry et al. 2004).

7.3.4 Technological Aids to Farm Business Decision Making

The functioning, productivity, efficiency, flexibility, stability, profitability and sustainability of rainfed farming systems all depend on the decision making by those who manage them. Technology, particularly that related to computers, has provided many aids to decision making (apart from the models discussed in the previous section). Nuthall (2004) found in a study of New Zealand farmers that while use of a computer did not necessarily make a farm more profitable, many farmers felt it saved time and assisted in decision making and complying with statutory requirements (e.g. taxation).

Many farmers have kept extensive records of management of their properties. However, previously they lacked the ability to analyse this information effectively and efficiently. Modern computer technology allows easier data acquisition and analysis of all aspects of farm management. Examples include the automatic recording of grain yield and other field data has already been discussed. However, it is also possible to electronically collect and analyse data as diverse as animal weights and weather conditions.

Good financial management is essential for profitable and thus sustainable farming. Technology is assisting farmers in this task in a number of ways. For instance, computerised financial programs are now common in the developed world, and these allow managers to plan and budget for the future, and accurately record all financial transactions. They can then compare the actual outcome with budget provisions instantly to make timely decisions if plans need to be altered. Before the advent of personal computers, this was a time-consuming and often neglected aspect of farm management. It is becoming increasingly possible to link financial and physical information to provide the manager with appropriate information on which to base management decisions.

Managing agriculture in developed economies frequently involves ‘investment’ over a long period. This generally involves different costs at different times over a number of years. The recognised method of deciding between alternative investments involves ‘discounting’ costs and returns to a common time period. Before the advent of spreadsheets this was a lengthy calculation and impractical for farm managers. Current computer spreadsheet models make it easy for a farm manager to make comparisons such as alternative machinery purchase or hire options.

Technology also plays a large role in providing farmers with a wide range of information – from market prices to the latest innovations. The technology used ranges from radio and television (particularly in developing economies) to the internet (in emerging and developed economies). Online banking and purchasing have improved management efficiency where they are available. Mobile phones have also vastly improved communication in both developed and developing countries. Improved weather forecasting has also improved farmers’ ability to manage such events as planting times and pest control.

7.3.5 Research and Development and the Resultant Technological Change

Agricultural research and development have resulted in more abundant and cheaper food, less poverty, and a decrease in the number of people going hungry (Alston 2000). It may also have resulted in a number of effects that are less clearly beneficial:

- More specialised and more intensive production on individual farms (and, for some, a greater risk of crop failure)
- A greater use of purchased inputs (and for some, a greater risk of financial ruin)
- A faster rate of consumption of natural resources (for example, soil nutrient reserves, underground stored water).
- Less biological diversity (Alston 2000).

While these may not necessarily be solely due to technological change, they emphasise the importance of taking a whole system view when introducing and assessing new technology. There can be no doubt that improved technology has contributed substantially to agricultural productivity and it seems likely that it will continue to do so in the future. However, new technology must also be designed and operated to suit the particular farm system, its economic and environmental sustainability and the sustained health and welfare of farmers and their families.

7.4 Emerging Technologies That May Improve Rainfed Farming Systems

The nature of rainfed farming systems is such that water supply will continue to be the major limitation to crop and pasture growth. An emerging issue is the ability of existing systems to respond in a sustainable manner to potentially increased variability in rainfall as a result of climate change. New systems with new technology that may have yet to be developed could challenge tradition and even social organisation in both developing and developed countries (Metzger 2005). Furthermore, since there is wide diversity in agricultural systems that have developed in response to the key limitation of water supply and a wide range of other factors (see Chap. 2), new technologies will also vary widely.

Technological innovation will be part of the response to challenges posed by population increase and other demographic change such as accelerated urbanisation. For example, China's level of urbanisation has doubled since the 1980s to 44% of the population living in cities in 2005. By 2025, it is predicted that over two-thirds of the population will live in cities (Woetzel et al. 2009). Broader environmental change, of which climate change has highest profile, also includes many changes to soils, (acidification, salinisation, erosion, compaction, loss of fertility), and loss of biodiversity through destruction of habitat for both flora and fauna. Technological change cannot be separated from these trends since it is part of their cause and part of the solution to their consequences. Technological change in agriculture will 'drive' part of the response to the challenges posed (pro-active), but will also have to be reactive (through development of new technologies) to the demands (stimuli for response) of other interested parties. For example, consumers and urban populations will almost certainly have a different perspective to that of agricultural practitioners (see also Chap. 13).

While new technologies have created some problems, it is hoped that they can help solve future challenges facing agricultural systems – such as climate change and reduced water availability; increasing demand for food, resistance to pesticides; soil degradation and increasing costs. However, solutions to problems will require integration of technology into farming systems, as well as providing specific technological advances. A number of technologies already discussed in this chapter are expected to contribute further to farm systems in the future, as well as those discussed below.

Agriculture will not only continue to provide and use technological innovations but will also benefit from advances in science and technology in 'high profit' industries such as the medical, defense, aerospace and computer industries (Lawton 2003). For example, agriculture has benefited from GPS technology which was developed by the aerospace and defence industries.

7.4.1 Biotechnologies

Among innovative biotechnologies predicted are those for extracting nutrients from soil reserves, particularly those for recovering previously applied nutrients, for example phosphorus, that have become fixed in the soil and unavailable to most plants. This technology will probably rely on transferring into crop and pasture plants the capacity – biochemical, physiological, or symbiotic – to utilise low-availability resources.

For nitrogen, improved efficiency of symbiotic nitrogen fixation by legumes, N fixation by non-symbiotic micro-organisms and associative relationships of grasses with diazotrophs[11] may reduce reliance on synthetic nitrogen fertilisers and reduce costs (Crews and Peoples 2004). Symbiotic fixation of N incurs a cost to photosynthesis in the plant as the bacteria use energy from the plants to fix N. However, this could be compensated for by the savings in the cost of N fertiliser. Further, some microbial species can also fix nitrogen non-symbiotically, without association with plant roots (see Chap. 6). N fixation, then, is a promising means of increasing soil nitrogen, and would be even more useful if symbiosis between microorganisms and non-legume plants could be enhanced and exploited.

[11] See Glossary.

Also, there are opportunities to enhance legume–rhizobium symbiosis. For instance, while there has been extensive, long-term research on the production and N fixation of temperate pasture legumes in moist environments (for example in New Zealand, Britain and parts of North and South America), less has been done to improve symbiotic N fixation in pasture legumes in drier climates. Some research has been done by organisations such as ICARDA (see Chap. 5, Sect. 5.7). Fundamentally, it is necessary for both legumes and rhizobia to be adapted to the climate and soil and to be compatible with one another, and to be highly productive and persistent. These and many other issues have to be dealt with in deciding whether to use pasture legumes in rainfed farming systems. Pulses and legume oilseeds are known to fix substantial amounts of N (Doughton and Holford 1997). Nevertheless, more research to improve their N fixation is also warranted.

Biotechnology offers techniques to improve the effectiveness of symbiotic associations, enhance the capacity to exploit them and, in the longer term, to create new plant–bacterial associations to enhance N fixing (Elmerich et al. 1998). In addition, biotechnology may also lead to diazotrophs that can enhance solubilisation of unavailable soil phosphorus, while retaining nitrogen fixing capacity (Vikram et al. 2007). New species of diazotrophs and other bacteria in the rhizosphere are being identified, and may also contribute to future development of biofertilisers, increasing the availability of nutrients in the rhizosphere, enhancing root growth, and promoting other beneficial plant–microbe symbioses (Vessey 2003).

7.4.2 Nutrient Recovery – 'Closing the Loop'

Finally, 'closing the nutrient loop' might be considered, at least in localised areas, in order to recycle or feed back nutrients into the system that produced them. This would help the system to 'survive' longer, with less cost of inputs (one way of describing sustainability – see Chap. 21, Case Study). The system of producing agricultural commodities in one area, transporting them, processing and consuming them elsewhere (e.g. in large cities) and disposing of residue, including sewage effluent in another location is inherently unsustainable – it is an open-ended system and promotes losses of nutrients. In some countries, both developed and developing, there is at least partial recovery of nutrients. This is principally from (1) collecting organic matter and sewerage in cities, composting the material and returning it to farm land, and (2) recovery of wastes from intensive livestock enterprises (Shepherd and Chambers 2005). It is conceivable that these processes will be more widely adopted to reduce environmental pollution (e.g. reduction of eutrophication of waterways) and for economic reasons (e.g. to obtain phosphorus when raw materials become scarce and expensive). The task ahead will be to devise a technology that recovers as much as possible of nutrient resources for return to rainfed farming systems (a closing of the loop). Constraints to be taken into account could include transport costs and the risk of introducing human pathogens or parasites into the food production chain where animal wastes or sewage effluent are recycled.

7.4.3 Agronomic and Livestock Husbandry Technology

Many of the agronomic changes noted in Sect. 7.3.2 will continue to be developed to improve the functioning of farming systems. Examples of potential integrated technologies include responsive in-season nitrogen management for cereals (Shanahan et al. 2008) where emerging computer and electronic technologies will directly assess plants' needs and apply the required nitrogen (by foliar spray or precision fertiliser application).

Technologies that monitor and measure are predicted by Michael Boejlje (Distinguished Professor in the Department of Agricultural Economics and the Center for Food and Agricultural Business at Purdue University) to be further improved and be more widely applied (Lawton 2003). He believes that improvements in sensor technology will take farmers to "a new level of measuring growth processes, the surrounding environment, the operation of machinery and much more. It will automate processes that previously required human intervention". For example, the soil physical characteristics will be sensed and power settings on a tractor automatically adjusted. Kitchen (2008) agrees that the information from precision agriculture increases in value when the data collection, data processing and management actions are integrated. He states that adoption of PA has been hindered, in part, by the lack of products that bring together engineering and agronomic requirements. Clearly integrated monitoring and management decision making will have positive effects on the efficiency, stability and sustainability of farming systems.

Precision livestock farming is another potential application of emerging monitoring technology. Sensors have been developed to monitor a large range of animal behaviour and health parameters, including movement, shape, size, weight, temperature, heart rate and sound produced. These can be linked with models and target outcomes to assist with management of the animals. The technology shows great promise, particularly in intensive animal production, but will require considerable research and development before it can be integrated into farming systems (Wathes et al. 2008).

7.5 Conclusion

While technological change has been a continuing factor in the development of farming systems worldwide, it must be adopted in relation to the whole system if unintended and possibly negative consequences are to be avoided. Advances in technology have allowed improvements in yield and quality of agricultural products. They should continue to bring changes to agricultural practice, and to enhance the efficiency with which limited resources are used, and thus contribute to profitability and sustainability of agricultural systems.

There will also be differences in rates and forms of adoption of new technology depending on the current state of development of agriculture in particular countries and regions. Existing and new developments will be adapted to suit particular farming systems, particularly in developing economies. A whole system approach will be needed, including consideration of social norms and expectations and economic factors in order for technology to be successfully adopted. Innovations must be profitable, low-risk, manageable, address a real problem, safe to use, supported by scientists and policy makers and be equitable.

Rainfed farming systems have benefited from a range of technologies including advances in plant breeding and genetics, improvements in no-till and crop residue management, use of cover crops, better pest control, more precise nutrient application and use, and developments in automation and precision field operations. Modelling will provide a tool for improved efficiency and together with other decision aids promote better management decisions.

Major emphasis will need to be placed on resource conservation and resource use efficiency. It will include adoption of biotechnology in order to, enhance such items as crop yield and quality, pest control, nutrient availability and uptake, nitrogen fixation, precision agriculture, automation and guidance, advanced decision support systems and information technology. Key concerns will continue to include control of biotic limitations to production, as well as adaptation to changes in the abiotic environment (especially climate change and associated changes in temperature regimes and water availability) in order to improve food security along with farming system productivity and environmental sustainability.

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Chapter 8
Weed Management in Rainfed Agricultural Systems

Principles and Methodologies

Colin Birch, Ian Cooper, Gurjeet Gill, Stephen Adkins, and Madan Gupta

Abstract The management of weeds is an important aspect of most farming systems. In rainfed systems, their control is usually critical in making best use of the available precipitation. Weed spectra change over time and with changes in the farming system. The reasons for these changes need to be understood so that integrated and holistic management strategies can be applied. New technologies including weed growth and population modelling and precision farming offer options that increase weed control efficiencies, slow the development of herbicide resistance and reduce costs.

Keywords Weed establishment • Weed impact • Integrated weed management • Herbicides • Herbicide resistance • Weed biology

8.1 Introduction

In considering the impact and management of weeds in a rainfed agricultural system we must define the term 'weed', determine why weeds are a problem, establish their effect on the system and devise ways of managing them. Since the system in which certain species are classified as weeds is dynamic, it is important to understand what influences change in weed spectra and what this means for the overall management of the farm system.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_8,

Defining what a weed is can be a complex problem and according to Kohli et al. (2006) depends on the discipline and point of view of the definer. Etymologically a weed is "a plant growing in a place where it is not required and/or is interfering with the growth of cultivated plants" (Crockett 1977). Kohli et al. (2006) and Crockett (1977) quote numerous authors who have differing definitions depending on their anthropomorphic, biological or ecological perspective. Most definitions of weeds point to negative aspects, particularly in terms of their interference with crops; however, Hammer et al. (1997) considered weeds to be important genetic resources and may be wild relatives of crop plants.

In agricultural production systems, weeds have evolved due to continuous selection pressure imposed by human activity, technological advancement or agricultural practices (Kohli et al. 2006), and consequently, there is a need to respond to continuing changes in weed population and the range of species present. In a farming system, the presence of a particular weed population can be the result of agricultural management practices (Sullivan 2003a, b). It may indicate that management practices may need to be modified and/or that the system as a whole may not be stable because of such situations as soil fertility decline, monoculture cropping, or simply the natural tendency towards diversity. Sullivan (2003a, b) argues for the use of proactive strategies that minimise weed populations by use of intercropping, crop rotations, crop-pasture rotations, use of cover crops and strip cropping, alone or in combination, rather than reactive strategies that are focussed on controlling weeds once they are present. The suggested strategies take advantage of well established principles of crop rotation and plant competition to reduce weed populations.

Weeds, though, remain of significant concern to the managers of farming systems in both developed and developing economies (see chapters in Part II and other Parts of his book), and the economic loss they cause is well recognised, though difficult to estimate. Global herbicide sales have been estimated at over US$36 billion (Agrow 2006).

It is important to understand the place of weeds in the operation and management of the overall farming system. With the advancement of agricultural technology, shifts in weed flora composition and the evolution of weed biotypes with herbicide resistance, the emphasis has moved to reducing weed density and minimising weed competition with crops. The aim is weed management rather than eradication which threatens ecosystem integrity (Kohli et al. 2006) and simply may not be feasible.

It is essential to integrate natural and management processes for weed control over a sequence of crops, rather than within individual crops (Buhler 2006). Integrated Weed management (IWM) is defined as an integration of effective, environmentally safe, and socially acceptable control tactics that reduce weed interference below the economic injury level (Thill et al. 1991). To this should be added the need to avoid over-use of particular chemicals so that development of herbicide resistance is avoided or at least slowed. IWM uses the principle that weeds are less able to adapt to a system that uses a range of control strategies. Integrated weed management must also be developed within the context of the wider ecosystem of the farm and the surrounding area and of the interactions of ecosystem health, population dynamics of weeds, and weed responses to management practices (Liebman and Gallandt 1997).

8.2 Management of Weeds in Rainfed Farming Systems

Herbicides have become the dominant weed control practice in agriculture particularly in developed economies, because of socioeconomic factors such as large farm size, limited time and labour, and the economics of tillage (Friesen et al. 2000). Herbicides allow the development of no-till and conservation farming technologies that reduce soil erosion and restore soil health. However, their economic cost, environmental concerns due to herbicide residues and spray drift affecting non-target areas, and constraints due to herbicide resistance in weeds have led to searches for alternative methods of weed management. This requires a better understanding of both the biological and management aspects of systems of which they are a part.

Management of weeds implies a move away from concentration on control of existing weed populations, towards prevention of propagule production (such as by crop topping or hay making) and the reduction of weed emergence and competition in a crop. These are techniques to 'anticipate and manage' rather than to 'react' to weed development.

Current weed research and management can be separated into two major categories – weed control science and technology, and weed population dynamics – applied through integrated weed management (IWM) (Sandow and Rainbow 2007). Weed control science and technology includes a wide range of strategies, including the use of:

- new herbicides – these have been continually developed since the end of World War II (Rao 2000).
- crop rotations these allow a range of herbicides and other control measures to be used, which helps to prevent weeds becoming adapted to any one crop system. For example, using pulses or canola in the rotation allows a variety of herbicides and a pasture phase allows other weed control measures as discussed in Sect. 3.1.
- biological control–mostly used for control of perennial plants in pastoral areas, though cropping areas can benefit from the control of invasive plants
- cover crops – for example winter cereals, which can produce allelotoxins from decaying residue. These can inhibit the growth of some weed species, but may also inhibit the growth of subsequent crops such as maize or soybeans (Singer et al. 1999). In addition, allelotoxins produced by some species can contribute to their success as invasive weeds (Weir and Vivanco 2008). Weeds may be smothered or prevented from emerging by cover crops which are mulched on the soil surface.
- tillage to remove weeds, though there has been a move world wide to reduce the use of tillage as described in Part II and Chaps. 7, 33 and 39. Inter-row tillage is

used to control weeds in a growing crop if the rows are wide enough apart, e.g. maize and sorghum.
- herbicide selection aids, (charts, web pages or computerised decision support programs) to assist in the selection of the most appropriate and effective herbicides (Hatfield et al. 1998)
- competition from crops to reduce weed populations. Crops need to be sufficiently advanced in order to provide effective competition against weeds (Zimdahl 2004)
- machinery hygiene, to prevent transfer of weed propagules between fields.
- regulation of movement around the farm or between farms, of hay and grain that may carry weed seeds.
- grazing by livestock, to eliminate edible weeds or at least reduce their use of soil water and production of seed. This may be particularly useful in fallow periods or, depending on timing and intensity of grazing, in the pasture phase of a rotation.

Methods of weed management can broadly be categorised as mechanical, cultural, biological and chemical. Each method has advantages and disadvantages, and a combination of two or more methods–integrated weed management (IWM)–is likely to be more effective than reliance on one method only. IWM aims to combine a number of strategies of weed control to contribute to sustainability of an agricultural system.

Mechanical weed control by hand weeding (subsistence agriculture), cultivation, inter-row tillage, or use of mulch is generally relatively inexpensive, may be considered environmentally friendly and can aerate the soil and break soil crusts. However, it may have to be repeated a number of times, leading to increased costs of machinery operation and labour; and it is reliant on weather.

Management practices that can be used to reduce weed populations include (1) retention of crop residues as a smothering mulch and a potential source of allelotoxins, (2) choice of planting time to allow prior weed control, (3) manipulation of crop density and competitive crops or varieties, to improve competition against weeds and (4) using rotations that facilitate weed control by varying crops and allowing alternative herbicides to be used.

Biological control is generally specific to one weed. Further, this method is generally slow acting as populations of the biocontrol agent must establish and thrive for effective control.

Chemical control came into widespread use after World War II, initially with 2, 4–D (Rao 2000). This chemical was selective (killed only certain broadleaf weeds) and systemic (killed roots as well as above ground plant parts), at very low application rates compared to those needed for previously used inorganic salts and oils. This stimulated research to find other organic compounds with herbicidal activity (Rao 2000). Many compounds have since been synthesized, varying widely in their selectivity, persistence, mode of action, efficacy, and human, animal and environmental safety. As developments have progressed, some highly specific herbicides which affect one or very few species (eg wild oat herbicides), or compounds with very high efficacy have emerged. Also, there are now a wide range of groups of herbicides, classified according to their selectivity, modes of uptake and action, time of application and chemical groupings (for details, see Rao 2000).

For example, herbicides may be;

1. non-selective (control a wide range of species) when applied to foliage (that is post emergence). Examples are glyphosate, sprayseed (paraquat plus diquat);
2. non selective (control of a wide range of species) when applied to soil prior to emergence of crop or weeds (that is pre emergence). Examples are trifluralin, pendamethalin, Glean® and the triazine herbicides.
3. selective, post emergence, controlling only grass weeds (eg Sertin®, Fusilade®) or broadleaf weeds (for example 2, 4–D, 2, 4, 5–T, MCPA, dicamba)
4. selective, and controlling only a few weed species, for example control of wild oats by the pre-emergence herbicides diallate and triallate or the post emergence herbicide mataven.

Herbicides may be absorbed by leaves (most post emergence herbicides) or roots (most pre emergence herbicides), while their modes of action are either contact or systemic, the former leading to desiccation of the plant and the latter to disruption of biochemical processes in the plant.

The availability of herbicides represents a technological development in response to cost and time pressures, reduced availability of labour for traditional weed control, and the need for greater production efficiency.

The development of reduced and zero soil tillage technologies has increased the need for herbicides that are effective under these conditions, or has facilitated such changes. For example, the availability of the non-selective, non-residual systemic herbicide glyphosate at affordable prices provided impetus to minimum and no-till farming, as it could be a substitute for cultivation and did not harm any crops grown after its use. However, as resistance to glyphosate and other herbicides (for example trifluralin) has emerged in some major weeds, alternative herbicides need to be sought, as well as changes made to the production system to prolong the usefulness of glyphosate. These changes may include diversification into other crops so that different groups of herbicides may be used, probably in combination with crop rotation. With diversification comes the need for differing herbicides, both to allow safe use with crops and to manage the changes in weed species and population densities and often their resistance to various herbicides (Beckie and Gill 2006).

The development of resistance has led to classifying herbicides by their mode of action. Two systems are mentioned in other chapters of this book. In the Herbicide Resistance Action Committee (HRAC)[1] system herbicides are grouped under letters of the alphabet according to mode of action. For example Group A chemicals work by inhibiting acetyl CoA carboxylase (Fusilade® with active

[1] HRAC is an international body founded by the agrochemical industry working in conjunction with the Weed Science Society of America. For more detail see http://www.hracglobal.com/Home/tabid/121/Default.aspx.

ingredient fluazifop-P-butyl is one). Subgroups are also created (C1, C2, C3), where different sites of action are involved. A second system using numbers rather than letters is used by the Weed Science Society of America (WSSA) and Canadian agricultural organisations.[2] The classifications are similar – Group 1 corresponds to HRAC Group A – but there are differences. Resistance to one member of a chemical group means that the plant may also be resistant to other herbicides in that chemical group. Some weeds carry resistance to more than one chemical herbicide group which means that alternative methods of controlling must be found.

Chemical weed control may lead to toxins (herbicides or residues of them) being introduced into the environment. These may adversely affect ecosystems where they are applied or even beyond – for example, in a study by the United States Geological Survey pesticides were found to pollute every stream and over 90% of wells sampled (Gilliom et al. 2007). There are also potential toxicological and carcinogenic risks to wildlife and humans, and concerns for food safety. These concerns may lead to the withdrawal from use of particular herbicides by Governments, for instance atrazine (one of the triazine herbicides) has been banned in the European Union and parts of the United States and Australia, and 'Sprayseed' (a mixture of paraquat and diquat, both post-emergence contact herbicides) has been banned in several countries for health reasons (for example see European community Directive 91/414/EEC).[3]

In developed economies, chemical methods of control have been dominant, but the associated problems of pollution of soil and groundwater and of toxicity of residues in food products are matters of concern (Merrington et al. 2002; Omaye 2004). Chapters 7 and 34 give examples of some technical innovations to combat weeds without using herbicides.

8.3 Agricultural Management Practices and Changes in Weed Populations

Three key management-related factors influence the rate of change in weed populations. These are: changes in rotation, changes in tillage systems and herbicide use.

8.3.1 Changes in Rotations

Agriculture has to respond to market forces, which can result in major changes in farming systems. Changes can include shifting the balance between summer and

[2] See http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/prm6487

[3] http://ec.europa.eu/food/plant/protection/index_en.htm

winter crops, where rainfall allows the option of growing both, changing the balance among cereal, oilseed and legume crops and shifting the balance of cropping and animal enterprises on individual properties or across whole regions. The combination of crop rotation and rotation of herbicides and other weed control measures provides a means of integrated weed control. Crop rotation also brings additional benefits by facilitating insect and disease control (Fischer et al. 2002) and, where legumes are involved, contributing symbiotically fixed nitrogen to the system. Such rotations require a range of herbicides for weed control without damaging the crop or pasture species. The avoidance of herbicide resistance also requires a varied range of herbicides with differing modes of action (Matthews et al. 1996; Boyles and Sanders 2009), integrated with other cultural practices in a farming systems context (Lanini; Roy 1999; Boyles and Sanders 2009). Other cultural practices may include intercropping (Sullivan 2003a, b), use of high plant populations and early planting as in wheat and barley production in Jordan (Turk and Tawaha 2003). Annual (rigid) ryegrass (*Lolium rigidum*) has become resistant to glyphosate and a range of other herbicides in several countries, including Australia, USA, Canada and Mediterranean countries. Its control therefore requires a number of methods combined with rotations, including growing pasture which is cut for hay before ryegrass and other weed components set seed.

An example of shifting the balance of livestock and cropping with subsequent changes in the range of weeds, is the large reduction in sheep numbers and increasing cropping area on farms in southern Australia since 1980, in response to economic changes that favoured cropping. This led to lengthening the cropping phase and reducing the pasture phase in the ley farming system, changes that can cause shifts in the range and population of weed species (Sullivan 2003a, b). Some broadleaf weed species of temperate pastures such as Capeweed (*Arctotheca calendula*), have been easy to manage in crops and so become less significant, but some grass weeds possess wide adaptation to varying land uses and can continue to be a major constraint. The best example is annual (rigid) ryegrass which has been reported resistant to 11 different herbicide groups in 12 countries and frequently shows multiple resistance (WeedScience.org 2009). The emergence of such resistance to some herbicides in ryegrass means its management as a weed in crops must increasingly rely on more integrated approaches to weed management, including rotations and cutting ryegrass-infested pastures for hay. Other species such as wild oat (*Avena sterilis sub species ludoviciana*), which may have been adequately managed by grazing with sheep, require control by chemicals or rotations or a combination of both. Chapters 11, 28 and 32 give examples of control of weeds using livestock and pastures.

8.3.2 Change in Tillage Systems

In developed countries, more intensive cropping and the need to reduce soil erosion has seen widespread adoption of no-till farming. This relies heavily on the use of herbicides and/or strategic grazing. Besides the positive impact of no-till on soil physical and biological properties, it has been shown to affect the spectrum of weeds in the mid-north of South Australia (Chauhan et al. 2006), and favours perennial rather than annual weeds in a wide range of environments (Rao 2000, Agriculture and Agri-Food Canada 2008). Factors responsible for changes in weed spectrum because of the tillage system include changes in the vertical distribution of weed seeds in the soil, and the favouring of herbicide-tolerant species or development of herbicide resistance (Rao 2000, Agriculture and Agri-Food Canada 2008). Chapters 19 (Canada), 20 (USA), 26 and 31 (southern Australia) discuss the effect of changes to tillage on weed populations.

8.3.3 Development of Herbicide Resistance in Weeds

Herbicides are highly effective selection agents and can strongly influence the weed spectrum. Introduction of phenoxy herbicides (2,4–D and 2, 4, 5–T) after World War II caused a major reduction in broadleaf weeds in western agriculture. Farmers in the developed economies adopted this and many other herbicides and herbicide groups (Sect. 3 above) as they were suited to the extensive nature of that agriculture. Herbicides are now being used increasingly in developing countries (see also Chap. 15). However, heavy reliance on herbicides has resulted in widespread development of herbicide resistance in weed species (Rüegg et al. 2007). The main factors that encourage major herbicide-resistant (HR) weed problems include:

1. multiple applications of highly effective individual herbicides or herbicides with the same mode of action.
2. annual weed species that are genetically variable and prolific seed producers, that have an efficient gene (seed or pollen) distribution system, and are widely distributed at high densities.
3. simple cropping systems that favour a few dominant weed species (Beckie and Gill 2006).

Failure of herbicides to control weeds, (leading to confirmation of resistance) and subsequent change in management both result in major changes in weed spectrum. However, failure to diagnose herbicide resistance in a timely manner can cause a large build-up in populations of resistant weeds (Neve et al. 2003, see also example in Chap. 31).

Weed resistance has developed to a number of widely used herbicides in a range of cropping systems. The WSSA has identified 341 unique herbicide resistant biotypes representing 17 HRAC groups. One hundred and seven of these were for HRAC group B (WSSA Group 2) ALS inhibitors. The United States of America has the most resistant weed species (130) followed by Australia (53) (WeedScience.org 2009).

Intensive use of one herbicide, for example glyphosate, is likely to enhance the rate of development of resistance (Rüegg et al. 2007). The examples of weed resistance

Table 8.1 Some glyphosate resistant weeds and their distribution[a]

Common name	Botanical name	Countries affected
Annual (rigid) ryegrass	*Lolium rigidum*	Australia, France, Italy, South Africa, Spain, USA
Italian ryegrass	*Lolium multiflorum*	Argentina, Brazil, Chile, USA
Johnston grass	*Sorghum halipense*	Argentina
Horseweed	*Conyza canadensis*	Brazil, China, Czech Republic, Spain, USA
Hairy fleabane	*Conyza bonariensis*	South Africa, Spain, Brazil, Columbia, USA

[a]Information from www.weedscience.com

to glyphosate (see Table 8.1) is of particular concern, as this herbicide is widely used in reduced and no-till systems.

Also of concern is resistance to trifluralin, widely used as a pre-emergence grass herbicide in legume crops and some cereals eg wheat. Numerous other instances of resistance also occur (Singh et al. 2006)

Adoption of integrated weed management (IWM) is recommended in various countries to delay or prevent the development of herbicide resistance (Carter 2008, Agriculture and Lands 2007; Storrie 2008). In particular, it is considered to be the major strategy to manage glyphosate resistance in ryegrass (Storrie 2008; Singh et al. 2006) and multiple herbicide resistances in wild oats (Singh et al. 2006). Wild oat (*Avena* spp.) has shown resistance in nine countries to one or more of Groups A, B, K, N and Z. Multiple resistance is found in Canada, South Africa, United Kingdom and USA.

8.4 Managing the Change in Weed Spectrum

A range of strategies can be used to manage the changes in the weed spectrum. These include: (1) development of new herbicides; (2) changing cropping methods including row spacing, diverse rotations and novel technologies to manipulate weed reproduction; and (3) using modelling for decision making in weed management.

8.4.1 Development of New Herbicides

There has been an expectation in the farming community that new herbicides will become available as required, i.e. when new weeds become important or when existing weeds develop herbicide resistance. However, discovery and release of new herbicide molecules is becoming more and more difficult and expensive (Rüegg et al. 2007). Estimates of research and development costs for each new active ingredient in plant protection, including all stages from initial synthesis to final commercialisation was around US$250 million by the mid 1990's, up from US$50 million in the mid to late 1970's (Rüegg et al. 2007). Lower figures are also quoted (Rao 2000) but may not include full costs of all stages of development. Nevertheless, costs of development continue to escalate in response to biological, environmental and regulatory constraints (Rao 2000; Rüegg et al. 2007). Thus, there is a growing realisation that the industry needs to optimise the use of available chemicals through combining a number of control measures in integrated weed management.

8.4.2 Changes in Cropping System Structure and Operation

Cropping systems can be manipulated to open additional opportunities for weed management. Some of the examples of this include:

8.4.2.1 Wider Row Spacing in Pulse Crops

Wider row spacing allows use of selective herbicides in the row only (over-the-row band application), to remove the weeds that are close to the crop and hence most competitive. Donald et al., (2004) showed zone herbicide application (ZHA) can greatly reduce application rates and input costs in maize. ZHA reduces herbicide use compared with conventional broadcast herbicide application by (1) banding low herbicide rates between corn rows (e.g. 80% of normal broadcast registered rate), (2) managing crops to favor crop competition, and (3) banding very low herbicide rates over crop rows (30% of normal rate). The best of trials averaged 53% of the normal broadcast herbicide rate.

The principles would apply to other crops, and be especially useful where very expensive herbicides are used. Research has shown that some of the pulse crops such as faba beans and chick peas grown under rainfed systems can be planted at wider row spacing and yet maintain or improve crop yield, provided weeds are controlled. Examples include chickpeas in USA (Corp et al. 2004), and in Queensland, Australia (Gentry 2009); faba beans planted in Western Australia (Reithmuller et al. 1998), South Australia (Kleeman and Gill 2008), and Jordan, (Thalji et al. 2006).Wide spacings used in these examples varied from 36 cm to 50 cm.

8.4.2.2 More Diverse Rotations

Diverse rotations allow use of a wider range of herbicides and cultural practices, which should prevent dominance by a single or few weed species, as can occur in monocultures. There is growing acceptance of the benefits of such strategies in cropping systems (Monaco et al. 2002). Diversity may be achieved through production of particular crops in alternate seasons, or by growing crops from different groups in sequence for example cereals, oilseeds and pulses. Growing a summer crop prior to a winter crop in north-eastern Australia leads to improved weed management in winter crops. Alternatively, moisture is conserved during winter through the use of non-selective herbicides for weed control during a fallow period prior to planting summer crops (such as sorghum, maize or sunflower), in spring or early summer. Production of both summer and winter crops is well established in north-eastern Australia and in other rainfed cropping areas with similar climate and soils, e.g. the Blackland Plains of Texas, USA, and parts of the Deccan in India.

8.4.3 Using Genomics in Weed Management

Genomics (use of molecular techniques for identification and functional analysis) is likely to have a positive effect on understanding of weeds and their management in various plant agriculture systems. Applications of genomics in weed science could include identification of genes involved in a crops' competitive ability. Genes controlling early crop shoot emergence, rapid early-season leaf and root development for fast canopy closure, production of allelochemicals for natural weed control, and resistance mechanisms, could be identified and used in plant breeding (Weller et al. 2001).

Genomics will allow determination the genetic composition of weed populations and how it changes over time in relation to agricultural practices. It will improve understanding of weed biology by determining which genes function to affect the fitness, competitiveness, and adaptation of weeds in agricultural environments and allow the development of improved management strategies (Weller et al. 2001).

Molecular control of plant reproduction is a rapidly developing field. Most of the research has been undertaken to understand the genetic controls over reproduction to enhance crop yields. However, it is possible to pose a different question – can we prevent reproductive success of weeds through manipulation of important genes involved in this process? In the future, the study of molecular genetics could help to minimise weed reproduction. Identification of key genes and proteins that regulate reproduction may allow development of chemicals that either stimulate or suppress expression of these genes thus giving a new way to suppress weeds (Weller et al. 2001).

8.4.4 Modelling and Decision Making in Weed Management

Developments in the capacity of computer hardware and software in recent years have made computer modelling available to the weed scientist. Models can be used to predict population dynamics of mixed weed flora, outcomes of crop-weed interactions, spatial dynamics (distribution) of weeds, spread and movement of weeds, and fate of herbicides in the environment. In addition, they can act as decision support systems (DSS) for various crop or farming systems. Such tools are able to help define the weed problem and optimise management strategies. Models are also available for the simulation of weed population dynamics (e.g. Kriticos et al. 2003). These are able to explore the potential impact of different management strategies upon the population dynamics of the weed, and predict the likely impacts of climate change. Models may be combined with other technologies, for example, precision weed control strategies, to provide an even more detailed assessment.

The basis of decision support systems for weed management in crops is the prediction of growth and development of the crop and weeds concerned, and the interaction of populations of each. DSS will predict the likely outcome on the basis of criteria provided by the user or built into it. Depending on the approach in the decision support model, competition for one or more plant growth resources – light, water, nutrients – may be assessed, and economic considerations may also be included. The model will then make a recommendation on appropriate control methods based on biological and economic grounds. Models can also be configured to provide advice on appropriate herbicides to use and details of application (Kropff and van Laar 1992, Lotz et al. 1993; Lutman et al. 2001; Parsons et al. 2009).

Other computer-assisted weed science tools are also becoming available. For example, a new method for plant identification has been adapted for the identification of the declared weeds of Australia. The system identifies a species using a limited number of simple morphological characteristics observable at any stage of the plant life cycle (Thorp and Wilson 1998).

Virtual plants are computer simulations of the structural (architectural) development and growth of individual plants in 3-dimensional space (Room et al. 1996) created from a model that contains rules for plant development. The 'virtual weed' can be used to try out management ideas before testing them in field experiments by simulating a range of environmental and other events, such as crop row spacing or pesticide application. The models allow land managers, policy makers and researchers to explore 'what if?' questions on the management of weeds. As more plant architectural models, particularly the recent functional structural models, become available, more sophisticated assessments will provide greater confidence in both the predictions and decisions generated. They will also help to maximise the effectiveness of pesticides and minimise off-target deposition of biocontrol agents (Birch et al. 2003; Dorr et al. 2006, 2007), and thus help to control costs and deliver improved economic and environmental outcomes. The use of modelling is further examined in Chap. 7.

8.5 Precision Weed Control

Traditional methods of weed control with blanket applications of herbicides over the entire field result in excessive use of the chemicals, with possible adverse economic and environmental impacts. As weeds generally grow in patches, herbicide usage can be substantially reduced by using site-specific herbicide application technologies (based on precision technologies discussed in this section) which can limit the application to weed-growing areas only (Medlin and Shaw 2000; Timmermann et al. 2003; Nordmeyer 2006). This minimises environmental risks (e.g. of ground and surface water pollution due to herbicide runoff and leaching) and can also slow the development of herbicide resistance (Oriade et al. 1996; Khakural et al. 1998). Site-specific weed management can be classified into two main systems – sensor-based and map-based.

8.5.1 Sensor-Based Systems

Sensor-based systems make use of optical sensors to identify weeds and apply herbicide instantaneously on-the-go, in one operation (Hanks and Beck 1998; Hummel and Stoller 2002). Present sensors can successfully differentiate between soil and vegetation and thus are suitable for weed control in fallow fields and row-crop production systems. However, new sensors are being developed which not only discriminate weeds from crop plants but also identify different weed species (Zhnag et al. 2006). These sensors will help in application of appropriate herbicides for different weeds within and between the rows. Hummel and Stroller (2002) found that savings of up to 80% in the amount of glyphosate used can be achieved in controlling weeds in corn and soybeans, using sensor-controlled herbicide applicators. For more details and practical application see Chap. 34.

8.5.2 Map-Based Systems

Map-based systems usually rely on prepared herbicide application plans and use sprayers controlled by a DGPS (Differential Global Positioning System) to apply herbicides to only those areas where weeds are present above economic threshold values (Gerhards and Oebel 2006).The weed density varies spatially in agricultural fields and economic threshold value refers to a minimum level of weed infestation that warrants herbicide application to give adequate return in additional crop yield. Weed maps are first prepared using remote sensing techniques (Lamb and Brown 2001; Thorp and Tian 2004; Shaw 2005); Geographical Information System (GIS) software is then used to prepare herbicide application plans based on the spatial variability of weeds in the field (Al-Gaadi and Ayers 1999). In a 4-year experiment conducted by Timmermann et al. (2003), an average saving of 54% in herbicide use was obtained for site-specific weed control on fields of wheat, barley, sugar beet and maize. Similarly, Nordmeyer (2006) found a significant reduction (>50%) in herbicide use over a 5-year period with site-specific weed control in winter cereals. For more details and practical application see Chap. 34.

8.5.3 Precision Mechanical Weed Control

Precision mechanical weed control is also gaining importance, because of concerns about the development of environmental contamination and herbicide resistance with prolonged use of the chemicals (Bond and Grundy 2001). In addition, high-precision guidance systems (±2 cm accuracy) for field machinery (Wilson 2000) allow inter-row cultivation closer to the intra-row strip. Innovative and precise cultivating tools are being developed to achieve both inter and intra-row weed control (Dedousis et al. 2007). Non-chemical weed control with intermittent use of mechanical cultivation, though not compatible with the use of no-till, may prove beneficial in slowing the development of herbicide-tolerant weed species.

Recent studies in Australia (Bromet 2006; Gupta et al. 2008) have shown that up to 90% weed kill can be achieved under wide-row cropping systems using a Real Time Kinematic Global Positioning System (RTK GPS) for controlled mechanical cultivation. Better weed control with less herbicide usage is also possible by combining mechanical and chemical weed control whereby inter-row weeds are controlled by mechanical cultivation and intra-row weeds are treated with herbicides (Mulder and Doll 1993; Hanna et al. 2000). The use of intermittent cultivation in combinations of mechanical and chemical control are not possible in no-till systems of production, but provide additional options in other crop management systems, potentially contributing to the extension of effective life of herbicides and maintaining benefits of reduced tillage.

Chapter 34 gives a detailed account of the use of precision agricultural techniques in a practical farm setting.

8.6 Conclusion

Weeds and weed management are important in all farming systems, their impact depending on the objectives and operation of the system. Soil moisture is critical in rainfed farming systems and given the potential for weeds to compete for water, weed control is of vital importance. Like most components of the system, appropriate management needs a holistic approach and consideration of the effect of control measures not only on the farm system but also on the wider environment.

Integrated weed management is based on the idea that weeds are less able to adapt to a farming system where a variety of control strategies are used. Traditional crop and crop-pasture rotations along with reducing seed production through hay cutting and crop topping are being used. However weed control science is investigating alternative methods of weed control such as biological control; use of cover crops to combat weeds by smothering or releasing alleotoxins; tillage and crop competition, as well as the development of new herbicides. There is growing concern that the rate of new herbicide discovery is not keeping pace with the rate of loss of use of herbicides because of the development of herbicide resistance in weed species. Herbicide selection decision aids can help in minimising the development of resistance.

Opportunities to maximise weed management opportunities include a careful assessment of crop and herbicide choice and of planting patterns and this may be assisted by weed and 'virtual weed' models.

Precision agriculture technologies may allow mechanical weed cultivation closer to crop rows and combinations of mechanical and over-the-row herbicide application. Application of molecular genetics to understand biochemical controls over weed reproduction may enable its selective manipulation in the future.

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Chapter 9
Principles and Methods for Sustainable Disease Management in Rainfed Agricultural Systems

David Backhouse and Thinlay

Abstract Plant diseases are a major constraint to productivity in rainfed agricultural systems. This chapter examines the nature of diseases in cropping systems, thresholds for management, major management tools, integrated disease management and the challenges for translating knowledge into practice. Inputs for disease management should be based on well-defined thresholds, but these are poorly developed for most diseases and regions. Disease management in rainfed agriculture relies mostly on alterations to crop husbandry and the use of resistant varieties; fungicide use is generally restricted to tactical application in higher value crops. Many tools such as rotation, nutrition and management of crop residues interact strongly with other components of the farm system and their effective use requires complex decisions. Much of the information required to give sustainable control of most crop diseases in rainfed agriculture is already known. There is a continuing need to convert this knowledge into forms that can be used for on-farm decision making, especially in traditional and marginal areas.

Keywords Pathogens • Fungi • Epidemiology • Thresholds • Quarantine • Residue management • Tillage • Rotation • Resistance • Tolerance • Fungicides • Biological control • Integrated disease management • Extension

9.1 Introduction

Plant diseases will be defined here as alterations to crop growth or physiology caused by infectious agents, or pathogens. The most important types of pathogens are fungi and other fungus-like organisms, nematodes, bacteria and viruses. Each of

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_9,

these has unique biological features which affect the way in which they interact with plants and their behaviour in the cropping system. The biology of the pathogens will not be dealt with here, but can be found in a standard textbook such as Agrios (2005). Most plant diseases are caused by fungi, and most examples in this chapter will be of fungal diseases.

Diseases affect most crops and pastures. Diseases become important considerations in the management of farming systems when they limit the ability of plants to use inputs efficiently or when they cause conflicts with the objectives of the system. This is mostly thought of in terms of reduced yield or economic value of the harvested product. However, when taking a systems approach, inter-relationships with other components of the system must also be considered.

By definition, water is a limiting resource in rainfed farming systems. Yield of grain or other harvested plant parts is a product of water uptake, water use efficiency and harvest index (Passioura 1977). Diseases can reduce the ability of plants to make use of available water by affecting each component of this relationship. Water uptake can be reduced by damage to the roots or vascular systems. Water use efficiency may be reduced by loss of biomass due to damage to above-ground parts of the plant, or increased soil evaporation if canopies are thinned. Harvest index can be reduced by mechanisms like damage to the flag leaf of cereals (Rees et al. 1981). Diseases are therefore a major constraint on the effective use of water resources, and disease management is a key tool for increasing efficiency of water use in rainfed agriculture (Turner 2004).

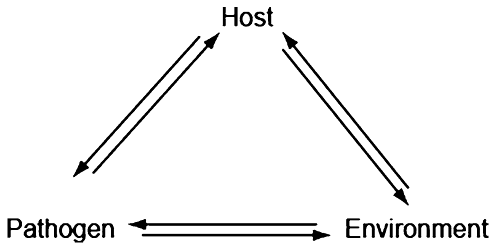
In many rainfed farming situations low or irregular rainfall often results in low yields and economic returns. This limits the level of inputs that individual farmers can afford to use to manage disease. On-farm options will tend to be restricted to those with the lowest direct monetary costs, or the lowest inputs of other resources such as energy or labour. However, large collective resources can be applied to disease management of major crops such as rainfed maize which in 2007 produced an estimated 784 million tonnes from 157 million hectares globally (Food and Agriculture Organization 2008). The most important of these disease control measures are selection and breeding of resistant and tolerant genotypes generally by national or international research and development organisations, such as the CGIAR[1] institutes.

For the typical rainfed farmer, responses to disease are mostly alterations to crop husbandry that must be integrated with other components of the farm system, together with the use of resistant genotypes when these are available. High-cost responses such as use of fungicides are restricted to low-volume, targeted applications such as seed treatment, or spraying of high-yielding and high-value crops.

This chapter will discuss the epidemiological basis of disease management, describe how each type of management tool is applied in rainfed systems, and then consider how disease management is integrated into the whole farming system.

[1] Consultative Group on International Agricultural Research (http://www.cgiar.org/).

Fig. 9.1 The disease triangle



9.2 Epidemiology and Management

The epidemiology of plant diseases is traditionally approached from the framework of the disease triangle (Fig. 9.1). This says that for disease to occur there need to be present a virulent pathogen, a susceptible host, and a suitable environment. Pathogens are usually present in most rainfed farming systems. In broad-scale cropping, for example cereals in commercial farming, inoculum of most pathogens present in a region can usually be found within most fields (Strausbaugh et al. 2004). Management involves manipulating the farm system to keep the populations of the pathogens, or their effects on the crop, below an economic threshold. For some diseases, it is possible to reduce the pathogen population directly. In most cases, disease management involves controlling host susceptibility, through choice of crop or genotype, or altering the environment, principally through crop husbandry (cultural) practices such as fallowing, rotation and removal of residues.[2]

Most diseases have an annual cycle linked to cropping cycles or environment. In rainfed agriculture, this may reflect the annual nature of crops or seasonality of rainfall or temperatures suitable for pathogen activity. The disease cycle can be divided into two main phases. The active, or parasitic, phase usually occurs during the growing season of the crop. Within this, there may be secondary disease cycles that allow the pathogen to spread from an initial point of infection to other parts of the plant or to other plants. The other main phase is the survival phase, which occurs when the host is absent or conditions are unsuitable for infection. This is typically during cold or dry seasons.

Plant diseases can be placed into two categories, depending on whether secondary cycles of infection occur during the growing season. The first is *monocyclic diseases* where there is no secondary spread and all infections start from inoculum present at the start of the epidemic. The amount of disease in the crop depends mostly on the quantity of primary inoculum (Vanderplank 1963). This is typical of soil-borne diseases such as Take-all in wheat or Fusarium wilt in chickpea. The second category is *polycyclic diseases*, where secondary cycles of reinfection occur during the season. The amount of disease in the crop will be more strongly influenced by the rate of spread within the crop than by the initial inoculum (Vanderplank 1963).

[2] Disease common names and the botanical names of their causal organisms are listed in a glossary at the end of the book.

This is typical of foliar diseases. Management tools differ in their effects on primary inoculum and on infection rate, which in turn determine their effectiveness against monocyclic or polycyclic diseases.

9.2.1 Thresholds for Management – When Should Something Be Done?

Thresholds for management of disease are usually defined as the level of disease above which the increase in value resulting from a management intervention is greater than the cost of management. This is most easily determined in monetary terms, but this may not always be the most appropriate way to determine thresholds, especially in subsistence farming or when key purposes of the farming system may not be expressed in economic terms. For example, removing pathogen inoculum by burning infested residues usually has a low direct cost compared with the value of its effectiveness against a variety of diseases. This would suggest a relatively low disease threshold before burning became economic. However, stubble burning has some undesirable effects such as loss of organic matter, soil structural decline, and increased risk of soil erosion (Chan and Heenan 2005). Though these effects are difficult to quantify their long-term outcomes (subject to discounting[3]) would probably require a much higher disease threshold. Recognition of this is one of the reasons why stubble burning as a disease control method has declined in many rainfed farming systems, such as cereal farming in Australia.

Management thresholds for polycyclic diseases are usually defined as levels of disease at a critical stage in the crop, or as environmental conditions that affect the infection rate, and help to decide when to apply fungicides (Eversmeyer and Kramer 1987). Such thresholds have been determined for major foliar diseases such as Ascochyta blights on legumes and rusts on cereals in many commercial agricultural regions in North America, Europe and Australia. Examples of such thresholds can be readily found in extension literature from these regions. However, these thresholds are not readily transferable to other regions because of the role of environment in disease expression and differences in the economics of production. For many diseases there has not been enough work done to define thresholds adequately. This means that, for most diseases in most rainfed farming systems, management decisions are based on intuition or past experience rather than a rigorously defined economic threshold.

For typical soil-borne diseases, the incidence of disease is dependent on the inoculum present at the start of the growing season. Management responses to soil-borne diseases also tend to be limited to measures that can be undertaken before sowing. This means that thresholds for intervention can be determined before the cropping season, based primarily on measurements of inoculum. For example, a

[3] See Glossary.

simple estimate of disease risk for the coming season for crown rot of wheat caused by *Fusarium pseudograminearum* in Australia can be obtained by monitoring yield and proportion of plants with symptoms in the previous wheat season (Backhouse 2006). For some diseases, inoculum estimation can be done by bioassays, such as those for cereal cyst nematode (Bonfil et al. 2004). In these, seedlings are grown in soil samples and rated for development of symptoms. More recently quantification of pathogen DNA has been used. In these systems, DNA is extracted from systematically collected soil cores, and highly specific probes are used to estimate populations of each pathogen of interest. The data are linked to epidemiological models that incorporate weather variables to refine risk categories (Roget 2001; Ophel-Keller et al. 2008). As with foliar diseases, the number of soil-borne diseases for which robust thresholds for intervention have been determined is still small.

9.2.2 Management Tools

9.2.2.1 Pathogen Exclusion

An obvious way to avoid disease is to keep the pathogens out of the crops. The best known way in which this is done is by quarantine on a national or regional scale. Most significant diseases of major crops of rainfed agriculture now have global distributions. However, there are still many diseases that are absent from many areas. The recent spread of sorghum ergot into the Americas and Australia (Bandyopadhyay et al. 1998) shows the potential for damage when pathogens are transported between continents. Karnal bunt of wheat, which is absent from Australia and Europe (Jones 2007), is a seed-borne disease whose global spread is currently controlled by quarantine. Broad-scale quarantine is usually the responsibility of national plant health agencies and is therefore external to the farming system.

On a field or farm scale, the feasibility of pathogen exclusion will depend on the dispersal ability of the pathogens. Soil-borne pathogens such as nematodes or vascular wilt fungi, which disperse only slowly, can be effectively excluded from areas within metres of inoculum sources by avoiding the movement of contaminated soil or plants. Local quarantine, including restricting movement of soil and plants, and rigorous hygiene of vehicles and footwear, is often used as a response to the emergence of new soil-borne diseases. These measures can never be completely effective but they do often slow the spread of an epidemic sufficiently to allow other control mechanisms to be brought in, such as the introduction of resistant varieties. Pathogen exclusion will only be useful for foliar pathogens if their effective range of dispersal is less than the distance between the protected crop and sources of inoculum. If even small amounts of inoculum do enter the crop, the high infection rate of most foliar diseases means that epidemics would develop within weeks if conditions are suitable. In Bhutan, Turcicum leaf blight of maize develops under cool, moist conditions even if no obvious sources of inoculum are present, so infection must occur from spores coming onto the farm from distant sources.

A very important method of pathogen exclusion is the use of disease-free planting material. This is used to control many seed-borne diseases, especially viruses, but is also effective against fungal and bacterial diseases such as common bunt and loose smut in wheat. Government or industry-sponsored seed certification schemes exist for many crops in large-scale commercial agricultural systems. These allow growers to exclude many pathogens, but certified seed usually has a price premium and this extra cost must be balanced against the risk of disease losses.

9.2.2.2 Cultural Methods

Cultural methods are alterations to the normal crop husbandry that reduce either the amount of disease or its effects on the plants. Most of them are directed towards the survival phase of the disease cycle, and therefore reduce the quantity of primary inoculum.

Residue Removal

Removal of infested residues directly reduces inoculum of pathogens which survive in crop debris. This includes *Fusarium* and leaf spot diseases of cereals and Ascochyta blights in legumes. Removal can reduce the incidence of infected plants in monocyclic diseases, or delay the onset of epidemics in diseases with high infection rates. Residues may be removed by burning, grazing, or harvesting for other uses such as straw. Smallholders in Bhutan routinely remove crop residues to use as feed or bedding for stock. However, it is not known whether feeding infected maize residues to cattle is effective in reducing inoculum of Turcicum leaf blight. While residue removal can be effective, it can have negative effects. Long-term burning of cereal residues reduces soil carbon and nitrogen levels and microbial activity, and increases erosion (Biederbeck et al. 1980). The decreased microbial activity can have a negative feedback effect by reducing soil suppressiveness to disease (see also Chap. 6).

Tillage

Tillage can be expected to have several effects on diseases, including burial of residues that are sources of air-borne inoculum, increasing the rate of decomposition of infested residues, damaging pathogen structures, and dispersing inoculum through the soil. Tillage may also have indirect effects on suppressiveness of soil to pathogens. With our current state of knowledge, predicting the effects of tillage on disease incidence or severity can be difficult to do from first principles and needs to be determined empirically for each disease.

Burial can have an effect on some foliar diseases such as *Pyrenophora* diseases of cereals (yellow spot of wheat, net blotch of barley) and Ascochyta blights of legumes such as chickpea which occur in all regions where these crops are grown. The pathogens causing these diseases typically survive in residues and produce a primary spore that is forcibly ejected into the air. Covering the residues with soil prevents the discharge of these spores and delays the onset of the epidemic. For example, Bockus and Claassen (1992) reported that mouldboard ploughing, which completely inverts the soil, significantly reduced the incidence of yellow spot in wheat.

Burial of residues enhances the rate of decomposition, which reduces survival of pathogens such as *Ascochyta* species (Davidson and Kimber 2007). However, this does not always lead to reductions in disease. Burgess et al. (1993) found that stubble incorporation had no effect on incidence of *Fusarium* crown rot of wheat compared with retaining residues on the surface, despite a large increase in rates of decomposition. They suggested that this was due to dispersion of residue fragments increasing the likelihood of contact between plants and inoculum. In western Canada, Gossen (2001) found that burial had little effect on the survival of *Ascochyta lentis* on lentil residue, and ascribed this to the harsh soil surface environment. Survival of some pathogens, such as sclerotia of *Sclerotium cepivorum*, the cause of white rot of onion, is actually enhanced by burial in soil (Coley-Smith et al. 1990).

Direct effects of tillage on pathogens are exemplified by root rots caused by *Rhizoctonia solani*, which are less severe in tilled than no-till soils in a wide variety of crops (Rovira 1986). Tillage mechanically disrupts the hyphae of the fungus during its survival phase (Roget et al. 1996). However, the tillage treatments that reduce Rhizoctonia root rot severity can increase incidence of common root rot in the same crop (Boer et al. 1991). This may be because tillage disperses spores of the causal agent, *Bipolaris sorokiniana*, more uniformly within the soil (Reis and Abrao 1983).

Crop Rotation

Crop rotation is one of the most widely used means of disease management. It works best with soil- and residue-borne diseases with limited dispersal. Essentially, it allows sufficient time between susceptible plants for the inoculum of the pathogen to decline through natural mortality to below an economic threshold. Growing a rotational crop rather than long-fallowing has benefits of an economic return. It may also stimulate biological activity in the soil and further reduce the survival of the pathogen, but there is as yet little evidence for this.

The most important factor in rotation is the time between host crops. This usually needs to be at least 2 years because of the longevity of inoculum of soil-borne pathogens, but may need to be even longer. Figure 9.2 shows a survival curve for inoculum of a typical residue-borne disease, crown rot of wheat, in the absence of susceptible hosts. This curve suggests that a break of 2 years between host crops would be necessary to give significant reduction in disease (Summerell and Burgess 1988). Wheat–sorghum rotations, in which the host (wheat) is grown every third

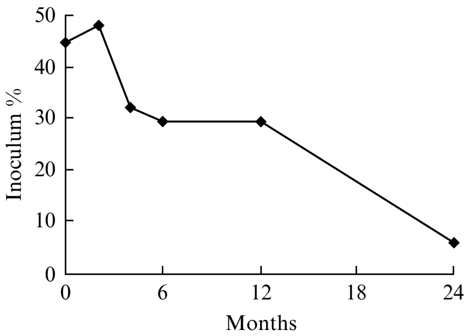


Fig. 9.2 Decline in inoculum of *Fusarium pseudograminearum* (Crown rot) in wheat stubble retained on the soil surface (From data of Summerell and Burgess 1988)

year, result in lower incidence of disease than wheat–chickpea rotations, in which wheat is grown every second year (Burgess et al. 1996; Kirkegaard et al. 2004).

Rotation is the most important disease management tool, but it is also the one with the strongest interactions with other components of the farming system. The choice of cropping sequence is rarely determined by the need for disease management alone. A significant constraint on rotation in many systems is the low availability of alternative crops, either because the environment is unsuitable or because they are unprofitable. This is especially the case for systems based on cereals, for which local and global demand is usually high. There may not be enough markets for alternative crops to allow every farmer to change to growing cereals only one year in three. Smallholders in marginal areas may also have limited options for rotation because the small size of farms or climatic limitations means they need to devote most of it to their major subsistence crop every year. Smallholders in Bhutan, for example, rarely rotate rainfed maize crops. However, they are able to gain some agronomic benefits by intercropping potatoes or grain legumes with the maize.

Weed Management

Weed management is critical to the success of rotations and many other disease management strategies. Weeds frequently act as reservoirs of inoculum for crop diseases, especially for biotrophic pathogens such as rusts which require green tissue for their growth and reproduction. The most troublesome weeds in many crops are those most closely related to the crop plant, such as grasses in cereal crops, as these are the plants most likely to act as alternative hosts. In-crop weeds have relatively little effect on most diseases because their biomass is small relative to that of the crop, and they therefore make only a small contribution to inoculum production.

Time of Sowing

Time of sowing can be used as a means of disease escape. This works best where the activity of the pathogen is constrained by a seasonal factor such as soil or air temperature.

For example, nematode eggs often hatch at specific times of the year defined by soil temperature ranges, and sowing susceptible crops before this can be beneficial. Cereal cyst nematode damage can be reduced by early sowing of wheat, allowing root systems to become established before hatching (Georg et al. 1989). However this can be offset by reductions in yield potential if wheat is sown before the optimum date for the variety (Georg et al. 1989). Sorghum ergot (*Claviceps africana*) infects sorghum ovaries only during the period between anthesis and fertilisation. Severity of the disease can be reduced by altering sowing date to make sure that the crop does not flower at a time when weather conditions are favourable for infection (Montes-Belmont et al. 2002). Sowing crops when soil temperatures are too low can make them more susceptible to damping-off and seedling diseases. This is especially noticeable with warm-season crops such as maize and sorghum where delaying sowing in spring to allow soil temperatures to rise improves plant establishment.

9.2.2.3 Nutrient and Water Management

The susceptibility of plants to disease is often affected by nutrient and moisture stress. This is generally due to a deficit of water or a key nutrient, but may also be due to an excess, especially of nitrogen. The management of water and nutrients are linked, in that sufficient nutrients must be provided to allow the plant to make the most efficient use of available water.

Many diseases are exacerbated by water stress because this increases susceptibility to infection and severity of symptom expression. For example, wheat seedlings become more susceptible to *Fusarium* crown rot under conditions of water stress (Beddis and Burgess 1992). The extent of stem browning and whitehead[4] formation, symptoms associated with yield loss, increases if the plants are water-stressed during grain fill (Cook 1980). Water supply cannot be manipulated in rainfed agriculture, but water demand can be – by choice of crops and varieties suited to available water and by altering row spacing and sowing rate.

The most important nutrient that affects disease is nitrogen. High levels of nitrogen can increase susceptibility to diseases such as stripe rust and *Septoria tritici* blotch in wheat (Ash and Brown 1991; Simon et al. 2003). On the other hand, nitrogen deficiency increases susceptibility of wheat to Take-all (Brennan 1992). High levels of nitrogen increase leaf area of many crops, which can lead to increased transpiration and early onset of moisture stress, thus increasing disease severity (Cook 1980). Nitrogen application therefore needs to be carefully balanced with crop needs.

Deficiencies of other plant nutrients, particularly calcium, manganese, zinc and silicon, have been associated with increased susceptibility to at least some diseases

[4] See Glossary for definition.

in a wide variety of crops (Dordas 2008). To date, the level of knowledge required to manipulate levels of nutrients other than nitrogen to manage diseases of field crops is generally lacking. However, in principle balancing nutrient supply to crop needs will minimise the risk of diseases.

9.2.2.4 Resistance and Tolerance

Resistance and tolerance are terms that are sometimes used interchangeably, but they have distinct meanings and importance in disease management.

Tolerance is the ability of a plant to grow and yield well despite being infected with the disease. It is a measure of the effect of the pathogen on the plant. For example, chickpeas are tolerant to root lesion nematode because the nematode has little effect on the crop despite causing extensive lesions on the roots. Varieties within crop species differ in their tolerance. Selection is rarely made for tolerance, except against nematodes and some other soilborne diseases. The opposite of tolerance is *sensitivity*.

Resistance is the ability of the plant to reduce the activity and reproduction of the pathogen. It is a measure of the effect of the plant on the pathogen. For example, a resistant plant may have smaller lesions caused by a foliar pathogen, and those lesions may produce fewer spores than on a susceptible variety. The opposite of resistance is *susceptibility*.

Types of Resistance

There are two basic types of resistance, known as *horizontal* and *vertical resistance* (Vanderplank 1963). Vertical resistance gives a high degree of resistance against some, but not all, races of a pathogen. In the most effective cases, such as many of the resistance genes to wheat stem rust (McIntosh et al. 1995), the reproduction of the pathogen is almost completely stopped by vertical resistance. Vertical resistance is due to individual identifiable resistance genes, making it easy to use in breeding programs. However, it is prone to breakdown because it can usually be overcome by single gene mutations in the pathogen. Typically it only takes a few years after a new resistance gene is introduced into a crop variety before a mutant arises in the pathogen population that is no longer affected by it.

Vertical resistance is introduced into crops by breeding. Surveys are made of pathogen populations to determine which resistance genes will be effective. These may come from varieties, landraces or wild relatives of the crop. A variety with the required resistance gene is crossed with an agronomically desirable variety, and then progeny with the resistance gene are backcrossed for several generations to the desirable parent. The result is an agronomically acceptable variety with the resistance gene. This process must be repeated continually to keep up with changes to the pathogen population.

The best-known example of the deployment of vertical resistance in rainfed agriculture is against rusts of wheat. There are three diseases, stem rust, caused by *Puccinia graminis* f.sp. *tritici*, leaf rust, caused by *P. triticina*, and stripe (or yellow) rust caused by *P. striiformis* f.sp. *tritici*. A large number of resistance genes have been identified in wheat varieties for each of these diseases (McIntosh et al. 1995).

Horizontal resistance is incomplete resistance to all races of a pathogen. This means that it does not stop the pathogen from colonising the plant and reproducing, but slows it down and therefore decreases the infection rate. Its effectiveness does not depend on the genotype of the pathogen, but is equally effective against all individuals of a pathogen species. Horizontal resistance is controlled by multiple genes, and is best thought of as a high level of the normal defence mechanisms of the plant.

Because horizontal resistance is due to many genes operating together it is difficult to breed for using classic breeding techniques, which target single genes. The level of horizontal resistance can be increased in a crop species by several generations of selection for the individuals that perform best in the presence of the disease. Although horizontal resistance does not give complete control, it generally does not break down so a variety will retain its level of horizontal resistance indefinitely. Unfortunately, modern breeding techniques have actually led to a decline in horizontal resistance in many crops compared with traditional varieties or wild ancestors (Vanderplank 1963). There is renewed interest in using recurrent selection to increase horizontal resistance, especially in legumes (Cowling 1996).

Where disease resistance is available, it tends to be widely adopted in broadscale commercial farming. In many cases, the use of resistant varieties is mandated; in parts of Australia at highest risk from wheat stem rust, only resistant varieties are approved for planting. The number of varieties with resistance to any particular disease is generally small, and these are most easily adopted in areas where environmental and agronomic conditions are relatively uniform over large areas, such as the lowland cropping areas on most continents. Development and adoption of resistance is more problematic in heterogeneous environments such as hill country. For example, in Bhutan rainfed maize is grown over an altitudinal range from 200 to 3,000 m above sea level, with a corresponding wide range of temperature, rainfall and soil type. Smallholders grow locally adapted outcrossing varieties. While resistance is available for the major disease problems like *Turcicum* leaf blight, there is an enormous challenge in deploying this in the diversity of locally adapted varieties that are required.

9.2.2.5 Fungicides

Fungicides are a relatively high-cost management tool for rainfed agriculture. In broad-scale commercial agriculture, the intrinsic cost of the chemicals and the energy (fuel) costs of application are the main constraints on their use. For smallholders in marginal areas, the cost and availability of application equipment may also be prohibitive. Fungicides therefore tend to be used only in situations where yield potential is high.

Fungicides are generally of limited use against soil-borne diseases in rainfed agriculture, except to protect the seedling and young plant from damping-off and other infections early in crop growth. It is rarely practical to apply enough fungicide into the soil to protect the root system of mature plants. However, applying fungicide to seeds or within the planting furrow allows protection of emerging seedlings at low rates of application. Most fungicides are used against foliar pathogens. It is important to remember that fungicides rarely give complete control of diseases; they slow down the rate at which epidemics develop.

Fungicides in rainfed agriculture are usually used as protectants which must be applied prior to infection. Most protectant fungicides are applied so that they form a continuous layer over the plant surface and inhibit spore germination and penetration of the plant surface. There are many protectant, non-systemic fungicides that have been developed in the last 50 years. Some of the more important of these are thiram, used as a seed treatment to control damping off in crops like maize, and chlorothalonil, zineb and mancozeb, which are used for protection against foliar diseases including *Ascochyta* blight in chickpeas and other legumes. Resistance is not expected to develop to any of these compounds because they have multiple sites of action at the biochemical level.

Newer types of protectant fungicides may be *systemic*, that is they are absorbed by the plant tissue and translocated within the plant. Systemic fungicides usually give better protection than non-systemics, especially in expanding leaves. The largest and most important group of systemic fungicides is the demethylation inhibitors (DMI). Examples are triadimenol, propiconazole, prochloraz and flusilazole. This group is the one most widely used against rusts and leaf spotting diseases in cereals.

Chemical control can also be used against other pathogens. There are no chemicals that are active against plant viruses; however, insecticides can be used to reduce vector populations. Antibiotics are not generally used against bacterial plant diseases. Copper fungicides also tend to have antibacterial properties, but are used more in horticulture than in rainfed agriculture.

Nematodes may be controlled by organophosphates and carbamates such as fenamiphos and aldicarb. However, nematicides tend to have much higher mammalian toxicity than related insecticides. These chemicals do not actually kill the nematodes, but temporarily inactivate them. The nematodes resume normal activity once the chemicals dissipate. In practice, nematicides are used extensively in only a few high-value crops such as tomatoes.

9.2.2.6 Biological Control

Biological control of diseases is not as well developed as for insects or weeds. There are few biocontrols used on a large scale in commercial practice, and most of these are restricted to horticultural crops (Fravel 2005). A huge amount of research effort has gone into identifying potential biocontrol agents for field crops and determining the parameters that influence their effectiveness. One of the best-known examples is that of fluorescent *Pseudomonas* species which have been implicated in natural suppression of take-all in wheat (Weller 2007). Despite three decades of research, this has yet to be commercialised. Research continues on the development of specific biocontrol agents, and some more examples may be expected to enter commercial use in the mid-term future.

The most promising avenue for biocontrol of diseases is exploiting the natural suppressiveness of soil to pathogens. This has been done in traditional agriculture for centuries through practices such as manuring, which increase soil biological activity. Most work in this field has concentrated on adding organic amendments, especially those high in nitrogen. These act by various mechanisms, including liberation of toxic levels of ammonia and stimulation of the soil microflora (Bailey and Lazarovits 2003). The large-scale adoption of this practice is limited by the availability of the material required, which usually needs to be added at several tonnes per hectare to be effective. Agricultural wastes obtained from off-farm also represent a transfer of carbon, nitrogen and other nutrients out of the source farming system.

Retaining crop residues also increases suppressiveness to diseases. This has been demonstrated for take-all in wheat (Donovan et al. 2006) and for nematodes in sugarcane (Stirling et al. 2005) among others. This is likely to be a general phenomenon but has not been widely reported because of technical difficulties in separating suppressiveness from confounding effects in most experiments. The effect is masked in the short term by the increased inoculum present in the residues, but when combined with rotation, residue retention makes a valuable contribution to disease suppression in the long term (see also Chap. 6).

9.2.2.7 Bringing It All Together – Integrated Disease Management

All management tools aim to reduce populations of pathogens or their effects to below economic thresholds, but they rarely eliminate them. Some loss to disease is inevitable within the constraints of the farming system. Management of most diseases in most farming systems is, and always has been, by integrated management practices. The use of fungicides or other chemicals is generally secondary to the use of cultural practices and selection of genotype (resistance and tolerance).

An integrated approach to disease management in a rainfed farming system based on annual crops would take the following form:

- Crop rotations used to reduce populations of soil- and residue-borne pathogens.
- Crop residues retained to maintain soil structure and organic carbon levels, and to ensure a high level of microbial activity for disease suppression.
- Crops sown at an optimum time to reduce seedling diseases and damping-off consistent with good emergence and establishment.
- Where disease risk is high, varieties selected with the highest levels of resistance and/or tolerance that could be traded off against other desirable characteristics.
- Sowing with high-quality seed, preferably from clean or certified sources and treated with fungicides if necessary.

- The sowing rate chosen to optimise use of available water and maintain competitiveness with weeds, but avoiding risk of late-season water stress.
- Inputs of nitrogen and other essential nutrients balanced against anticipated crop demand (and water use) to avoid increased susceptibility due to deficiencies or to excess nitrogen.
- Tactical sprays of fungicides used against foliar diseases when disease or environmental parameters reach a threshold that suggests an economic benefit from spraying.
- The crop harvested in a timely fashion and stored appropriately to avoid post-harvest spoilage.

This sounds like a common-sense approach to crop management, and it is. With the exception of fungicide use, it is also a description of the way in which farming systems that have proved sustainable over centuries have been managed. However, as stated, it is not a foolproof guide to avoiding losses from diseases under all conditions. Climatic variability, the introduction of new pathogens, and changes in economic circumstances may force rapid responses to diseases in ways that would not normally be considered sustainable. These include burning after severe outbreaks of residue-borne diseases, or soil fumigation to eradicate quarantine incursions. Integrating disease management principles into all aspects of the farming system will increase the effectiveness of any emergency responses.

The goal of all longer-term responses to changing disease situations is to manage them within an integrated framework (Davidson and Kimber 2007). For example, *Ascochyta* leaf blight diseases of legumes including lentils, chickpeas and field peas have increased in importance in North America, India and Australia as more legumes are used in rotation with cereals, and as pathogens have spread. The response has been to develop integrated management programs based on seed health, residue management, rotation, resistant varieties, and tactical fungicide applications (Davidson and Kimber 2007).

9.2.3 The Role of Information in Disease Management

The general principles of integrated disease management are easy to understand, but their effective implementation requires a large amount of specific information, from nutrient requirements of crop species to economic thresholds for fungicide application. This usually has to be adapted for local or regional use because of environmental differences. Modern commercial agriculture is supported by an extensive research and extension infrastructure for the major crops, and a large amount of high-quality information is available to growers in developed and many developing countries. Despite this, diseases remain a problem and many farmers do not adopt best practice for their management. Common examples of sub-optimal practice are growing varieties with inadequate levels of resistance, failing to rotate, or applying fungicides at the wrong time. In part, this results from the sheer volume of information available, and the complexity of the decisions that need to be made.

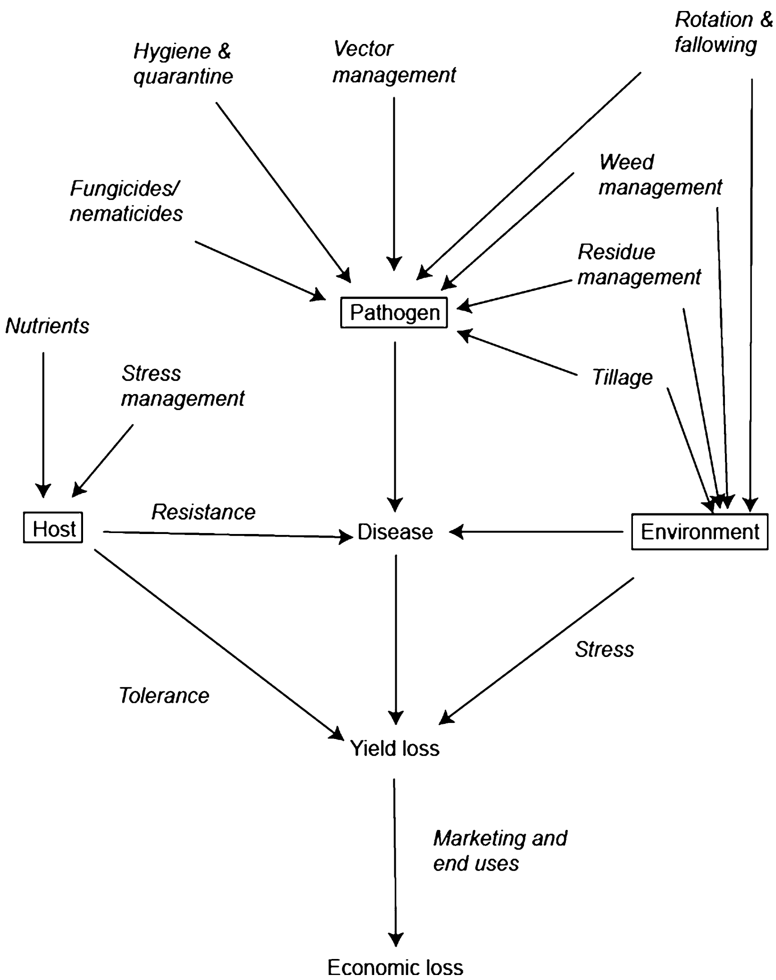


Fig. 9.3 Interactions between disease management tools (italics), components of the disease triangle (Host, Pathogen, Environment), yield loss and economic loss

Figure 9.3 shows some of the interactions between disease management tools and the components of the disease triangle, leading to crop loss and economic loss. The farm manager needs to consider all of these interactions, as well as interactions with other aspects of the farming system such as animals, insect pest and weed control, labour and energy inputs.

A wide range of technologies have been developed to bridge the gaps between information and decisions, from simple paper-based guides to computerised decision support systems (Newton et al. 2006). None of these has proved completely satisfactory for all users, reflecting both inherent weaknesses in each technology and the diversity of ways in which individuals make decisions and assess risks.

While farmers in developed countries are generally sufficiently well educated to be able to understand the information they are being provided with, this is not always the case in developing/subsistence agriculture or poorer areas. Bentley and Thiele (1999) reviewed the literature on the knowledge of plant diseases by traditional people. Many of the traditional practices were found to be extremely effective at disease management, but many of the studies also showed important gaps in knowledge. Traditional farmers were frequently unaware of the microbial nature of plant pathogens, were unable to distinguish between diseases caused by different types of pathogens, or did not understand the epidemiology of diseases, such as insect vectoring of many viruses. These gaps in knowledge could be expected to limit the farmers' ability to make best use of new disease management technologies, or to manage diseases of newly introduced and therefore unfamiliar crops.

There are several approaches that can be taken to overcome the knowledge gap. In Bhutan, a network of extension agents is posted throughout the country. Whenever farmers observe a problem, they report it to the extension agents who are trained to give advice on management. Problems that are too difficult for the extension agent are referred to the nearest research or plant protection centre. An alternative approach empowers the farmers by involving them in experiments which compare integrated management to conventional practice. This can be done at a farmers' field school in a central location, as has widely been practiced for Asian rice farmers, or by participatory research on the farmers' own holdings, as has been done for potatoes in Peru (Nelson et al. 2001).

To a large extent, the scientific community already knows most of what is needed to give a reasonable level of control of most crop diseases of rainfed agriculture. Continued research will improve effectiveness and sustainability, and keep abreast of changes in pathogens and cropping systems. The biggest challenge in making a real difference to farmers and their communities is in improving the ways in which all of this information is translated into effective day-to-day decision making.

9.3 Summary and Conclusion

Sustainable disease management implies that both (1) the management tools themselves are sustainable, and (2) disease management contributes to the sustainability of the system. Plant diseases are a significant constraint on production in rainfed agriculture because they affect the ability of crops and pastures to make use of available water. The low yield and value of most rainfed crops limits the inputs that can be used for disease management at the farm level. It is possible to exclude some diseases from farming systems but, for most, the aim of management is to reduce the populations of pathogens or their effects to a level that allows the commercial or subsistence goals of the system to be met.

Traditional practices of crop rotation, residue management, adequate nutrition, reducing plant stress and using locally adapted varieties that have been selected for disease resistance still form the core of sustainable disease management in rainfed agriculture.

For major crops, large global production has enabled cooperative development and deployment of resistance to many diseases. Newer tools such as fungicides have been added as options for tactical responses to disease. In some cases, these have not been sustainable as fungicide resistance has developed. There is often a trade-off between disease management tools, such as rotation and choice of varieties, and other desirable agronomic practices. A systems approach requires that disease management is not considered as an isolated component, but is integrated with the other components of the farming system.

Global changes in climate, crops and the spread of pathogens present new challenges for disease management. There is a need for more work to define thresholds for management for major diseases, especially in areas where there are strong regional differences in environment and farming systems. The principles of integrated disease management and much of the base knowledge for major diseases are well known. There is a continuing need to convert this knowledge into forms that can be used for on-farm decision making, especially in traditional and marginal areas.

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Chapter 10
Sustainable Pest Management in Rainfed Farming Systems

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Abstract Insect pests are estimated to cause losses of 16% to world attainable crop production with post-harvest losses another 10%, in spite of widespread use of pesticides. Losses due to pests have been estimated for key rainfed crops in different regions of the world. Pest species attack every phenological stage of crop growth; sometimes they are the same species and sometimes different. No one tool can be used to successfully control a pest; integrated pest management principles have been widely adopted and include determining the economic threshold at which control is cost effective. Chemical control is widely used but excessive use can cause resistance in the insect and adverse environmental effects. The enhancement of use of natural enemies of pest insects, and use of crop cultivars resistant to the insects are both very important. Crop management practices used to reduce the impact of pests include crop rotations, intercropping, sowing rates, sowing time and soil tillage. Management of pests requires growers to understand the interactions between the pests and crops in their regions and to use the most appropriate tools to reduce the potential damage. While no one system would be applicable to a crop or to a pest in all rainfed farming systems, some general principles are relevant across regions.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_10,

Keywords Insect pests • Crop losses • Nature of damage • Integrated pest management • Economic threshold • Chemical control • Biological control • Crop complexity

10.1 Introduction

Global productivity of all crops has increased five-fold over the past five decades. High-yielding varieties, irrigation, fertilisers and pesticides have delivered rapid economic growth and also reduced poverty (Lenne 2000) in countries with access to these resources. However, the expanding human population and degradation from more intensive production has resulted in a decrease in per capita availability of arable land (Dyson 1999). While developed countries have adequate food supplies, many developing countries, particularly in Africa, do not have adequate food, and many people suffer from malnutrition (Weber 1999). One practical way of increasing crop production is to minimise the losses from pests. Oerke et al. (1994) estimated that more than 42% of the total attainable production for eight major crops is lost due to pests – 16% due to insects, 13% due to diseases and 13% due to weeds. Post-harvest losses in grains are a further 10%. The total value of losses due to all pests (the difference between attainable production and actual production) is estimated to be $578 billion annually, and this occurs despite the application of pesticides valued at $30 billion annually (Crop Protection Compendium 2004).

10.2 Losses in Value of Production and in Yields Due to Pests Across Regions and Crops

Losses in value of attainable production due to animal pests, pathogens and weeds vary regionally; in Africa and Asia losses are estimated at around 50%, in Oceania 36%, and in North America and Europe at around 30% (Oerke 1994). The average dollar value of the economic losses caused by animal pests is 12% in the five crops for the regions considered to have substantial rainfed agriculture and for which data are available (Table 10.1). When the data are expressed as yields (kg/ha), the difference in actual and potential yield losses are similar for wheat, barley and soybean, but for maize and oilseed rape, potential losses due to insects are far greater than the actual losses; and pests are a greater threat to production in maize and oilseed rape (Table 10.2). Grain stored after harvest is infested by pests unless protected. Chickpea storage losses from the bruchids, *Callosobruchus chinensis* and *C. maculatus,* can range from 7% to 70% in Syria, and from 24% to 100% in Jordan (Clement et al. 1999). There are clearly substantial benefits to be obtained from maintaining and improving pest management in rainfed farming systems.

Table 10.1 Actual crop losses caused by animal pests (invertebrates and vertebrates) in relation to actual crop production (arranged by regions) (Reproduced from the Crop Protection Compendium (2004). ©CAB International, Wallingford, UK)

	Value ($US M) of actual production and losses from animal pests									
	Wheat		Barley		Maize		Soybean		Oilseed rape	
Region[a]	Production	Losses	Production	Losses	Production	Losses	Production	Losses	Production	Losses
North America	7,958	1,000	1,249	89	23,888	1,967	11,977	1,130	1,016	120
Southern South America	2,246	783	92	7	5,625	914	12,549	1,538	14	1
North Africa	1,426	178	217	31	646	80	2	0	14	1
Southern Africa	246	28	12	1	962	206	44	6	0	
Southern Europe	1,595	137	742	62	1,749	160	117	3	7	0
European CIS	6,048	1,019	2,146	230	577	119	74	12	46	7
Near East	4,256	542	878	92	384	60	32	4	0	
South Asia	9,889	1,002	119	12	1,533	474	967	240	823	165
Asiatic CIS	2,351	387	235	25	126	27	2	0	1	0
East Asia	9,809	934	301	25	11,299	1,440	2,736	425	2,006	306
Oceania	1,989	264	463	54	56	6	12	0	236	35
Total	47,714	6,274	6,454	628	46,845	5,453	28,512	3,358	4,163	635

[a]See end-note for countries in regions

Table 10.2 Actual and potential crop losses due to animal pests (invertebrates and vertebrates) in relation to actual and potential crop yields across regions and crops (Reproduced from the Crop Protection Compendium (2004). ©CAB International, Wallingford, UK)

		Actual production (kg/ha)		Attainable production (kg/ha)	
Crop	Region	Yield	Loss	Attainable yield	Potential loss
Wheat	Oceania	1,629	216	2,494	238
Barley	European CIS	2,076	223	3,219	213
Maize	North America	8,397	691	10,769	1,688
Soybean	South America	2,677	328	3,628	353
Oilseed rape	East Asia	1,494	228	2,160	402

10.3 Insect Pest Damage

Although damage is the result of insect feeding, it may appear some time after the feeding has occurred. Larvae of the scarab, *Sericesthis nigrolineata*, feed on the roots of perennial ryegrass (*Lolium perenne*), but leaf production is reduced only when the plants are also grazed. Despite feeding by high densities of larvae, patches of dead grass are not seen until the plants are water-stressed – which may be long after the larvae have fed on the roots (Ridsdill-Smith 1977).

Insects feeding on leaves may cause plants to produce fewer pods; yellow lupins (*Lupinus luteus*) attacked by the redlegged earth mites, *Halotydeus destructor,* at the seedling stage produce smaller mature plants with a lower seed yield (Liu et al. 2000). However, some plants can compensate for insect feeding by producing more pods (Tingey 1981); chickpea and pigeonpea produce extra pods to replace those damaged by the cotton bollworm/legume pod borer, *Helicoverpa armigera*, feeding (Srivastava and Srivastava 1989). Strategies to reduce damage require an understanding of the plant–insect interactions.

10.4 Regional Differences in Pests Causing Damage

Every phenological stage of the crop is attacked by a suite of pest species which are different in each region (Tables 10.3–10.7). Pests of crop seedlings include mites, wireworms, weevils and cutworms. Several noctuids and leaf miners feed on leaves; pyralids, Hessian fly, sorghum shoot fly and aphids feed on shoots whereas wireworms, termites, and larvae of scarab beetles and weevils are root feeders. Pests of green pods/grain include budworm, pod borers, pod-sucking bugs, sorghum midge and pea weevil, while the post-harvest pests are mainly beetles, in particular *Callosobruchus, Tribolium, Rhizopertha, Trogoderma*.

An insect species may become a pest in a region as a result of the introduction of new crops or plants. In Australia, several species have become pests of pastures

Table 10.3 Some economically important insect pests of rainfed crops in Australia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Redlegged earth mite	*Halotydeus destructor*	Pasture legumes (Pavri 2007)
			Canola (Berlandier and Baker 2007)
			Cereals (Hopkins and McDonald 2007)
Leaves and stems	Common armyworm	*Leucania convecta*	Cereals (Hopkins and McDonald 2007)
	Diamondback moth	*Plutella xylostella*	Cruciferous crops (Berlandier and Baker 2007)
Roots	Redheaded pasture cockchafer	*Adoryphorus couloni*	Pasture grasses (Pavri and Young 2007)
	Sitona weevil	*Sitona discoideus*	Pasture legumes (Pavri 2007)
Green pods and seeds	Corn earworm and native budworm	*Helicoverpa armigera* and *H. punctigera*	Grain legumes and cereals (Miles et al. 2007; Fitt 1989)
Dry post-harvest seeds	Lesser grain borer	*Rhyzopertha dominica*	Stored grain and cereal products (Emery 2000)
	Rust red flour beetle	*Tribolium castaneum*	Cereal products (Emery 2000)

Table 10.4 Some economically important insect pests of rainfed crops in North America

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Wireworms	*Ctenicera destructor*	Wheat (Oerke 1994)
Leaves and stems	Fall armyworm	*Spodoptera frugiperda*	Maize (Oerke 1994)
	Corn earworm	*Helicoverpa zea*	Cereals (Oerke 1994)
	Greenbug	*Schizaphis graminum*	Sorghum (Smith et al. 1999)
Roots	Corn rootworms	*Diabrotica* spp.	Maize (Oerke 1994)
Green pods and seeds	Hessian fly	*Mayetiola destructor*	Wheat (Smith et al. 1999)
	Pea weevil	*Bruchus pisorum*	Peas (Clement et al. 2000)
	Sorghum midge	*Stenodiplosis sorghicola*	Sorghum (Sharma 1993)
Dry post-harvest seeds	Bruchids	*Callosobruchus* spp.	Grain legumes (Sharma et al. 2007a)

following the introduction of exotic grasses and legumes and changes in management (Panetta et al. 1992). Host identification by post-harvest grain pests occurs with the flowers. For example, *Bruchus lentis* requires pollen and nectar of the lentil, *B. dentipes* requires the pollen and nectar of the faba bean, whereas *B. pisorum* produces eggs most readily when fed on pea pollen (Clement et al. 1999).

Table 10.5 Some economically important insect pests of rainfed crops in West Asia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Sitona weevil	*Sitona crinitus*	Lentils (Beniwal et al. 1993)
Leaves and stems	Cereal bug	*Aelia rostrata*	Cereals (Oerke 1994)
	Leaf miner	*Liriomyza cicerina*	Chickpeas (Clement et al. 1999)
Roots	Sitona weevil	*Sitona lineatus*	Faba bean, Peas (Clement et al. 2000)
Green pods and seeds	Pea weevil	*Bruchus pisorum*	Field peas (Clement et al. 2000)
		B. dentipes	Faba bean (Clement et al. 1999)
Dry post-harvest seeds	Bruchids	*Callosobruchus chinensis* *C. maculatus*	Grain legumes (Clement et al. 1999)

Table 10.6 Some economically important insect pests of rainfed crops in South Asia

Plant stage	Common name	Latin name	Plant attacked
Seedlings	False wireworms	*Gonocephalum* spp.	Chickpea (Sharma et al. 2007a)
	Sorghum shoot fly	*Atherigona soccata*	Sorghum (Sharma 1993)
Leaves and stems	Stalk and stem borers	*Chilo partellus*	Maize (Sharma and Ortiz 2002)
		Sesamia inferens	Sorghum (Sharma 1993)
	Oriental armyworm	*Mythimna separata*	Cereals (Sharma 1993)
Roots	Termites	*Odontotermes obesus* *Microtermes* sp.	Chickpea (Sharma et al. 2007a)
Green pods and seeds	Pod borer	*Helicoverpa armigera*	Chickpea, pigeonpea (Clement et al. 2000; Sharma and Ortiz 2002)
	Sorghum midge	*Stenodiplosis sorghicola*	Sorghum (Sharma 1993)
Dry post-harvest seeds	Bruchids	*Callosobruchus chinensis* *C. maculatus*	Grain legumes (Clement et al. 2000)

Seasonal climatic factors also influence the occurrence and abundance of pests in a region. Some have resting stages to overcome adverse seasonal conditions. The mite, *H. destructor,* is winter-active and undergoes a summer diapause to avoid a hot dry summer (Ridsdill-Smith et al. 2005), whereas *H. armigera* is summer-active and has a winter diapause to avoid a cold wet winter (Fitt 1989). Species present in a region may attack only one of the crops present, or may cause damage only at certain times of the year. Knowledge of the biology of individual species is required for planning appropriate control measures.

Table 10.7 Some economically important insect pests of rainfed crops in East and southern Africa

Plant stage	Common name	Latin name	Plant attacked
Seedlings	Cutworms	*Agrotis* spp.	Most crops (Van den Berg and Drinkwater 1999)
	Redlegged earth mite	*Halotydeus destructor*	Pasture legumes and cereals (Prinsloo et al. 1999)
Leaves and stems	Maize stalk borer	*Busseola fusca*	Maize (Van den Berg and Drinkwater 1999)
	Russian wheat aphid	*Diuraphis noxia*	Cereals (Prinsloo et al. 1999)
Roots	Termites	*Microtermes* spp.	Annecke and Moran (1982)
	Black maize beetle	*Heteronychus arator*	Prinsloo et al. (1999)
Green pods and seeds	African bollworm	*Helicoverpa armigera*	Rainfed crops (Prinsloo et al. 1999)
	Sorghum midge	*Stenodiplosus sorghicola*	Prinsloo et al. (1999)
Dry post harvest seeds	Maize beetles	*Sitophilus* spp.	Maize (Oerke 1994)

10.5 Integrated Pest Management

It is seldom that a single tool can be used to successfully control a pest. More commonly, growers need to apply a combination of tools including chemical control, biological control and cultural control. The most effective control is achieved with chemical insecticides. However, in many cases, the use of chemicals is not economically viable, and the repeated use of the same chemical year after year is not biologically sustainable because it leads to non-target environmental impacts and development of resistance to chemical pesticides in the pest population. The approach of using multiple tactics to manage pests is called *Integrated Pest Management* (IPM). IPM "is a decision support system for the selection and use of pest control tactics, singly or harmoniously coordinated into a management strategy, based on cost-benefit analyses that take into account the interests of and impacts on producers, society and the environment" (Kogan 1998). Chemical control and biological control are principal tools in the IPM toolbox that can be integrated into a sustainable production system. However, many interactions occur between the individual elements of an integrated control strategy, and this complexity, combined with the difficulty of correctly applying each element, has been a barrier to the adoption of integrated strategies by farmers (Orr 2003; Rodriguez and Neimeyer 2005).

10.6 Economic Thresholds

The economic threshold is the pest density at which a control tactic should be applied in order to both minimise yield losses and cover the cost of control. Economic thresholds, where controls are applied only when the pest population exceeds the threshold, are considered the keystone for implementing IPM strategies (Pedigo and Rice 2006). Effective use of thresholds requires active monitoring of pest populations. Monitoring is achieved mostly by visual observation, but also by counting the numbers of insects caught using methods such as a sweep nets, light traps, or traps baited with pheromones specific to the pest.

Economic thresholds vary with the species of insect and the crop. In Australia, control of pea weevil, *B. pisorum*, in field peas is proposed when there is more than one adult beetle per 10 sweeps; the control of native budworm, *Helicoverpa punctigera*, in field peas when there are more than 1–2 larvae per 10 sweeps, and the control of native budworm in chickpeas when there are more than 2–5 larvae per 10 sweeps (Miles et al. 2007). In India, economic injury levels are judged by visual assessments when there are 0.1–0.2 adults per panicle for sorghum midge (*Stenodiplosis sorghicola*) on sorghum (Sharma et al. 1993), or one larva per plant for the pod borer (*H. armigera*) on chickpea (Wightman et al. 1995).

The economic threshold will vary with phenology of the plant. Thus, the economic threshold for diamondback moth (*Plutella xylostella*) in Western Australian canola is 50 larvae per 10 sweeps in the pre-flowering plants, 100 larvae per 10 sweeps in mid-flowering plants, and 200 larvae per 10 sweeps in plants with mature pods (Micic 2005).

The threshold will also change with the level of resistance of a cultivar. The economic threshold of sorghum midge can vary by a factor of 10 between susceptible and resistant sorghum cultivars (Sharma 1993). Economic thresholds usually involve only a single pest in a system and do not consider the synergistic or antagonistic interactions between several pest species and with other pest organisms such as weeds or plant pathogens. In canola grown in western Canada, early weed removal is the promoted practice, but this increases the damage to canola caused by root maggots, which increases the need for insecticide application (Dosdall et al. 2003). Weekly scouting of wheat is advised in Australia since different pests attack the crop at different development stages (Emery 2000). Economic thresholds are determined using the direct costs of control, but they should also include non-target effects of pesticides on the environment, on human health, and on beneficial insects – which are harder to assess (Higley and Pedigo 1993). Although economic thresholds are not easy to use in practice, they do provide a useful guide to help growers make cost effective decisions about pest management and to integrate multiple tactics for control into the production system.

10.7 Chemical Control

The principle element of insect pest control is the use of chemicals, the main groups being the organophosphates, carbamates, and the synthetic pyrethroids. As chemicals are relatively easy to apply and the results usually immediate, the use of pesticides (in the widest sense) has increased ten-fold since 1970 (Dehne and Schonbeck 1999). It has been estimated that more than three-quarters of the world use of pesticides is in North America, Western Europe and Asia, but less than one third of all cropland in the world is treated with a pesticide (Dehne and Schonbeck 1999). In Australia, nearly all the sorghum crop, about 80% of canola and field peas, half of chickpea and lupins, and 16% of wheat and barley crops are treated with pesticides (Ridsdill-Smith 2002).

Forecasting and modelling have been used to improve the decisions on timing and need for chemical control of pests in crops (Apel et al. 1999; Clement et al. 2000). A model can optimise application time; for example, from the prediction of the onset of summer diapause in redlegged earth mite, a single spray can prevent development of the over-summering generation and provides good control of mites in the following autumn – 8 months later (Ridsdill-Smith et al. 2005). A relatively simple simulation model of *H. armigera* on pigeonpea, based on the flowering phenology of the crop, has been developed to optimise insecticide use (Holt et al. 1990). Nietschke et al. (2007) have developed a database of temperature development requirements for 500 insect species for use in decision support systems in pest management.

No insects are permitted in grain exported from Australia, and this is maintained by inspection and fumigation. Virtually all grain that is exported is therefore treated with insecticides, and restrictions are in place to help manage pesticide residues in grain and to avoid the development of resistance to insecticides (Emery 2000).

While repeated applications of pesticides may kill the pests effectively, they can also leave harmful residues in the food, cause adverse effects to non-target organisms and the environment, and may lead to the evolution of resistance in pest populations. Once a resistance gene is present, it increases in frequency in the population every time that pesticide is applied to the progeny of the same insect species, even if the insects are on different crops grown in rotation. Resistance to one insecticide may also confer cross-resistance to other insecticides, particularly where these insecticides have similar modes of action; i.e. they inhibit insect biochemistry in a similar way. Following repeated applications over several years, if there is a period of several generations when the insecticide is not applied to the progeny of the resistant pest, then the frequency of resistant alleles in the population will be expected to fall, and resistance will not continue to develop. Approximately 500 arthropod species have developed resistance to at least one pesticide, and some key pest species are resistant to nearly all of them (Devine and Denholm 2003). The likelihood of developing insecticide resistance in a pest population is reduced if compounds with different modes of action are used alternately to control pests, and if repeated use in the same field of a particular insecticide is avoided.

Many plants are naturally resistant to insect pests because they possess chemical defences to attack from insect pests. In India, natural plant products, such as the leaves of the neem tree (*Azadirachta indica*), are used in on-farm grain stores to reduce damage by insect pests (Shanker and Parmar 1999). Some of these compounds have been identified as potential insecticides. The insecticide pyrethrin, for example, is derived from plants of the genus *Chrysanthemum*. Although a number of plant products, such as azidirachtin from neem, and compounds from the custard apple (*Annona reticulata*), are considered safer than conventional insecticides

(Shanker and Parmar 1999), the chemical structures of these compounds are very complex, and it is not feasible or cost-effective to synthesise and produce them on a commercial scale.

10.8 Biological Control

A large number of parasites, predators, bacteria, fungi and viruses reduce populations of insect pests under natural conditions (King and Coleman 1989), and farming practices can be developed that will enhance their abundance and activity. The most obvious method is to reduce rates of insecticides applied or to use selective insecticides that conserve the natural enemies. Booth et al. (2007) observed that lacewings are less sensitive to insecticides than are their prey, the bird cherry-oat aphid, and reduced insecticide rates are therefore quite effective against the aphids, but kill few lacewings. Similarly, spinosad (spinosyn A and spinosyn B) has less affect on *Harmonia axyridis*, a ladybird beetle and natural enemy of soybean aphid (*Aphis glycine*), than indoxacarb (Galvan et al. 2006).

Enhancing the spaces between crop rows or around the crops provides refuges for natural enemies. Many cereal fields contain habitats for spiders, ants, beetles and other predatory invertebrates that feed upon cereal aphids (Brewer and Elliott 2004). Predators can effectively reduce early populations of soybean aphid (Costamagna and Landis 2006). Weeds within a crop may act as a niche for natural enemies of the pests (Sharma and Ortiz 2002); sunflower, niger (*Guizotia abyssinica*) and canola act as refuge plants that support the predatory assassin bug, *Pristhesancus plagipennis,* in annual field crops in Australia (Grundy and Maelzer 2003). Many parasitoids and predators have prolonged longevity and fecundity when provided with access to carbohydrate-rich foods such as floral and extra-floral nectar. Provision of flowering plants in hedge plantings or uncultivated areas has also been suggested as a means of conserving natural enemies. However, Prasad and Snyder (2006) argue that because many predators are generalists, they will feed on both pest and non-pest species in a crop which may reduce the effectiveness of other predators in controlling the target pest species. Therefore, while it is evident that provision of supplemental foods is of benefit to natural enemies, it is important that such approaches are evaluated in each system to determine the overall benefits for pest management. *Augmentative biological control* can be used for pest suppression; a natural enemy is reared in an insectary and then released into the crop to control pests. Augmentative release of *Trissolcus basalis*, a parasitic wasp, reduced stinkbugs (*Nezara viridula*) by 54% in soybean in Brazil (Correa-Ferreira and Moscardi 1996), but this has been less effective in Australia (Knight and Gurr 2007). However, augmentative releases of the assassin bug (*P. plagipennis*) reduce the numbers of *Helicoverpa* spp. and mirids in cotton and soybean crops in Australia (Grundy and Maelzer 2003). The egg parasitoids, *Trichogramma* spp. and the chrysopid, *Chrysoperla carnea,* have been recommended for biological control of *H. armigera* in India (Sharma et al. 2007b). *Classical biological control* occurs when living organisms are introduced from another country and released in a new environment to suppress pest densities, typically in regions the pest has invaded without its natural enemies. In Australia, the spotted alfalfa aphid (*Therioaphis trifolii*) appeared in 1977 and devastated lucerne crops. Three exotic wasp parasitoids (biological control agents) were introduced and, within 6 years, one of these (*Trioxys complanatus*) had successfully controlled the aphid (Hughes et al. 1987). This provided time for the plant breeders to develop and plant aphid-resistant lucerne varieties. Plant resistance has now become the key factor in controlling the aphids.

10.9 Host Plant Resistance

There are many varieties of crop plants being grown on farms that are resistant to insect pests. These varieties can play a major role in integrated pest management (Smith 1989; Sharma and Ortiz 2002), and investment in breeding plants for pest resistance could provide a larger benefit than investment in insecticide research (Smith et al. 1999). In spite of this, the adoption of insect-resistant cultivars has not been as rapid as adoption of disease-resistant cultivars (Muehlbauer and Kaiser 1994), partly a result of the relative ease of insect control with insecticides. Progress in developing insect-resistant cultivars has also been slow because of the difficulties of conducting large-scale resistance screening effectively. However, the total value of genetic resistance in wheat, to greenbug (*S. graminum)*, Hessian fly (*M. destructor*) and the wheat curl mite (*Aceria tosichella*) that transmits wheat streak mosaic virus in the USA, has been estimated to be $US250 million annually (Smith et al. 1999). Host-plant resistance in sorghum has been effective in managing sorghum midge (*S. sorghicola*), greenbug (*S. graminum*), mites (*Oligonychus* spp.) and head caterpillar (*H. armigera*), but needs to be supplemented with other methods for controlling shoot fly (*A.soccata*), stem borers (*C. partellus*), armyworm (*M. separata*) and head bug (*Calocoris angustatus*) (Sharma 1993). Partial resistance in sorghum to greenbug (*S. graminum*) has delivered a benefit/cost ratio of 13:1 in terms of reduced insecticide use, and to sorghum midge a benefit/cost ratio of 9.9:1 (Teetes et al. 1999). New sources of resistance to pests are being investigated in several wild relatives of crop plants (Clement et al. 1999; Sharma et al. 2005).

The benefits of plant resistance are greater when deployed with other control tactics. Sorghum varieties with low to moderate levels of resistance against a range of pests can assist pest suppression over time by reducing pest density, assisting in control with natural enemies, and reducing the number of insecticide treatments needed (Sharma et al. 1993). For example, partial plant resistance that reduces the rate of increase of sorghum midge can allow natural enemies to have a greater impact in controlling the midge (Sharma 1994). Higher levels of parasitisation of stem borer (*C. partellus)* by *Cotesia flavipes* have been recorded on stem borer-resistant genotypes of sorghum than on susceptible ones (Duale and Nwanze 1997).

Resistance can be developed transgenically by adding exotic genes from novel sources into crop plants through genetic engineering. Most transgenic crops with resistance to insect pests contain genes from only one species, *Bacillus thuringiensis*. Since the mid-1980s, there has been a rapid growth in the area planted with transgenic crops in USA, Australia, China and India. The global area planted to transgenic crops in 2006 was approximately 100 million hectares (ISAAA 2006). Continuing investigations are underway to broaden the range of genes for pest control, but other genes are not yet widely available for use by farmers (Hilder and Boulter 1999; Sharma et al. 2002).

10.10 Managing Crop Complexity

The crops and pastures in farming systems can be managed to reduce the impact of pests. Rotating crops reduces the continuity of the food chain for pests, and thus prevents the build-up of damaging populations. In India, the rotation of sorghum with cotton, groundnut, sunflower or sugarcane[1] is used to reduce the damage by shoot fly, *A. soccata*, *S. sorghicola* and *C. angustatus* (Sharma 1985). In Western Australia, larvae of the scarab, *Heteronyx obesus,* cause damage when cereals follow pasture, but are not a problem when cereals follow lupins (Emery 2000). In India, damage from *A. soccata, C. partellus, H. armigera* and *S. sorghicola* is reduced when sorghum is intercropped with pigeonpea (Hegde and Lingappa 1996). Intercropping with red clover reduces the damage by the European corn borer, *Ostrinia nubilalis*, to maize in Canada (Lambert et al. 1987). Small areas of trap crops can be planted to attract pests, which can be destroyed using insecticides or biological control to protect the main crop. In southern Queensland and northern New South Wales in Australia, both summer and winter crops may be grown in the same year. Chickpeas grown in winter have been used to trap *H. armigera* before the pest moves onto the main summer crops (Miles et al. 2007).

The use of crop rotations and intercropping also has other benefits to the system such as provision of favourable habitats for the natural enemies of pests. Strip cropping, where two crops can be planted in alternating strips at widths used by harvesting equipment, can also be exploited to suppress pests by breaking up the spatial continuity of the crop and slowing movement of pests. Ma et al. (2007) found that strip cropping wheat and alfalfa in China improved the biological control of the wheat aphid (*Macrosiphon avenae*) by the mite, *Allothrombium ovatum*, by providing a better habitat for the mite. In Brazil, the egg parasitoid, *T. basalis,* is released into early-maturing trap crops, where it reduces the population of the stinkbug (*N. viridula*) by 54% (Correa-Ferreira and Moscardi 1996).

Crop growth can be improved by increasing sowing rates and by fertiliser use, which can reduce pest damage. A high sowing rate helps to maintain optimum plant

[1] See Glossary for botanical names.

density and reduce insect damage in cereals (Gahukar and Jotwani 1980). Shoot fly and midge damage in sorghum are higher when plant densities are low because of a reduced ratio between the host plant density and natural populations of the target pests (Sharma 1985). Nitrogenous and phosphatic fertilisers decrease the impact on seed yield in sorghum by shoot fly, *A. soccata,* and the stem borer, *C. partellus* (Chand et al. 1979). Similarly the application of potash and nitrogen to sorghum reduces shoot fly and borer damage (Balasubramanian et al. 1986). However, for some pests and under some conditions, the addition of fertilisers may make the damage worse. Application of nitrogen to winter wheat increases the severity of attack by *Metopolophium dirhodum* and, under favourable conditions, by *Sitobium avenae*; under less favourable conditions, it can lead to lower populations of this species (Duffield et al. 1997).

Sowing time can be manipulated to reduce the exposure of the crop to pest populations. Synchronised sowing of sorghum early in the season reduces damage because the pests are not provided with a continuous food supply that allows multiplication on sequentially sown crops (Sharma 1993). Harvesting of a crop can reduce the resources available for the pest. For example, in pastures the quantity of resources available for pests is influenced by grazing intensity, and high stocking rates of sheep and cattle can reduce the food available for herbivorous insects and mites and thus the populations of foliage-feeding (East and Pottinger 1983; Grimm et al. 1994) and root-feeding pests (Roberts and Morton 1985). Farming systems can be managed to reduce the time that susceptible crops are exposed to pests, and to enhance the role of natural enemies, while retaining the productivity of the system. This is possible with rotations of crops, intercropping, trap crops where the pest is controlled, by increasing plant vigour through increasing sowing rates, or fertiliser use, by changing sowing times, and by grazing pastures with animals. The best options will vary between regions, crops and pests, and require an understanding of the plant-insect interactions.

10.11 Tillage

Ploughing a field before planting reduces the abundance and carryover of white grubs, grasshoppers, hairy caterpillars and stem borers in soil by exposing them to parasites, predators and adverse weather conditions (Gahukar and Jotwani 1980). It also kills weeds. Stubble management, such as collecting and burning stubbles and chaffy earheads reduces the carryover of *C. partellus* and *S. sorghicola* in sorghum (Sharma 1985). Stalks from the previous season should be fed to cattle or burnt before the onset of monsoon rains to reduce the carryover of stem borer (Gahukar and Jotwani 1980). Piling and burning of trash in the field at dusk attracts the adults of white grubs (*Holotrichia, Pachnoda, Melolontha*, etc.), blister beetles (*Mylabris*, *Cylindrothorax*, etc.) and the red hairy caterpillar (*Amsacta moorei*), and kills them. Reduced tillage is widely practiced in south-western Australia to conserve soil moisture, but can lead to greater survival of pests such as webworm (*Hednota* spp.), especially in grassy situations (Emery 2000). The widespread adoption of reduced tillage or no-till farming has been accompanied by an increase in pest problems, and an increase in the use of pesticides to control both pests and weeds.

10.12 Conclusions

Insect pests cause a substantial loss in the production and value of crops worldwide. There are many pest species which attack crops in rainfed farming systems, and the tools needed to manage them vary with each situation. Use of synthetic insecticides is increasing rapidly. They are easy to apply and the results are immediate, but the development of resistance in many pests requires a reduction in dependence on chemicals, and adoption of a more integrated approach using other tools such as plant resistance and cultural management; this involves the manipulation of farming systems to make them less favourable for the pest and more favourable for natural enemies. Different tools should be used in an Integrated Pest Management System, but vary for each crop/region/farm. A farmer growing grain legumes in a developing country may find that insecticides are unavailable or too expensive (Clement et al. 2000). Under these circumstances, use of cultivars with low to moderate levels of resistance can result in reduced populations of the pest, a substantial increase in the effectiveness of natural enemies, an increase in the benefits of cultural control methods, and consequently reduced crop loss. For a grower with better access to insecticides, pest-resistant varieties will reduce the number of pesticide sprays required, and thus, the cost of pest control. Our ability to improve pest management using new tools will be based on a better understanding of the underlying biological interactions between the plants and the insects for sustainable crop production.

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Chapter 11
Interactions Between Crop and Livestock Activities in Rainfed Farming Systems

Edwin C. Wolfe

Abstract The organisation of crop–livestock systems, both on farms (mixed farming) and between farms (integrated businesses), is explored from a world perspective. Over a continuum from semi-arid to humid regions, mixed farming is favoured in intermediate areas, with specialised crop and livestock businesses at the extremes. Tradition, land tenure, government policies and management complexity add further constraints and benefits to both mixed and integrated farming systems. Natural synergies and skilful management produce positive interactions between crops and livestock, at both the farm and regional levels. These interactions are described for a range of countries. Mixed and integrated farming systems provide options for coping with potential future shocks such as climate change and fuel shortages. However, these systems are potentially complex and many managers prefer the apparent simplicity of specialisation. In response to future challenges, there is scope for farm managers and policy-makers to promote business partnerships and social adjustments that enable simultaneous specialisation and diversification in mixed and integrated crop and livestock businesses.

Keywords Mixed farming • Ley • Phase farming • Specialisation • Diversification • Synergistic • Antagonistic • Supplementary • Complementary

11.1 Introduction

Although crop and livestock production have existed side by side since the beginning of agriculture, the way they have interacted has varied with location, culture and time. In this chapter, the interaction of rainfed crop and livestock enterprises is

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_11,

examined for two main situations at the farming systems level. The first is the *mixed farming system*, where crops and livestock are part of the same farm system. The crops and livestock may be managed by the same individual or, as in large family units or on corporate or collective farms, they may be managed separately by different individuals or by teams of people. The second, more common form of interaction is where crop production and livestock production are conducted as *separate* businesses which are integrated, intra- or inter-regionally, to achieve certain benefits; this arrangement is termed an *integrated farming system*, such as where one or more cropping farms supply grain to a cattle feedlot or a piggery. The above specific definition of mixed farming is different from that of Schiere et al. (2006), who characterised 'mixed farming' generically as any type of farming system involving animals and crops. The trade-related export of feed grains, from one region into another region or country for intensive livestock production (Zhou 2003), is not considered here.

In this chapter, principles governing the types of relations between crops and livestock are explored from perspectives that include:

- the organisation of crop–livestock systems
- positive and negative relationships between crop and livestock enterprises
- examples of crop–livestock systems in Australia, North America, eastern Asia and north-eastern Africa
- management of mixed and integrated farming systems.

From these perspectives, the future directions of mixed and integrated farming systems are discussed.

11.2 A Geographical Perspective of Crop–Livestock Systems

The relative importance of cropping and livestock activities in agricultural production systems is determined physically by climate, terrain, soil type and proximity to markets. For rain-fed areas, Jahnke (1982) graphed the general relationship between the amount of annual rainfall and the potential level of human food production from livestock or crops (Fig. 11.1). Whilst the actual and relative levels of food production from plants and animals depend on a range of factors, the amount of rainfall is the predominant one. However, interactions between crop and livestock production occur widely – from dry to humid regions and at all levels of the continuum from high-technology agriculture in wealthy countries to subsistence agriculture in poor countries (Table 11.1).

In arid and semi-arid localities (less than 250 mm annual rainfall) and in areas that are non-arable because of adverse terrain or soil type, extensive grazing of livestock is favoured, particularly in societies that allow the migration of livestock herds to access available forage. Examples include the drier parts of several states of north-western USA; Mongolia, southern Kazakhstan and western China in Asia; areas of sub-Saharan Africa; northern Mexico, central Brazil, Paraguay and western

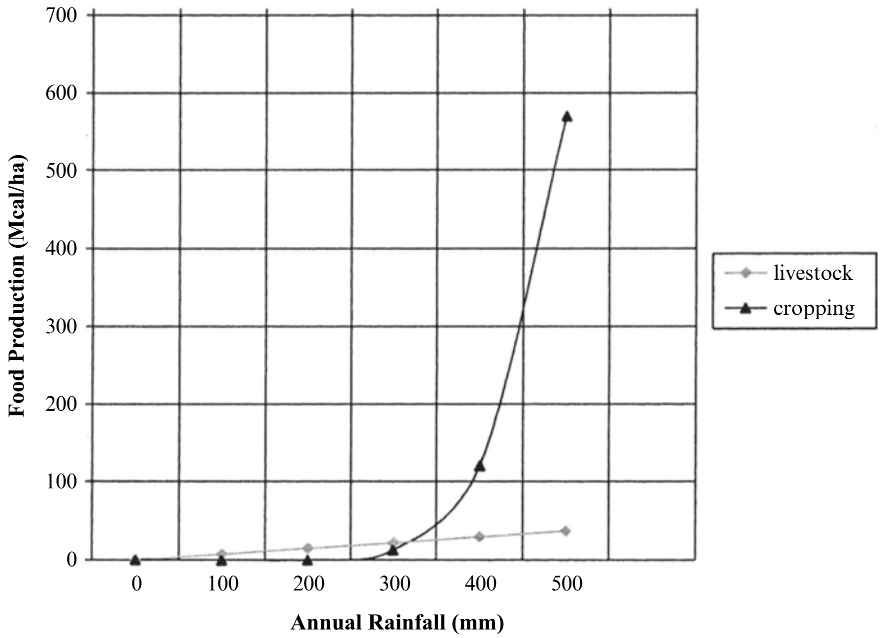

Fig. 11.1 The potential of livestock and cropping enterprises to produce food energy – Schiere et al. 2002, after CRW Spedding (Jahnke 1982)

Argentina; and the semi-arid regions of inland Australia (Kruska et al. 2003). Whilst grazing livestock is the predominant undertaking in the subsistence economies of such regions, plants are also grown for household or village food production. Animals are important not only as food but also as a source of transport (cattle, donkeys, camels) and as power for cropping activities (ploughing, harvesting) – topics that are discussed in System Example D (see later). In crop–livestock systems that are well-managed, livestock benefit crops through weed control and nutrient recycling while obtaining their feed from crop residues and conserved plant materials.

At the other extreme, in localities with at least moderate rainfall (and/or irrigation), favourable terrain and fertile soils, the predominant activities are crop production and/or horticulture. Such areas occur in the mid-western corn belt of the USA, central Europe and Ukraine, central and eastern China, parts of India and SE Asia, southern Brazil and eastern Argentina. These areas produce food plants for human consumption either as fresh produce (fruit, vegetables), stored grain (rice, wheat) or processed foodstuffs (sugar, soybeans), and are characterised by high productivity. For example, in the irrigated portions of the Murrumbidgee and Murray River valleys of Australia, a single crop of paddy rice can provide 125,000 megajoules (MJ) of food energy per hectare from water inputs of 15 ML – sufficient to feed 35–40 people for a full year. The croplands also produce large quantities of

Table 11.1 Examples of integrating crops and livestock in world agricultural systems

Type of agricultural systems and some characteristics	Rating[a] of properties for each agricultural type	Examples of crop–livestock interactions in mixed farming or integrated farming systems	Type of agriculture (Schiere et al. 2006)
High technology/high input agriculture			
Substantial R&D inputs into innovation (e.g. GM plants, cloned organisms, new chemicals, precision agriculture). High energy and infrastructure costs (e.g. power, machinery, electronics, glasshouses, feedlots and animal housing). Profitable but competitive. Potential pollution and high energy consumption are sustainability issues. Can lead to social and political concerns	Productivity–high output Sustainability–low Profitability–low to moderate Social worth–low to moderate Politics–vested interests	Peri-urban North America, Europe, China. Dairies, beef feedlots, intensive piggeries and broiler production are based on the availability of feed as by-products of intensive crop production and/or food processing. Suited to countries with limited land and cold climates, where animals must be housed for at least some of the year. Crop and animal production systems may be separated in terms of distance and management, but they are integrated by commerce, trade. See System Examples A, B, C.	High external input agriculture (HEIA) e.g. dairy farming in the Netherlands HIGH Intensification, specialization, scale, focus on outputs
Conventional/medium-input agriculture			
A mixture of traditional farming (e.g. crop rotations, grazing animals) and new technology (e.g. improved crops and animals from conventional breeding, strategic applications of fertilisers and pesticides)	Productivity–moderate output Sustainability–low to moderate Profitability–low to moderate Social worth–low to moderate Politics–vested interests	In the wheat–sheep belt of Australia (System Example A), sheep/cattle grazing and crop production are conducted as mixed enterprises on most farms. On the Great Plains of North America (System Example B), crop–livestock integration occurs primarily between farm businesses.	Conventional agriculture
Conventional/low-input agriculture			
A development of agriculture in response to factors such as global warming, the waning supply of energy resources or a lack of liquidity to purchase needed resources. Lower external inputs of fertilisers and energy. Fuller use made of natural systems such as nutrient recycling, biodiversity, free-range animal production	Productivity–moderate output Sustainability–moderate Profitability–low to moderate Social worth–low to moderate Politically sound	Mixed and/or integrated farming occurs at various scales. In mixed farming on large cooperatives in China and North Korea (System Example C), teams of farm workers manage crop and livestock operations. Animal waste and straw are composted. There is some use of animal power.	Low external input agriculture (LEIA) e.g., West African agro-pastoral systems Ecological impact

Organic agriculture (OA)				
There is a strong demand for organic food products ('natural', nearly chemical-free) but organic food is difficult to produce, and the products may spoil. Some OA practices are unsustainable, such as tillage for weed control (erosion risk) and exploitation of soil fertility.	Productivity– low output Sustainability– moderate Profitability– low to moderate Social worth– high Politically attractive	Village agriculture in SE Asia. The best land is reserved for crops. Animals for food and draught power live year-round on limited grazing, crop residues, and 'cut and carry' forage. See System Example C.	New conservation agriculture (NCA) e.g., rotation farming with legumes	LOW
Subsistence/low input agriculture				
No special expertise or investment is needed but it is labour intensive and can be exploitative of soil and water resources. Potentially unstable – human populations are vulnerable to drought and other natural disasters (insect pests, diseases)	Productivity– low output (but often efficient) Sustainability– low to mod. Profitability– low Social worth– high Politically difficult	In Eritrea and Ethiopia, livestock and crop production are separately owned-managed but integrated. In semi-arid areas, mobile herds of animals graze rangelands, then crop residues and crop fallows in the long off-season (autumn to spring). Animals are used for draught in crop lands. See System Example D.	Expansion agriculture (EXPAGR), an historical type of agriculture that occurred at a time when land was abundant	

[a]The 5 properties in column 2 are a variation of the multidisciplinary indicators (productivity, stability, sustainability, equitability) used by Conway (1986) to analyse the performance of agricultural systems. A subjective scale (low, moderate, high) plus a comment on the political property are used by the author to compare the properties of each type of agricultural system

food for animals, either directly (crop residues, feed grains) or as by-products of food processing (bran and pollard from wheat, brewers' grains from barley, oilseed cake, and fruit and vegetable waste). Intensive livestock facilities such as piggeries, broiler sheds and cattle feedlots convert feed grains and wastes from crop production and food processing into meat. Within a district or region, these business-to-business operations comprise an important form of crop–livestock interaction. Integrated business operations balance the trend towards on-farm specialisation that usually accompanies the intensification of agriculture.

Between the extremes of rangelands and intensive croplands are areas where mixed and integrated (business-to-business) crop–livestock farming is favoured. Schiere et al. (2006) estimated that "mixed/integrated systems cover about 2.5 billion (10^9) ha of land, of which 1.1 billion ha are arable rainfed cropland, 0.2 billion are irrigated cropland and 1.2 billion are grassland". A detailed assessment of the area of mixed/integrated systems was provided by Kruska et al. (2003) who mapped the distribution of 'solely livestock' and 'mixed' (i.e. crop–livestock) systems in developing countries in Central and South America, Africa, the Middle East and Asia. An area of 31% (2.5 billion ha, Table 11.2) of the total area was classed as 'mixed systems'. They included in these systems crop farms with no livestock since the outputs (grain and stover) are potentially integrated, intra- and inter-regionally, with livestock production. They mapped the areas of mixed/integrated systems, which occur throughout most of sub-Saharan Africa, Turkey, Iran and other North Asian countries, most of India, central China, SE Asia, Indonesia, the Philippines, Central

Table 11.2 Land use[a] in developing countries (Kruska et al. 2003)

	Livestock only (rangeland)	Mixed/integrated crop/livestock systems				
		Irrigated	Rainfed	Rainfed	Other	Total
Region	%	%	%	ha × 10^6	%	10^6 ha
Asia (central, south and south-east	28.8	15.6	27.4	661	28.2	2,415
Central and South America	26.9	2.0	25.7	523	45.4	2,034
Sub-Saharan Africa	37.3	0.5	27.1	653	35.1	2,407
West Asia–North Africa	14.7	6.7	12.7	156	65.9	1,229
Total –ha × 10^6– %	2,319	512		1,995	3,259	8,085
	28.7	6.3		24.7	40.3	100

[a]Rangeland systems were separated from mixed/integrated systems on the proportion of dry matter fed to animals: Rangelands = >90% feed sourced from rangelands, pastures, forages and purchased feeds; Mixed/integrated = >10% feed (% of total sources) from crop by-products and stubble or >10% of the total value of production comes from non-livestock farming activities; Irrigated = a subset of the mixed/integrated systems in which >10% of the value of non-livestock farm production comes from irrigated land use. Urban areas (>450 persons per km^2), which may contain some of the 'landless' mixed systems (intensive dairies, feedlots, pig- and poultry-raising facilities in which <10% of animal feed is sourced from the farm), are not included in the table. Other = tundra, forest, plantations, desert, wasteland and lake areas

America and large portions of Argentina and Brazil. In the developed economies, there are likewise areas of integrated or mixed farming lands in the southern Australian wheat belt, parts of Russia, most of Europe, eastern USA, the Great Plains of USA and the prairie provinces of Canada (Schiere et al. 2006). The combined area of mixed and integrated farming systems is responsible for most of the world's human food production.

11.3 Relationships Between Livestock and Crop Enterprises

At the farm level, the outcome of managing livestock and crop enterprises in mixed farming systems can be represented by a substitution diagram similar to that in Fig. 11.2 (Schiere et al. 2006), which illustrates food output with different ratios of crops and pastures–livestock. When mixed farming is done well, positive synergy occurs between crops and livestock and total food output is enhanced, as seen in the convex dashed line in Fig. 11.2. The line is concave for badly managed systems.

Figures 11.3a–d indicate the different forms of the relationship between crop and livestock enterprises on mixed farms. The skill and timeliness of management will determine the positive, negative or neutral impacts of diversification or specialisation on the outputs of the production system(s) and on farm profit. Positive interactions occur from *synergies* (Fig. 11.3a) and *complementarities* (Fig. 11.3d).

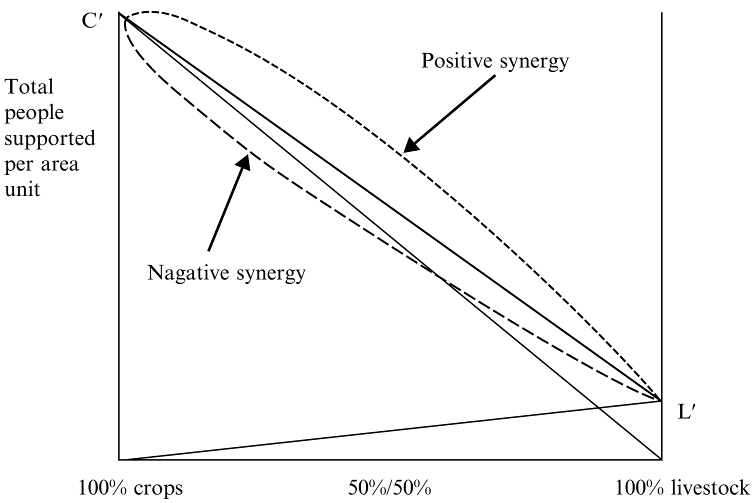

Fig. 11.2 The number of people fed from crops (*left*) or by animals alone (*right*) and at various proportions of the total area of a hypothetical mixed farm (*continuous lines*). Broken lines indicate positive and negative synergy, depending on management expertise (after Schiere et al. 2006). The ratio of L′ to C′ depends in part on rainfall – there needs to be sufficient rainfall to produce grain (edible plant biomass). This representation is for an environment with about 400 mm growing-season rainfall

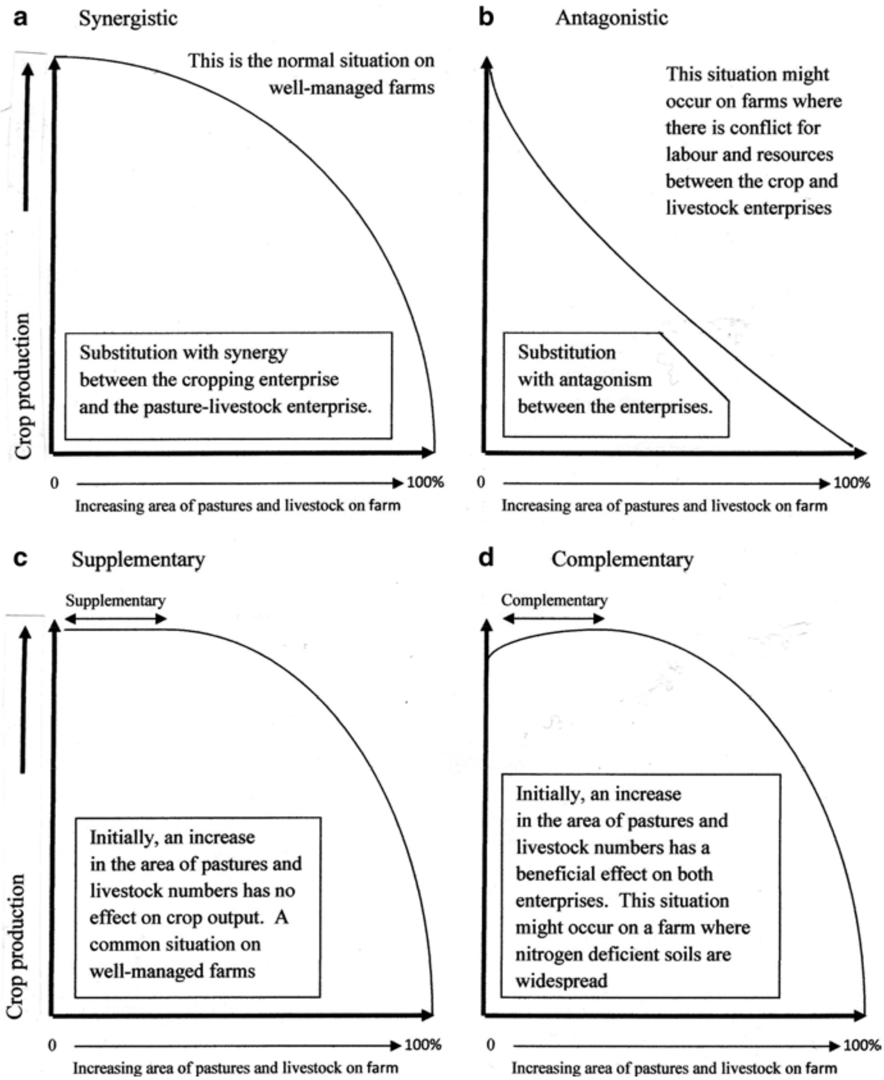

Fig. 11.3 (**a**–**d**). Graphical representations of the different effects on farm crop production of increasing the pasture–livestock area on mixed farms, indicating different forms of the crop–livestock relationship. The effect of legumes/livestock on nutrient dynamics and the utilisation of crop residues by livestock are crucial for synergy

Synergies (mutually beneficial interactions between livestock management and crop management) include: the benefits of nitrogen-fixing legumes that improve both forage quality and soil fertility; the return of dung and urine to the soil; the use of deep-rooted pasture species that extract more soil water for production and environmental benefits; and the use of pasture–crop rotations to break disease and pest cycles. Examples of complementary (additive) effects include the consumption of weeds by livestock thereby reducing weed populations in subsequent crops; the benefit to animals and crop sowing operations from the consumption of crop residues; and the utilisation of the grassy understory by cattle in developing rubber tree plantations. Negative interactions (Fig. 11.3b) come from *antagonistic* effects, such as the distribution of some crop weeds by livestock and *competition* between enterprises for labour, resources or investment. A neutral (*supplementary*) relationship (Fig. 11.3c) occurs when the expansion of one enterprise has little effect upon another; for example, below a certain threshold area, the presence of livestock (grazing crop stubbles, laneways and tree lots) is not competitive with the area allocated for crop production.

The relationships in Figs. 11.2 and 11.3 also can be applied to the integration of crop and livestock businesses at the regional level. However, since integration of businesses (region level) occurs at a larger scale and over greater distances than mixed enterprises (farm level), more mechanisation and hence greater energy use is usually involved per unit of agricultural output. Furthermore, integration involves a broader range of players (e.g. entrepreneurs, trucking companies, other middlemen) in addition to farmers. Hence, the socio-economic nature of integrated agricultural businesses will usually differ from the relationship structure in mixed farming.

Some of the reasons that might encourage or discourage farmers from mixing livestock with cropping in farm systems are listed in Table 11.3, which is based on the ideas and examples of Wolfe and Cregan (2003), Entz et al. (2005) and Schiere et al. (2006). These reasons, especially the issue of diversification versus specialisation, are discussed further in the System Examples to follow. The potential benefits from pastures and livestock include reducing the impact of variable climatic patterns and markets on farm production and profit since the impact on livestock production is less drastic than on crops. However, the addition of livestock to a cropping system results in complexity, increasing the number and difficulty of decisions that must be made by the managers. Livestock require additional infrastructure, at least in developed countries, to manage and contain them. Careful planning is needed to achieve a complementary or supplementary fit, rather than a clash, of labour and budgetary requirements throughout the year. Many farmers are generalists who may not have the time or the specialist knowledge to manage each enterprise according to the combined expectations of specialists such as agronomists and animal scientists.

Overall then, mixed farming (and integrated farming) brings ‘mixed blessings’ (Schiere et al. 2006) since crop and livestock enterprises have conflicting as well as common interests. Schiere et al. (2006) explained that the relative importance of crops or livestock varies according to the context of each agricultural/regional system, as well as the individual perspectives of stakeholder groups (e.g. scientists, farmers, agribusiness firms) within the system. Some examples of the variation in crop–livestock interactions follow.

Table 11.3 Possible reasons for and against mixing or otherwise integrating livestock with on-farm cropping systems (Wolfe and Cregan 2003; Entz et al. 2005; Schiere et al. 2006)

Impact	Effects	Relevant to[a]:
For:	Reduced risk: In mixed crop/livestock systems, farm income is buffered from crop or livestock downturns caused by supply/demand problems or trade issues. Diversification reduces or spreads risk.	System Examples A, B
	Balanced land use: In some countries, diversification into livestock is in line with government policies to reduce subsidies for grain production or to encourage multiple objectives in natural resource management.	System Examples A, B
	Improved crops: A pasture phase may improve cereal crop yields and/or grain quality, due to N fixation by pasture legumes, a break in disease/pest cycles and/or better utilisation of water and vegetation resources.	System Examples A, B, C, D
	Climate change: In marginal cropping lands, livestock production is less affected than crops by climate fluctuations	System Examples A, B, D
	Integrated pest management. A well-managed pasture phase may produce benefits by reducing weed, insect pest and disease incidence.	System Examples A, B
	Grazing and grain: Livestock fit well with dual-purpose (grazing and grain) crops.	System Examples A, B
	Enhanced sustainability: Potentially, deep-rooted pasture species improve soil health, reduce the risk of salinity and minimise groundwater contamination with pesticides.	System Examples A, B
	Soil erosion control: Pasture cover reduces the rate of soil erosion.	System Examples A, B, C, D
	Animal power and manure: In low-input and subsistence systems, animal draught power and manure are available for the cropping enterprise. Animals recycle plant nutrients.	System Examples C, D
	Human diet and nutrition: Mixed crop/livestock systems improve food choice and enhance the conversion of plant materials into human food (milk, meat) and materials (fibre, hides).	System examples C, D
	Energy efficiency: Integrated systems appear to be more energy efficient, when all on-farm and off-farm energy requirements are assessed.	System Examples A, B, C, D
Against:	Reduces peak profitability: Diversification may reduce profitability since specialisation targets the most profitable enterprise, and achieves economies of scale.	System Examples A, B
	Management complexity: Diversification adds to the complexity of management.	System Examples A, B
	Labour clashes: Seasonal conflicts may occur in crop and livestock operations.	System Examples A, B, C, D
	Labour, infrastructure considerations: Livestock need constant attention and they require infrastructure – fences (or shepherds), water points, yards/corrals and other facilities. Pastures and livestock require skilled management.	System Examples A, B, C, D
	Soil compaction: Poor management of livestock can exacerbate surface soil compaction, which may lead to more water runoff and cultivation/sowing difficulties.	System Examples A, B, D
	Adverse effects on crops: Livestock increase the risk of crop damage and may transfer weed seeds.	System Example D

[a]System Examples:

A and B = A comparison of the sheep/wheat belt in Australia (A) with the plains/prairies in USA/Canada (B)

C = City/village and collective systems in eastern Asia, including North Korea

D = Rangelands and croplands in Eritrea

11.4 Some Examples of Crop–Livestock Systems

11.4.1 Overview

In the Australian sheep–wheat belt (see System Example A), most farms are mixed – crop and livestock enterprises occur on each farm. Farmers are familiar with the range of reasons for and against mixing (Table 11.3). In Australia, a key reason for the popularity of ley[1] farming (Puckridge and French 1983) and/or phase farming (Reeves and Ewing 1993) is the relatively infertile nature of the local soils. A legume pasture–livestock phase provides farmers with opportunities to exploit the natural synergies of mixed farming such as provision of high-quality fodder, together with improvement in soil nitrogen content (Wolfe and Cregan 2003), and to reduce their exposure to risk. On the other hand, farmers who prefer to specialise cite economies of scale and simplified management. The nature of the advantages and disadvantages of mixing (or integrating) livestock production with crop production are somewhat location-specific (Schiere et al. 2006), and some of this specificity is indicated in Fig. 11.3.

In North America (System Example B), a continental climate (cold winters, hot summers), the availability of cheap nitrogenous fertiliser, a culture of cropping and a low level of interest in sheep (compared to cattle and pigs) help explain the preferences of most American prairie farmers to integrate crop and livestock businesses from farm-to-farm rather than on-farm. Although the interest of grain farmers on the US Great Plains in conservative farming systems was presumably stimulated by the 1930s 'dustbowl' era, Krall and Schuman (1996) found that the current level of interest in mixed farming is relatively low (excluding winter wheat for grazing), responding to neither the profitability of pastures and livestock nor government policies. In many global regions, the American model of integrated farming (i.e. business-to-business) may be more appropriate than the Australian mixed farming (wheat–sheep) model.

While mixed farming is an obvious form of enterprise diversification, farmers who specialise in either crops or livestock are also able to diversify. For example, in the Australian sheep–wheat belt, members of a farm family who specialise in the production of Border Leicester x Merino (BLM) ewes, ideal as mothers for the production of lambs for meat, may also manage other livestock-oriented enterprises (Table 11.4). Similarly, a farm that is devoted to continuous cropping may also contain an array of crop-related enterprises (Table 11.4). The extent of diversification or specialisation within farm businesses may depend on the economic relativities of particular enterprises, the business opportunities that are available or created, pressures originating off the farm (for example, sustainable agriculture policies)

[1] In Australia, 'ley farming' is a generic term that was commonly applied to the short and long forms of the crop–pasture rotation. There is a recent trend towards the use of 'ley' to denote a 1-year self-regenerating pasture between crops and 'phase' to denote several consecutive years of re-sown pasture after a sequence of crops.

Table 11.4 Examples of enterprise diversity on specialised and mixed farms in the Australian wheat–sheep belt

A specialised livestock farm	A mixed farm	A specialised cropping farm
Border Leicester stud	Production of wheat, canola and lupin grain	Production of wheat, barley, canola and peas
Self-replacing Merino flock producing fine wool	BLM ewes and Dorset Horn rams for fat lamb production	Contract harvesting and seed cleaning
Fattening operation to turn off male BLM wether lambs	Small-scale pasture seed production	Small flock of wether sheep used as 'weed eaters'
Small cattle herd	Livestock agistment service	A part-time agronomy consulting service
A special interest in breeding and training sheep dogs	High school teacher[a]	Rural counsellor[a]

[a] These enterprises are relevant to the farm family but independent of the farm business

and the personal preferences of the farm manager/family. Of these, personal preference is the least understood. In the industries of agriculture and horticulture, where past research has focused either on applying 'hard' science to problems or applying economics to farm management, there is considerable scope for exploring further the social aspects of decision-making on farms (McCown and Parton 2006; Pannell et al. 2006, Chap. 30).

In eastern Asia (System Example C), agriculture is represented by small-holders or by large collective farms. Crop and livestock enterprises are usually close-at-hand, facilitating mixed farming or the integration of these enterprises. On collective farms, mixed farming is assisted by the availability of different teams, each specialising in an aspect of the farming system. Another Asian example of integration is the operation of 'landless' or industrialised farming systems (Kruska et al. 2003) in which intensive pig and poultry production take place in or near cities, consuming waste from food processing or the human food supply chain.

In north Asia, India, sub-Saharan Africa and in countries around the Mediterranean Sea, the small size of farms, together with traditional systems of land tenure and livestock ownership, generally favours interaction between small landholders and livestock owners (as in Eritrea, System Example D) instead of mixed farming in the Australian sense. While Australian ley-farming practices appeared technically attractive for adoption in West Asia and North Africa (WANA) (Thomson et al. 1995), their application was thwarted by a range of factors (Boyce et al. 1991; Thomson et al. 1995; Christiansen et al. 2000) that included research-extension problems, insufficient farm size, land tenure issues, and price subsidies for wheat (human food) and barley (for fattening lambs).

In summary, integrated crop–livestock farming can occur in several forms: on-farm (mixed), between farms and even between businesses in different regions. The ratio of these forms is fluid in both time and place, with the optimum combination of crop and livestock activities within and between agricultural systems depending on local constraints and opportunities.

11.4.2 System Examples

11.4.2.1 System Examples A and B – Mixed Farming Systems in Southern Australia (A) and Some Comparisons with North America (B)

In southern Australia, the sheep–wheat belt (39,200 farms in 2005) lies in an intermediate location between the predominantly coastal High Rainfall Zone (27,600 farms) and the semi-arid Pastoral Zone (4,000 farms). This mixed farming zone has a mainly Mediterranean-type climate and gentle topography that allows regular cropping of wheat in conjunction with other cereals, pulses and oilseeds. These crops are sown in late autumn and harvested in late spring before the advent of the hot, dry summer. Sheep for meat and wool are grazed year-round on pastures and crop residues, supplemented with conserved fodders (hay, silage) or grain in poor seasons.

In 2005/2006, mixed farms in the Australian wheat belt averaged 1,950 ha in area, of which 700 ha were sown to crops, and they carried a population of 1,625 sheep and 78 cattle (ABARE 2006). The main sown pastures are self-regenerating annual legumes, notably cultivars of subterranean clover (*Trifolium subterraneum*) and annual medic (*Medicago* spp.), with smaller areas of several other important legumes (Nichols et al. 2006). Lucerne (= alfalfa, *Medicago sativa*) and mixtures of lucerne with other legumes and grasses (Wolfe and Dear 2001) are becoming more popular due to production and sustainability benefits from the perennial, deep-rooted lucerne. Puckridge and French (1983) and Wolfe and Cregan (2003) described the history and impact of ley pastures on crops and livestock, while Reeves and Ewing (1993) outlined some of the problems of maintaining the ley-crop system. The management of animal production from ley pastures was described by Mann (1991).

Ewing and Flugge (2004) discussed evolutionary trends in mixed farming in the Australian wheat–sheep zone. Overall, there has been a gradual trend towards an increase in the cropping area and corresponding decreases in livestock numbers. In Western Australia (WA), these trends reflected the widespread adoption of lupins (*Lupinus angustifolius*) as a pulse crop, crop/livestock price relativities, the availability of new herbicides and machinery for minimum tillage, and the manual labour required for livestock management. During the last two decades of the twentieth century, when both wool and meat prices were depressed, concerns about the long-term sustainability of continuous cropping tempered the extent of the intensification of cropping. Recently, factors that have favoured maintaining mixed crop and livestock activities include the increased cost of nitrogen fertiliser inputs for crops, the development of herbicide-resistant weeds, the risk of crop diseases and pests, a run of unfavorable seasons for crops and a steady rise in the value of sheep meat and beef.

Two examples illustrate some differences and similarities in how farming systems operate in the rainfed croplands of Australia (System Example A) and North

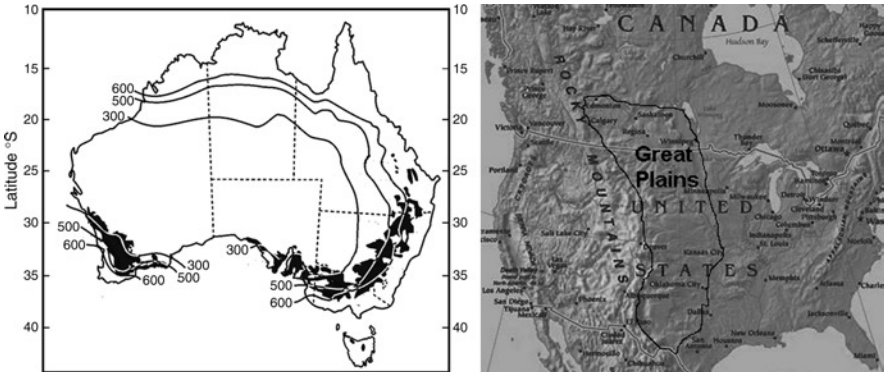

Fig. 11.4 Maps showing the Australian wheat belt (and annual isohyets in mm) and the North American Great Plains

America (System Example B), in relation to mixed and integrated crop–livestock production:

A. In parts of the Australian wheat belt that receive a median monthly rainfall in autumn greater than 40 mm, such as in southern and central New South Wales (NSW) and eastern Victoria, cereal varieties with a 'winter habit' (i.e. with a short-day or cold requirement for floral initiation) may be planted in early autum (March–April in Australia). In order to obtain early feed, part of the intended cropping area may be planted to a suitable forage or dual-purpose (DP) cereal cultivar (Fig. 11.4*,* System 2) which *substitutes* for a grain cultivar planted later (May–June). Herbage produced during autumn is valuable to fill the usual late autumn trough in the supply of forage for livestock, a trough that is due to the depletion of crop stubbles by grazing and slow regeneration of annual legume pastures. The area of forage/dual-purpose crop *supplements* the pasture area available for livestock. Although it was once common for mixed farmers in NSW to plant dual-purpose cultivars (Hoogvliet and Wheeler 1977), the popularity of the practice has declined to 2–4% of plantings in recent years. This decline may be the result of a run of dry autumns and a higher priority given to canola and pulse crops, which also are sown earlier than cereal grain cultivars.

The proportion of crops for both grazing and grain is puny in this situation compared to the US Southern Plains region, where 30–80% of the 8 M ha annually under wheat are planted early to winter wheat and grazed in fall-winter (Pinchak et al. 1996). In this region (Epplin et al. 2000; F. Epplin, personal communication), there are a variety of business arrangements, ranging from mixed farming (the operator owns or rents the land, farms the wheat and owns the cattle) to integrated farming (the operator owns or rents the land, farms the wheat and leases the wheat grazing rights to a cattleman). Grazing wheat is a practice that is unique to the Southern Plains, where wheat is planted in early September on conventionally-tilled land (to minimise the risk of a severe Hessian

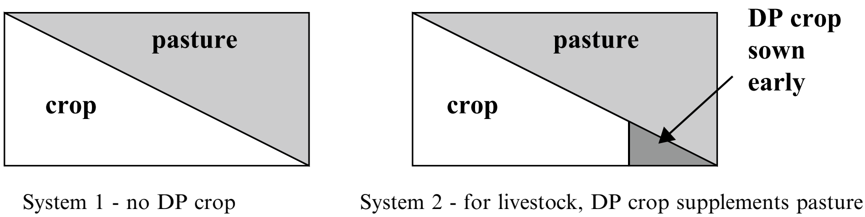

Fig. 11.5 Alternative systems, with and without a dual purpose (DP) crop

fly infestation) and where the winters are mild enough for livestock to graze in winter with little supplementation or shelter.

B. On the colder Great Plains of central/northern USA and southern Canada, few landholders conduct both cropping and livestock (predominantly cattle) activities on their farms (Krall and Schuman 1996) despite the scope for greater integration of pastures grazed with cattle into crop rotations (Perilla et al. 2004). According to J.M. Krall (personal communication), some Wyoming farmers negotiate grazing rights for the use of corn stover but the practice is not universal. Cattle are traditionally fattened in intensive animal facilities, even though grasslands may be available locally for much of the year. Intensive feeding in part reflects winters that are relatively severe and in part an American culture of high technology in livestock production. Hence, rather than mixed farming, the emphasis in the USA and Canada is on integrating the activities of specialist grain producers with specialist cattle businesses.

In Australia, only in areas with favourable rainfall and soils, such as the fertile Wimmera region of Western Victoria and the Darling Downs of southern Queensland, does cropping predominate to the extent of squeezing livestock off many farms. These cropping heartlands attract farmers who prefer cropping activities over livestock activities. As in North America, some Australian farmers are influenced by people with vested interests in commerce (e.g. tractor and implement manufacturers, GM crops) and by government (e.g. through food and crop policies). Social factors, such as the personal preference of crop specialists for machinery instead of livestock, may over-ride bio-economic factors and dictate the enterprise balance in mixed farming.

Before the recent improvement in profits from livestock in Australia, extension officers acknowledged the difficulty of improving or expanding livestock production on Australian mixed farms. Farmers specialising in crops were not motivated towards livestock production; many merely tolerated the presence of livestock as a means of capturing some of the synergies of mixed farming. For example, in the Victorian Mallee, Robertson and Wimalasuriya (2004) attributed sub-optimal sheep husbandry to farmer apathy and ignorance, suggesting inadequacies in the community, education or extension/industry organisations. At the time of the peak popularity of the ley farming system (1950–1975), there was a more positive attitude to sheep and their contribution to the farm system. During the last two decades, while the Australian agribusiness sector has accepted a need to employ graduate agronomists to supplement the reduced advisory services provided by government, few agricultural specialists are employed in commercial livestock production, either extensive or intensive. Hence, at least in Australia, the application of new technology to grazing livestock production lags behind that applied to crop management, or to intensive livestock.

These examples support the notion that agricultural systems can be studied effectively only when (1) the boundaries of such systems are extended to include influences and feedbacks that are off-farm as well as on-farm, and (2) 'soft' (socio-economic) as well as 'hard' (technical) constraints to system performance are evaluated (Schiere et al. 2006; McCown and Parton 2006).

11.4.2.2 System Example C – Agricultural Systems in China and the Democratic People's Republic of Korea (DPRK)

In developing countries generally, and in China in particular, the per capita and absolute demand for livestock products is growing strongly, and will continue to grow as a consequence of changing food preferences and higher consumer incomes (Zhou 2003). This growth will lead to a further decline in per capita consumption of grains as human food, an increase in the proportion of grain used as livestock feed (currently <20% in developing countries *v*. 64% in industrial countries) and increased demand for feed grains, particularly cereals. According to Zhou's (2003) analysis, the importance of feed grain in China will rise from consumption of 160 Mt and export of 10 Mt in 2000 to production of 280 Mt and a total demand of 310–346 Mt in 2010.

This change in food preference also represents an opportunity for mixed farming. For example, grass-livestock systems have a role to play in the sustainable control of wind erosion and pollution in China (JB Schiere, personal communication). However, Zhou (2003) argued that the potential of pasture as a source of feed for Chinese animals was limited. The expansion of intensive (industrial) livestock production was proceeding at a rate twice as fast as traditional farming systems (small-scale urban and rural subsistence agriculture, collective farms) and six times the expansion rate of grazing systems. Nevertheless, traditional mixed systems still dominate amongst small land-holdings. There is marked complementarity in resource use in these small-scale systems, such as use of draught animal power and manure for crop production, and crop residues and food waste as animal feed. Devendra and Thomas (2002) described the positive interactions that exist in many Asian crop–animal systems (animal traction, animal feeds from crops, weed control by grazing, introduction of improved legume forages for building N fertility with soil erosion control and supply of manure–also see Table 11.3). Unlike in Australia, the management complexity of mixed systems is not a special constraint in Asia, where 'many hands make light work' through the careful allocation of duties to individuals and teams in the populous urban, village and rural areas.

Fig. 11.6 Rice paddies (foreground) and maize (lower slopes) near Pyongyang, DPRK, 2003

In 2002–2005, the author was directly involved in a collaborative Australian–DPRK project that evaluated the potential impact of a leguminous forage crop (*Vicia sativa*–hairy vetch), grown over autumn–winter–spring, on the production of the staple summer crops – rice (paddy) and maize (hill-slopes). At sites near Pyongyang and Anju City, the benefits of a legume phase included:

- a contribution of 40–65 kg N/ha, equivalent to about 90–140 kg/ha of urea each year, to rice production (Evans et al. 2009)
- a substantial decrease in water runoff and erosion in maize fields (P Eberbach, personal communication)
- enhanced forage supplies for farm livestock.

A search for additional cold-tolerant legumes (Evans et al. 2004) has yielded several annual *Medicago* genotypes as alternatives to hairy vetch, which is stemmy and fibrous in late spring. The future replacement of the fallow–crop system with the double crop (forage legume–cereal) short rotation (Fig. 11.7) will depend on: (1) the availability of P and K fertilisers needed by legumes; (2) the relative practicalities of incorporating, grazing or harvesting the green forage immediately prior to cropping operations; (3) the feasibility of substituting grazing for the laborious ‘cut and carry’ system of feeding livestock; and (4) the results of analysing the costs and returns of each system. A potential advantage in DPRK is that proven technologies can be adopted rapidly in the centralised, collective farm systems that prevail (Michalk and Mueller 2003).

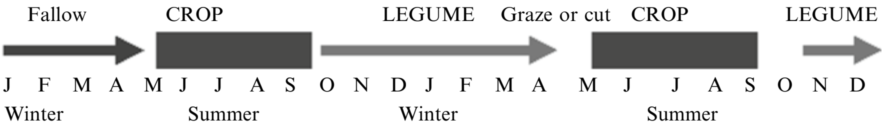

Fig. 11.7 Diagram of a potential forage legume–crop system instead of the current fallow–crop systems for paddy rice and hill-side maize in DPRK

11.4.2.3 System Example D – Rangelands and Croplands in a Semi-Arid Region of North Africa (Eritrea)

Eritrea is located at the eastern edge of the Sudano-Sahelo belt that crosses Africa between the latitudes of 10°N and 20°N. The country has an area of 120,000 km^2, a human population of approximately 4.2 million, 70–75% of whom are located in rural areas, and a livestock population that in 1998 comprised 2.0 million cattle, 2.1 million sheep, 4.6 million goats, 0.3 million camels, 0.5 million equines (predominantly donkeys) and 2.5 million poultry (Chedly et al. 2002). The country depends on its livestock industries for the production of meat, milk and hides, for cultivation by oxen and for transport by donkeys and camels. In addition, livestock constitute a 'walking wallet' for farmers and herders.

Broadly, the agricultural systems of Eritrea are livestock-dominant (Kruska et al. 2003). The animals derive more than 90% of their dry matter requirements from rangelands – most of which are in a degraded condition. However, there are important interactions between the livestock herds and the small areas of crop production. In the synergistic sense, animals consume crop residues, control weeds and provide draught power for sowing early in the wet season (June–August). On the other hand, almost all plant material is removed by animals during the long dry season (September–May), exposing the landscape to potential erosion during the wet season when monthly rainfall totals in the highland areas lie within the range 40–180 mm. Thus, the nature of land management during the dry season influences the production of the livestock and subsequent crops, the quality of natural resources (water, soil and vegetation), and human wellbeing (food security, air quality, and pollution). The introduction of forage legumes for livestock feed, soil fertility-building and fodder conservation could have far-reaching, beneficial impacts on agriculture and the environment.

The management and integration of crop and livestock activities in Eritrea are complicated by the system of land tenure, which is based on traditional land ownership rules. The government reallocates land every 7 years to farmers, ostensibly to ensure that:

- each family has sufficient arable land for subsistence purposes (1–2 ha)
- animals for food, draught and transport have sufficient common land for grazing
- the government retains the control of land in a strategic sense, for purposes such as catchment protection, defence and special development.

This modified-traditional system of land tenure spreads the responsibility for land and vegetation management. At one end of the continuum of responsibility, the government and its agencies can successfully intervene to protect the upper catchment of a river system for downstream irrigation. At the opposite (individual) extreme, it is remarkable how quickly livestock are removed to common rangeland areas from arable areas, which are rapidly planted once the rainy season starts. However, for the most part, the individual control of grazing is *ad hoc* and unsustainable, with overgrazing contributing to the rapid erosion of croplands.

In 2006–2008, with funding from the Australian Department of Agriculture, Fisheries and Forestry, Australian forage specialists undertook a collaborative 'Forage Options' project with officers from the National Agricultural Research Institute in Eritrea. They introduced and evaluated more than 400 varieties of tropical, subtropical and temperate forages. The evaluation and distribution of new legumes, grasses and shrubs for rangelands and farmlands in the main agroecological zones of Eritrea are achievable technical objectives. Several legumes appear promising (Wolfe et al. 2008), and some are well established in neighbouring Ethiopia; improvements in forage quantity and quality of around 20% could be expected.

The government has the authority and capacity to declare areas for protection or remediation, but Eritrea will need financial assistance to (1) embark on land/vegetation programs and (2) progress them to the point where they are productive, sustainable, profitable and equitable. New forages, particularly legumes, are a potential catalyst for systemic improvement towards achieving a balance between livestock production, cropping activities, vegetation protection and soil conservation at the catchment/regional scale. A start has been made towards these objectives in Ethiopia (Amede et al. 2005).

11.5 The Dynamics of Mixed and Integrated Farming Systems

Numerous factors influence the dynamics of mixing or integrating crop and livestock enterprises. Schiere et al. (2006) drew on their world experience to provide examples of the ever-changing balance of crop and livestock production within farming systems. Their examples included:

- In the north-eastern (subtropical) section of the Australian grains belt, cattle enterprises predominate over sheep. The commercialisation of new, perennial pasture legumes has, along with improved beef prices and the declining organic matter content of croplands, increased pasture sowings, cattle numbers and productivity, and the numbers of mixed cattle-crop systems (Whitbread and Clem 2004). The legumes include lablab (*Lablab purpureus*), burgundy bean (*Macroptilium bracteatum*) and butterfly pea (*Clitoria ternatea*).
- In Cuba (and DPRK), the collapse in the late 1980s of the USSR undermined the Soviet style of agriculture – a specialised crop production system based on cheap oil and fertilisers. With increasing prices for these inputs and their reduced availability, agriculture in these countries moved towards a low-input, mixed

farming model with animal production re-integrated as a source of recycled plant nutrients, draught power and food. In Central Asia and the Caucasus, a similar readjustment took place, but an additional driver was the 'environmentally damaging, specialised crop monoculture systems of the Soviet era, which left farmers with problems such as soil salinity, depleted groundwater levels, and crop pests and diseases' (Schiere et al. 2006). Currently, the Syria-based International Centre for Agricultural Research in Dry Areas (ICARDA) is developing solutions for Central Asia based on smaller-scale mixed farming approaches, with a greater reliance on pastures for soil fertility improvement and animals for income from meat and milk production.

- In Syria, Schiere et al. (2006) traced the transition from traditional village crop–livestock systems to animal-dominated systems (1970s) and then to specialised (largely separate) crop and livestock systems (1990s). Initially, the changes were driven by population pressures, competition for land, erratic rainfall patterns and out-migration of the rural population in favour of off-farm employment. Recently, rising incomes have stimulated the demand for meat, leading to policies that support specialised farms for barley grain production and intensive lamb production.

Entz et al. (2005) discussed an equally interesting set of examples to illustrate the evolution, over the last two to three decades, of crop–livestock interactions in world agricultural systems. They mapped the trends in crop and livestock production by way of a flexible state and transition model, which allows for multiple pathways towards diversification or specialisation, depending on circumstances. Their examples included:

- In West Africa, the independent nature of crop and livestock activities evolved into mixed farming, driven by the need to increase soil fertility by the use of grazed pastures. These developments were in turn driven by population pressure to increase food production.
- In India, urban centres have attracted dairies that rely on a network of specialised forage farms nearby. However, since the transportation of milk is less expensive than for forage materials, dairies are now moving out into rural areas and integrating with local forage suppliers.
- In Argentina, the transition of the pampas from natural and cultivated grasslands grazed by cattle (Viglizzo et al. 2001) to specialised cropping based on corn, soybeans and no-tillage technologies is being questioned on sustainability grounds (lack of perennial plants in the rotation, over-reliance on glyphosate). In Argentina and Uruguay, there is pressure on agriculture to reconsider the mixed farming and grazing systems, which are more stable ecologically (Viglizzo et al. 2001; Rotolo et al. 2007).

In Australia, the dynamics of mixed farming systems in Western Australia have attracted special attention in recent years because of the large scale of their agricultural enterprises and environmental problems, compared with the other Australian states. This large scale reflects the ease of farming on the sandy soils of

WA which suit broad-area wheat–lupin–canola–barley cropping and self-regenerating annual pastures based on subterranean clover, annual medics and serradella (yellow serradella *Ornithopus compressus* and pink serradella *O. sativus*). Environmental problems arise because these sandy soils hold little stored water. Clearing the original tree cover has rendered the farmed WA landscape susceptible to acidification and salinisation – consequences of drainage below the root zone of crops/annual pastures and thus raising the saline water tables. Ewing and Flugge (2004) used economic models to evaluate recent trends in mixed farming in WA. Although rainfall, soil types and product prices have influenced the ratio of cropping to livestock at which profit is maximised, profit changes are small over a substantial part (up to 40 percentage points) of the substitution range. Therefore, whilst some individual producers responded to low wool and meat prices by changing wholly to crop production during the last 20 years, most WA farmers retained their livestock and gradually increased their cropping area towards 60% cropping in the Central Wheatbelt Region (350–400 mm mean annual rainfall) and 20% in the Great Southern Region (550–600 mm mean annual rainfall). For the future, Ewing and Flugge (2004) argued that there will be an increase in livestock production at the expense of cropping area, driven by weed control problems in extended crop sequences, a rise in meat prices, the need for perennial species to reduce deep drainage through sandy soil profiles and climatic change (See also Chap. 26).

By way of comparison is the continuing downward trend evident in the livestock component of the cereal–sheep system in the Castilla–La Mancha region of south-central Spain (Caballero and Fernández-Santos 2009). In this integrated system, the main stakeholders are arable farmers and pastoralists. The pastoralists, most of whom are landless (80%), are squeezed by several factors, including: strict regional regulations that affect the mobility of flocks and their access to feed resources; European Union policies that contribute 32% and 13% of total farm income for cereal and sheep farmers, respectively; and a lack of professional shepherds. Arable farmers have no incentive to facilitate the sheep sub-system. Castilian sheep farmers are responding by either indoor feeding or exiting the industry. Consequently, large expanses of pastoral resources are underused and sheep farmers are more prone to the vagaries of the cereal grain market.

In summary, the balance of livestock and cropping in mixed and integrated farming systems is influenced not only by technological changes, for example new crops or high-quality pasture legume cultivars that enhance the marginal profitability of one enterprise over another, but also by broader-scale environmental, economic, social and political factors. The above examples indicate that productivity and short-term profit are likely to become relatively less important as the drivers of crop–livestock systems. Current trends indicate that the future of both mixed farming and crop–livestock integration at the regional level will be increasingly determined by externalities such as the availability and cost of oil and fertilisers, population pressures for increased food production, community attitudes and other socio-political considerations.

11.6 Enhancing the Future Success of Crop–Livestock Systems

Globalisation has removed the independence of farmers in one part of the world from those in other parts, potentially hastening the processes of readjustment needed to managing mixed farms and integrated agricultural businesses. Greenhouse gas emissions, the availability/cost of fossil fuels, water scarcity, climate change and population pressures are big issues that may transform the world's agricultural systems. These escalating issues increase the difficulty of drawing conclusions from trends to date in world agriculture.

In Australia, past agricultural R&D has been an important factor in mixed farmers steadily increasing their productivity (Angus 2001) through genotypic and agronomic improvements for crops (Turner and Asseng 2005) and pastures (Nichols et al. 2006). Other productivity innovations have been improvements in farm machinery (e.g. tractors and their guidance, minimum tillage seeders), the use of labour-saving devices (e.g. the ag-bike, computers and mobile phones), and identifying and building farm business skills. Further technical advances in the management of crops and livestock are important, and they are pursued diligently by researchers. As well, research and extension bodies have developed and promoted the use by farmers of protocols/tools/services for monitoring the productivity, sustainability (Ridley 2007) and financial viability (Clark and Harrop 2004) of their livestock and cropping enterprises.

In spite of this progress, there are problems at the system level that are unresolved. Although the ingredients of successful extension campaigns are now well known (Petheram and Clark 1998), personal and social constraints to 'adoption' still occur (Pannell et al. 2006). For example, on mixed farms in Australia, the lower prices for livestock products during the 1970s–2000 accounted for a declining focus on the pasture-livestock component of mixed farms. This phase may have created an anti-livestock mentality amongst farmers – one that contributes to the current poor performance of sheep flocks on mixed farms (Robertson and Wimalasuriya 2004). Now that (1) the outlook for the prices of livestock products has improved and (2) crop failures seem to be increasing in frequency, it is important to erase or overcome this mindset.

Globally, the management of farm businesses is becoming more complex in terms of scale and detail. Any attempt to capture the potential synergies available in mixed or integrated enterprises may require a combination of hard systems concepts and tools, such as farm management models, and soft systems approaches that involve farmers in the learning process (McCown and Parton 2006; Pannell et al. 2006). Soft system methodologies utilise interview techniques and group discussions to uncover the beliefs, attitudes and goals of the stakeholder groups and so steer a pathway towards an agreed state of 'system improvement'. It is desirable that each situation analysis should embrace ratings on productivity, sustainability, economic viability, social well-being and political acceptability (Table 11.1). The need for social indicators in agriculture is acknowledged but there are, as yet, no agreed protocols for the routine collection of these indicators. The example above of the

Spanish cereal–sheep system (Caballero and Fernández-Santos 2009) underlines the difficulty of implementing political 'solutions' in complex agricultural systems; in this case, specialisation has made the system even more complex politically.

The size/complexity issue has been an important driver of crop specialisation over the last several decades. However, there are sound reasons to retain and/or enhance animal production at the farm, regional and national levels. At least in some areas, grazing livestock, mixed farming and integrated crop–animal systems could be favoured relative to specialised crop production by the impacts of climate change on the amount and reliability of regional rainfall, by the diversion of water from rural to urban areas, or through more rational policies of food production and distribution. However, the escalating size of human population will ensure a high priority for crop production, provided world oil supplies are sufficient to sustain it. In all agricultural systems, there will be a need to conserve and ameliorate soils through the use of conservation agriculture (no-tillage, stubble retention) and biological systems (nitrogen fixation, carbon sequestration, nutrient recycling). More effective use will need to be made of crop stubbles (not burnt but perhaps part-harvested for animal use, leaving enough on the surface to protect the soil) and other waste materials for animal production, of animal and human wastes for fertiliser, and of all forms of waste for the production of industrial fuels.

The large size of farms is a particular constraint to the efficient management of mixed crop–livestock farms in the Australian wheat belt. Not only are there high average values for farm size (~2,000 ha in 2005/2006), cropping area and livestock numbers (see System Example A) but also the distribution of farm sizes is highly skewed: Kingwell and Pannell (2005) reported that in WA, the state with the largest average farm size, 25% of the grain growers deliver 54% of that state's wheat, while 14% of woolgrowers produce half the state's wool. In most cases, farms of this size are run by a single farm family with occasional outside labour. Kingwell and Pannell (2005) expect that the current trends in farm management (increasing complexity, more sophisticated management and greater reliance on outside advisory expertise) will continue. In their view, diversification also will continue, providing resilience to cope with further changes in the operational environment (jumps in fuel prices, shifts in consumer demand, changes in the policies of governments). Their concept of diversity embraced not only the core mixed farming system but also off-farm interests. Diversification creates additional opportunities to control agricultural pests and diseases, enhances the options for dealing with greenhouse gas emissions and helps achieve hydrologic stability through the use of more perennial plants. Kingwell and Pannell (2005) believed that the success of well-run, diversified farms will be underpinned by ongoing opportunities in grain and livestock markets, new crop and pasture options and a greater variety of livestock types and breeds. Also, farmers may cope through a greater reliance on contracted labour and professional services, innovations that promote technical and scale efficiency. However, depopulation in rural areas associated with further increases in farm size is another future consideration (Kingwell and Pannell 2005).

There still remains a basic conflict between the need to encourage diversity in on-farm enterprises and the pressure on farmers to simplify their enterprise mix in response to the drive towards larger scale. How will farmers handle the increased complexity of managing towards multiple goals (agricultural, environmental, economic, social and political)? What will be the impact on mixed/integrated farming of continuing local and global perturbations? This ‘specialise or diversify’ conflict could be addressed in several ways.

First, when farms become bigger there are extra opportunities to delegate management responsibilities to individuals in the family, allocating them a specific enterprise to manage while still preserving the family partnership in mixed or integrated crop–livestock production.

A second possible way of allowing specialisation within Australian mixed farming systems may be to sever or vary the traditional link between livestock ownership/control and land ownership, and develop new partnerships that place crop and livestock operations in the care of enthusiasts. For example, a livestock specialist could be responsible for livestock production on (say) 5–6 mixed farms, providing livestock services to crop specialists while exploiting economies of scale through larger flocks and the consolidation of livestock facilities (yards, shearing sheds, supplementary feeding set-ups) across several farms. In Sect. 4.2.1, reference was made to the flexibility of current business arrangements on the US Southern Plains, sometimes involving three parties – a wheat farmer who rents land for wheat farming and leases the grazing rights to a cattle owner (F. Epplin, personal communication).

A potentially useful analogy for mixed crop and livestock production in the Australian wheat belt and further afield, and perhaps for integrated crop and livestock businesses in developed and less-developed economies, comes from the field of grape and wine production. These ‘wine-growing’ operations are integrated but under the separate control of viticulturists and winemakers respectively. Such arrangements encourage simultaneous specialisation and integration so that the main enterprises operate at larger scales, leading to savings in the cost of infrastructure, such as wineries, combine harvesters (wheat) and shearing sheds (sheep). However, because the adoption of innovations involves complex social factors (McCown and Parton 2006; Pannell et al. 2006), new business models will need to be introduced cautiously and nurtured carefully.

Thus, there are pressures on professional agriculturalists to broaden their focus on sustainable productivity to include wider issues, such as the responsible use of natural resources and the socio-economic well-being of farmers and rural communities. Agricultural scientists and farmers need to be more aware of ‘non-linearities’, a term used by Schiere et al. (2006) to encompass processes that interact rather than behave in a straightforward manner (Fig. 11.3a–d), and exploit these interactions. Schiere et al. (2006) referred to important events, such as the ‘dust-bowl’ era on the North American Great Plains, the post-World War II boom in pasture improvement in Australia and economic reforms in China, that produced ‘non-linear paradigm shifts’ or ‘mode changes’ – rapid rather than incremental advances or failures – in agricultural systems. Future perturbations to world agriculture arising from climate change or fuel shortages may interact with agroecosystem types (Table 11.1) or government policies, and trigger major changes to agricultural systems.

The challenge for agronomists, animal scientists, economists, social scientists, bureaucrats, politicians, merchants and farmers is to maintain a capacity for big-picture analysis and improvement. As well as education, research and development in the fundamental disciplines and in trendy areas such as genomics, there must be continuing investment in professional studies to enrich ‘agricultural systems’. Systems specialists are needed to assist farmers and agribusiness sustain and enhance mixed farming and other integrated models, and so retain the diversity and resilience that protects world agricultural landscapes and communities.

11.7 Conclusions

The systems examples revealed a range of ways of managing and integrating crop and livestock activities, depending in part on tradition, rainfall (and hence cropping intensity), type of agriculture (from subsistence to industrialised agriculture) and scale. Around the world, mixed crop–livestock farming is now secondary to the systematic integration of separate crop and livestock businesses. The main reason for integration rather than mixing of crop and livestock enterprises is that it is simpler for farmers/managers to concentrate on the components (crops, livestock) of integrated agricultural businesses. The continued popularity of mixed farming on arable lands in Australia is due to the need to improve and maintain soil fertility, which was initially low; leguminous pastures on mixed farms enhance both sheep production and crop production. Further, the pasture–sheep enterprise buffers farm incomes during poor crop production years, which may be increasing in frequency due to climate change

In terms of managing the potential interactions between livestock production and crop production, similar principles apply on both mixed farms and in integrated crop–livestock businesses. The challenge for managers is to understand and manage these interactions in order to release synergy and offset antagonism. However, there are some important differences between these forms of agriculture. First, mixed farming is controlled by farmers whereas integration also involves managers and regional authorities who may view ‘farming’ more in business terms than the farmers, who also regard it as a way of life. Second, integrated businesses may occur at a larger scale and over greater distances than mixed enterprises; hence more mechanisation and greater fuel energy use is usually involved per unit of agricultural output. This potential loss of efficiency may be offset by the benefits of scale and specialisation. Furthermore, there are potential community benefits through optimising the location of the regional enterprises, such as the placement of animal production facilities remote from towns and of processing works near them.

The future may bring greater operational diversity in agriculture, at least at the regional level. Resource limitations and other constraints may encourage many farmers to seek a lower input, more ecologically-focused production system such as mixed farming. However, the strong demand for food may lead to a greater number of larger, specialised farms that achieve synergy through integration with complementary businesses. At a world level, the range in the types of agriculture, from subsistence to high-input agriculture, will remain the same but the ratio of these types will vary from the present to the future and from country to country. In Australia, the complexity of managing large, mixed farms may be offset through innovative business partnerships that not only retain mixed farming (diversification) but also encourage simultaneous specialisation, essentially by separating the management of crops and livestock and placing each enterprise into the hands of enthusiasts. Greater benefits may come from innovation in the economic and social aspects of agriculture, rather than refining the technology of production.

Acknowledgments I thank Dr JB (Hans) Schiere and the editors of this book for their interest in and contributions to the production of this chapter.

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Chapter 12
Economic and Social Influences on the Nature, Functioning and Sustainability of Rainfed Farming Systems

Ian Cooper

Abstract Farm systems are designed by humans to produce a desired product; they require a holistic view that considers the impact of the managers of the system. Many factors will influence the goals of farm managers and how they operate their systems. Physical, technical, social and political influences both within and from outside the farm are discussed along with lifecycles, functions and fields of management.

Keywords Management • Goals • Technical • Social • Political • Economic factors

12.1 Introduction

Farming systems are created by people – individuals and families. Thus, to understand these systems, it is necessary to consider the factors that influence farmers in their choice of system structure, their management and the effect of their actions on the productivity and sustainability of the system. These factors are examined in this chapter.

The farmer or farm family can be regarded as an external influence or an integral part of the system. As an external influence, the farm family has an input of labour, finance and management. However, if feedback mechanisms operate between the farmer/farm family and the biological/physical components in the field, these people should be considered an integral part of the system. Either approach is acceptable depending on the purpose of the system study or analysis. For many purposes, it is probably more useful to regard the farmer as part of a wider system, interacting both with the physical-biological farm system and with various other family, economic, cultural, social, political, environmental and technological issues. This chapter explores some of these interactions and how they affect the design and structure (nature), management and operation (functioning) of the system and its ability to respond to change (sustainability).

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_12,

12.2 The 'Whole-Farm' Business System

Most farms are family businesses. Understanding how farm families manage their businesses involves an understanding of the 'whole-farm' business system, as well as the economic and social systems beyond the farm gate. Analysing 'farm management' is about understanding why managers make changes in the resource use on their farms. Farm management is the process by which managers consider the information they have about the resources available in farm systems and the potential for improvements. They can then evaluate the potential costs and benefits of any change and make a decision based on their goals (Malcolm et al. 2005).

It is important for farmers to consider all the aspects of their system to achieve goals that may include a quadruple bottom line of financial gain, environmental improvement, viable society and protection of cultural heritage. However, this does not remove the need to understand the physical and biological farm system to ensure its productivity and sustainability.

12.2.1 Goals of the Farm Family

All farm families will have their own set of goals that will affect the way they operate their system. A sustainable farming system will have an interacting set of aims that include environmental goals, natural resource conservation objectives, economic priorities, production goals, family quality-of-life objectives, local community quality-of-life activities and needs of the wider community (Kelly and Bywater 2005). Managers and farm families have to reassess these goals continually as economic, political, and environmental conditions change along with family relationships and situations. When considering why members of a farm family do or do not take actions that will affect the farm system, the starting points are with their needs, wants, stage of life, history, view of the future and attitudes to risk. Most farmers want to "do a bit better and to make a bit more gain in the short and long run, when most, but not all, of the gain is profit. This applies as long as they don't have to sacrifice other things they value highly, such as health, family life, leisure, and outside interests" (Malcolm et al. 2005).

12.2.2 Influences on Individual Goals and the Management of the Farm System

Some of the processes and factors that should be considered in managing a farm system are indicated in Fig. 12.1. The figure shows that management functions, management fields and 'life cycles' all interact. The many influences on management can be classified as physical, technological, social, political and economic.

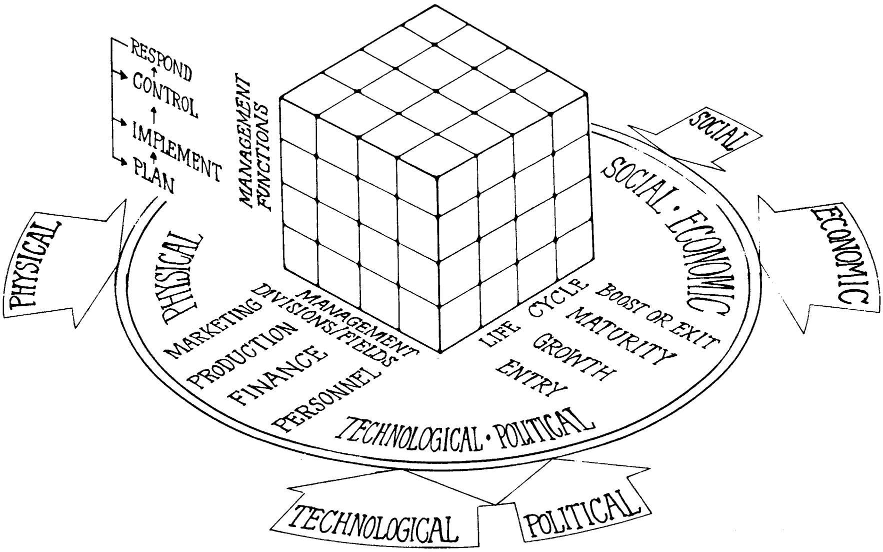

Fig. 12.1 The management cube: influences on management of a farm system

They may arise either within the farm system – where the farmer may have some control over them – or be external from the wider environment – over which the farmer has little control.

These influences on the farm system have a profound effect on the decision making of the farm family and hence the operation of the farm system, as discussed in the following subsections.

12.2.2.1 Physical Factors

The physical factors internal to the farm system (such as topography, soil condition and water-holding capacity, biological processes and perhaps resistance of plants and insects to chemical control) are covered in detail in other chapters. In some circumstances, the stress of adverse physical conditions (such as prolonged drought) could affect a manager's decision making, attitude to risk or, in severe cases, the stability of the farm family and consequently the farm system. External physical factors are harder to differentiate from social and technological factors but land and water availability, climate, climate change and issues of sustainability could be considered as they impact on the other influences (technological, economic, political and social) on the farm system. For example, climate change is currently at the forefront of technological, economic, political and social decision making.

On a world scale, there are three main sources of increase in agricultural production: expanding agricultural land area, increasing the intensity of use (often through irrigation or reduction in fallowing) and boosting productivity (generally though increased yields). A number of countries are approaching the limit of what is possible in one or more of these. The Food and Agriculture Organization of the United Nations (FAO) predicts that, in the future, less new agricultural land will be opened up than in the past. They predict an increase of 12.5% over the coming 30 years, only half that of the previous three decades. They also predict that water (both in rainfed and irrigated agriculture) will be a major limiting factor particularly in South-east Asia (FAO 2002). The consequences of these predictions are that farming systems will have to produce more with less water.

FAO (2002, 2008) suggests that while global warming is not expected to depress food production at the global level, it may have severe impacts at the regional and local level. Their current expectations are that the potential for crop production will increase in temperate and northerly latitudes whereas it may decline in parts of the tropics and subtropics. Rising sea levels may threaten crop production and livelihoods in countries such as Bangladesh and Egypt with large areas of low-lying land. The effect of climate on rainfed farming systems is discussed in Chap. 3; it is likely to increase uncertainty and risk for farm decision makers. The dual challenges of climate change and limitations on land and water will need to be addressed by both researchers and farm system managers, and will require an understanding of both the technological and economic issues. For example, producing a genetically-modified (GM) variety that requires less water would be of little value if it is expensive or risky to grow or if there is a limited market for the product due to consumer resistance to GM foods.

In developing countries, the main pressures threatening sustainability of agriculture are likely to be those emanating from rural poverty as more people attempt to extract a living out of dwindling resources. When increased population pressures occur in an environment of fragile and limited resources and when the circumstances for introducing sustainable technologies and practices are not propitious, the risk grows that a vicious circle of poverty and resource degradation will set in. For example, the shortage of fuel for household use in many developing countries has led to either deforestation or to animal dung being burnt for fuel rather than returned to the land. The poverty-related component of environmental degradation is unlikely to ease before poverty reduction has advanced to the level where people and countries become significantly less dependent on the exploitation of agricultural resources. There is considerable scope for improvements in this direction and there is a range of technological and policy options that could be adopted. Technological improvement may include biotechnology, no-till or conservation agriculture and lower-input approaches of integrated pest management. The FAO believes that provided such improvements in sustainability are put in place, pressures on world agricultural resources could ease in the longer term with reduced pressures on the physical environment (FAO 2002).

12.2.2.2 Technological Factors

Changes in technology offer promise of improved production and alternative ways of managing farm systems. The implications of technological change are discussed in Chap. 7. However, changes in technology can impact on the farm manager's goals and ability to manage the farm system.

To remain viable, managers of farming systems must evaluate and adapt new technology to their particular situation. This is not always easy and increasing access to information can result in information overload (Wesseler and Brinkman 2003; Robbins et al. 2003). In developed economies, so much information is available that farm managers may have difficulty establishing what is relevant to them. Anecdotal evidence gathered by the author from South Australian farmers indicates they have difficulty choosing what organisations and other information sources to subscribe to. Many are turning to the internet as a source of information but this may exacerbate the overload problem. Easdown and Starasts (2004) state that the internet content lacks appropriate context and does not match the way that farmers make decisions.

Information is a key input of any system and is invaluable to any business (Kohl 1999). Wesseler and Brinkman (2003) see it as a prerequisite to development. "Without the exchange of information, no innovation would be able to spread. However, to be useful, information has to be relevant, reliable, timely, and delivered via an appropriate medium." The key to successful communication of information is a tailor-made approach combining a range of different and locally appropriate means.

Information gathering and use may be related to the age/lifecycle stage of the manager. This cycle is discussed later.

Biotechnology offers promise of more sustainable choices in management provided its perceived threats to the environment are addressed (FAO 2002). Genetically-modified crop varieties – resistant to adverse conditions – could help sustain farming in marginal areas or reduce the use of pesticides, but their widespread use depends on their public acceptance.

12.2.2.3 Social or Family Factors

That most farms are managed by farm families adds an extra dimension to the decision making. Decisions are made not only to satisfy the business but also the needs of the farm family and must consider their attitude to risk.

In developing countries, food security – having enough food to feed the farm family – continues to be a high priority, and this concern may inhibit entrepreneurial activity (system change).

Passing the farm to the next generation is a goal of many farm families, and any decisions have to take into consideration the effect on future generations. Families want to protect their assets and avoid unnecessary taxes.

Planning is needed if one of the next generation wants to join the farming enterprise (Stephens 2003). This may lead to changes in the farming system – for example increasing income by increasing the stocking rate considerably with consequent need for more fertiliser, fencing and feed-lotting of animals in some seasons. A son or daughter returning to the farm after extended education or training may have different ideas; this may be an opportunity to create a more efficient or stable system or be a source of family conflict.

Succession planning is a complicated process involving the farm family and legal and institutional requirements. Often there are more family members than the farm can support. The assets need to be divided fairly – not necessarily equally. Planning must be started early to provide for children not returning to the farm so that undue stress is not placed on the system in the future. Funds may have to be invested off-farm to satisfy non-farming family members, and this may place constraints on the management or improvement of the farm system.

There are many social influences from outside the farm on its decision making although it is often difficult to distinguish between what is 'social', 'political' or 'economic'.

Particularly in developed economies, there is an increasing shift in consumer attitudes (e.g. Ballenger and Blaylock 2003). Cost, quality, taste and availability will still be important but the structure of the farm system will be influenced by pharmaceutical standards of research, production, distribution and pricing (see also Chap. 13). Key elements will be transparency and traceability (Urban 1998). The impact of these and other 'quality' requirements are discussed below.

Public perceptions about the environment are resulting in governmental efforts to protect the natural ecosystems. For example the potential harm of unfettered tree clearing (e.g. salinity, erosion, carbon emissions) has caught the public's attention, and many governments are trying to curtail it. Fundamental differences between farm business growth and profit objectives and public environmental concerns will force government to enact legislation for environmental protection. Farms will be required to track environmental practices and keep the non-farm public informed (see Chap. 27). Kohl (1999) predicts that, in the next 25 years, top producers will have to develop systems to obtain the most out of their resources in a more natural, biological manner (in contrast to an industrial approach) in order to survive.

12.2.2.4 Political or Institutional

Within the farm, there are political and institutional matters that will affect decisions on how the system is run. Families often consist of a number of generations, each with partners marrying into the family. This can lead to 'political' difficulties and issues; for instance, a daughter-in-law may feel she is not given proper recognition in the family decision making. As the long-term sustainability of a farm may rest on harmonious family relationships, the legal structure of the farm is carefully planned. The break-up of a marriage of one of the farm family could lead to the break-up of the farm itself. Another source of conflict could be disagreement between generations in the way the farm should be run. These types of disagreements mean that the management of the farm is unlikely to be the most efficient or effective.

Changes are occurring in the legal and organisational structure of many agribusiness firms including larger farms. Increasing investments are being made in 'soft' assets of research and development, human resources,[1] and an organisational structure that can respond quickly to changing consumer demands and environmental conditions. For example, farmer groups in Australia are engaging in more on-farm research specific to their needs with the help of public and private research organisations. Hard assets including machinery and equipment are increasingly being obtained through leasing, joint ventures (equipment sharing) and strategic alliances Australian Productivity Commission (2004). This may impact on how we view the farm system, and makes it more difficult to decide where to draw the 'boundaries'.

In many countries, the taxation regime can influence decision making. Managers should concentrate on profit maximization and not place undue importance on tax minimisation.

Over the last few decades, many countries have seen a shift from traditional production-driven agriculture to a market-driven agriculture. Producers no longer grow a crop and then hope someone will buy it, but produce a product for a predefined market. In developing countries, producers are having to move from mainly subsistence systems to those that produce goods for sale. Farmers have become more businesslike, with marketing and finance decisions being as important as production ones. Greater emphasis has needed to be given to the financial efficiency and sustainability of the business (Malcolm et al. 2005).

Agricultural change is being driven by technological innovation and by global market forces, by change in institutional arrangements among input supply organisations, and increasingly by commercial firms, organised in extended processing and marketing chains. Although most people still 'think at the farm level' when talking about agriculture, farming has increasingly become part of larger systems and organisations, both government and private, of increasing geographic scale, i.e. national and global rather than local (Jiggins et al. 2004). A farmer considering a change to his system can no longer only consider the effects on the farm but also how it may affect the processing of the product and the final marketing of it (see also Chap. 13).

In developed countries, and increasingly in less developed countries, there has been an industrialisation of agriculture with increased integration, coordination and partnering of firms in the agricultural supply chain. Relationships and cooperation between these firms have become more important with less emphasis on adversarial (win/lose) arrangements. For instance, it has become common, particularly in developed economies, for farmers to establish a relationship with a particular supermarket company. The farmer has to adapt the farm system to deliver the required quantity and quality of a product and receives a premium price; the supermarket is guaranteed supply.

Food processing is being concentrated in the hands of relatively few transnational companies that require large quantities of consistent, reliable and safe products. For example, Walmart had a turnover in 2004 of US$250 billion, equivalent to the GDP of a small country. This concentration tends to disadvantage the

[1]Competent workforce with up-to-date skills, motivated and adapted to the organisation.

small producer who has to accept the price offered by the large companies. In order to remain viable, small producers have to join together (for example, establish a cooperative) or find some way of differentiating their product (for example, becoming organic).

The chain between producer and consumer is shortening with large producers marketing direct to processors or retailers. The chain between input manufacturers and farms is also changing with large farmers or farmer 'groups' dealing directly with manufacturers. Chemical, seed and machinery suppliers are becoming more integrated, and there is a greater emphasis on patents and property rights to obtain profits from company-funded research. This group is also becoming heavily involved in advice or 'extension'. 'Bundling' of inputs (including finance and advice) has become common. Large chemical firms are supplying patented seed and specifying many of the production processes with an obvious effect on the farm system.

There is an ongoing reduction in the number of farms and increase in farm size. In many developed economies, a relatively small proportion of farms will produce most of the output. In the USA it is reported (USDA 2007) that as few as 30,000 farms (1.4% of total) produce nearly half (46.4%) of all agricultural products. This has led to a steady increase in part-time farming as smaller units need outside income to survive in a sustainable manner. Large-scale farms should be able to be financially sustainable and thus capable of adapting their systems to improve their production and environmental sustainability.

It can be argued that agriculture is inextricably linked to social and environmental benefits that cannot otherwise be produced by society, and so should be provided with support to continue to provide such benefits. This is usually termed 'multi-functionality'. The 'functions' have been divided into negative externalities[2] and positive externalities. The former may include destruction of ecosystems, habitat or vegetation and pollution by chemicals, manure and greenhouse gases. Positive externalities include conservation of open space and rural landscapes for aesthetic reasons or as wildlife habitats, locking up of greenhouse gases in soil and plants, improved rural viability, food security, cultural heritage, as well as plant, animal and human health. There is a debate as to whether these externalities can be separated from agricultural production (Blandy 2004). If they cannot, they are a further set of factors that the manager of a farm system must take into account.

Industry assistance is an example of hierarchy of systems. When one sector of the economy receives special treatment such as subsidies or tax concessions, the competitiveness of other sectors will be reduced as they will have to pay more taxes. Further, the supported industry will be larger than it otherwise would be and will therefore use more inputs such as labour and capital (Australian Treasury 2006). For example, the Australian Productivity Commission (2004) found that government subsidies to the ethanol industry raise the price of wheat products, and so raise the cost of feed for the pork industry.

[2]In economics, an externality is a cost or benefit resulting from an economic transaction that is borne or received by parties not directly involved in the transaction.

The agricultural sector, particularly in developed economies, is coming under increasing scrutiny because of its contribution to environmental degradation, particularly in relation to water pollution by nitrates, phosphates and pesticides, together with soil salinisation, acidification and erosion. This scrutiny will be enhanced by improved scientific analysis, instrumentation and monitoring techniques. The result will be an increased vulnerability of the sector to regulation or liability (Boehlje et al. 1995). This, and consumer concern, has led to an increased emphasis on quality and quality management (see Chap. 27). National and international bodies have set guidelines for food safety and hygiene – for example the joint FAO/WHO Codex Alimentarius[3] established in 1963, the European Food Safety Authority, and Food Standards Australia and New Zealand. A number of countries have introduced Good Agricultural Practice (GAP). This lays down methods of land use which can best achieve the objectives of agronomic and environmental sustainability. They are described in several different Codes of Practice designed by producers' organisations, importers' and retailers' consortia and government bodies representing consumers. Many supermarkets have, in addition, their own codes of practice which their suppliers must satisfy. American retailers use a different standard called SQF 2000, which is based on HACCP (Hazard Analysis and Critical Control Point systems) (Luning et al. 2002, 2006).

The European Retailers Group (EUREP) is attempting to consolidate the agronomic and environmental components of all these codes into one universal set of rules or guidelines under the name EUREPGAP[4] (EUREP Good Agricultural Practice). This is intended to present a clear message to suppliers and to reduce the confusion that flows from the current multiplicity of codes. The EUREP website sets out the rules and procedures which growers or traders must comply with in order to qualify for EUREPGAP certification.

These standards have obvious system management considerations including the control of persistent chemicals in soils, and reducing possible contamination of food by fertilisers, soil additives, water and people.

All of the above are part of the external environment that the farm decision maker faces. They will affect the choice of crops or livestock to be produced and how they are managed.

12.2.2.5 Economic Factors

The purpose of a farm system is to produce products for consumption or sale and so improve the farm family's life. Decisions on what to produce have a pervasive influence on the nature of the system. In the long term, the demand for a farmer's products and the price he receives is determined by the economics of food production and consumption. The consumption patterns of agricultural products vary

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[3] http://www.codexalimentarius.net/

[4] http://www.eurepgap.org/Languages/English/about.html

between and within countries and over time. Economists measure longer term trends using **income elasticity of demand**. This measures the degree to which consumers change their consumption in response to changes in income. For low income families on 'subsistence' diets, a high proportion of increased income may be spent on food. In wealthy, developed countries where only 20% of income goes on food, increased income has little effect on food purchase. As incomes increase, consumers become more interested in factors such as convenience, healthiness, and freshness (Martin et al. 2005). While these factors are often more under the control of others in the marketing chain, the requirements of supermarkets have an increasing influence on the design of farm systems.

In the medium term, consumers' decisions on what product to buy are determined by price and quality. The effect of price changes on purchasing varies with the product. Consumption of products that are necessities and that have few substitutes (e.g. petroleum in developed countries) are not affected much by price changes while luxuries or those products with a range of substitutes are highly responsive to price changes (Martin et al. 2005). These economic concepts will affect the choice of crops and livestock in a farm system and the way they are produced.

In most developed countries, farmers are facing a declining 'terms of trade' or a 'cost-price squeeze' – the prices they pay are rising faster than those they receive. Fig 12.2 illustrates the declining 'terms of trade' over the 30 years to 2007 in Australia and the USA.

In order to survive, farmers have had to improve their productivity. Often this requires an increase in scale that can be achieved by intensifying, or by expanding the farm by buying or leasing land. Either option will have ramifications on the operation of the system. Intensification, such as moving to higher value, more

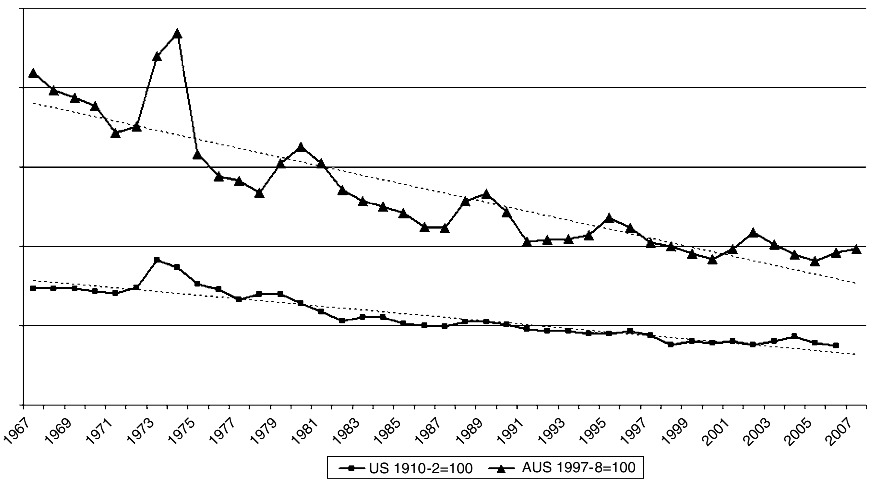

Fig. 12.2 Terms of trade, Australian (1966–1997 to 2006–2007) and USA farms (1967–2006) (Sources: ABARE (2008); USDA-NASS (2008))

closely managed crops, requires considerable change in the system. Buying more land can necessitate changes in machinery operations and increase time pressures; either existing machinery has to work longer or new, larger capacity machinery must be purchased.

The ‘cost–price squeeze’ is generally accepted as one of the main reasons for the increase in farm size and the fall in numbers of farms in developed economies.

One way farmers try to improve their returns is through paying more attention to the marketing of their products. Many farmers deal in large volume, undifferentiated commodities with low, and probably declining, margins. Such products are sold on national or world markets and the farmer can do little to influence the price received. If farmers can produce a certain volume of a commodity to the specification required by a processor, they may be able to negotiate an attractive return. For example, some farmers in South Australia produce wheat specifically for a local pasta manufacturer; other producers have tried niche marketing of highly specific products (for example organic) to improve their returns. A further option is for producers to try to capture some of the returns from further up the marketing chain by processing or value-adding their products. Whichever option is chosen, it will affect the final product and hence the whole production system. For example, moving to wheat of specified protein content and other required characteristics requires careful manipulation of fertiliser regimes as well as close monitoring of the crop and attention to all aspects of production.

In the past, farmers were less aware of their links with the external economic environment; they tended to concentrate on production and hope buyers would accept the products at a reasonable price. In order to survive and prosper, they now need to be aware of consumers’ needs and produce to meet them. Once again, a systems approach is needed as many of the decisions about the management of the farm system will be dependant on consideration of the requirements of the consumer.

World trade in food and fibre is increasing with better transport and communication, aided by lowering of trade barriers, the so-called ‘globalisation’ of agriculture. Every operator in the system (including every farmer) is in competition across the globe with the best in the world. The 200 largest transnational companies account for 25% of the world’s economic activity (FAO 2001). Globalisation affects not only the marketing of agricultural products but also sources of agricultural inputs and research and development activity (Boehlje et al. 1995). This globalisation of food and agriculture presents both opportunities and threats to producers. It has generally led to reduced poverty in Asia (through providing better paying markets for their products), but the rise in power of multinational companies has the potential to disempower farmers in any country (FAO 2002).

Globalisation has tended to lead to increased volatility of world markets. This has implications for risk management by individuals, producer organisations or government bodies.

Small businesses are under pressure from larger ones. Small businesses have limited purchasing, information and marketing power, and lack economies of scale and limited access to capital. Particularly in developed economies, restructuring of both farms and agribusiness firms is likely to continue. Mergers and acquisitions continue in the input supply, farm production and product processing sectors, which will reduce competition. Reduced numbers of farms will mean fewer customers and larger areas for input suppliers, increasing suppliers' costs. These trends will apply upward pressure on farm input costs.

Consumers are becoming used to considerable product choice, year-round availability, product consistency, inexpensive food, convenience and food safety. This will influence what farmers choose to produce. However overall, the growth in demand for agricultural products is likely to decline from an average of 2.2% over the 30 years to 2002 to 1.5% for the next 30 (FAO 2002). This is attributed to the slowing in population growth rates since the 1960s, and to fairly high levels of consumption per person being reached in many countries. But a high proportion of the world population remains in poverty and so lacks the necessary income to increase demand for food.

The world as a whole has been making progress towards improved food security and nutrition. Agricultural trade will play a larger role in securing the food needs of developing countries as well as being a source of foreign exchange (FAO 2002). For this to occur, international trade barriers must be lowered and appropriate policies developed by the governments of developing countries. The latter include removal of domestic bias against agriculture; investment to improve product quality to the standards demanded abroad; and efforts to improve productivity and competitiveness in all markets.

In making management decisions, producers must be aware of all the changes in the factors affecting their farm system (Fig. 12.1). They must also consider the production and marketing of their products, together with the requirements that this places on the operation of their system.

12.2.3 Risk Management

The decisions made about a farm system will depend on the decision makers' attitude to risk – which varies amongst farmers and with individuals over time. While risk worries decision makers, its existence creates opportunities and rewards for business people to capture. There are many sources of risk for farmers. Topp and Shafron (2006) list five:

1. *Production risk*: This includes risks that derive from the uncertainty of production processes of crops and livestock due, for example, to weather, disease or pests.
2. *Price or market risk*: Refers to uncertainty about the prices that producers will receive for commodities or the prices that they pay for inputs. The nature of price risk varies significantly from commodity to commodity.
3. *Financial risk*: Occurs when the farm business borrows money and creates an obligation to repay debt. It includes rising interest rates, the prospect of loans being called in by lenders, and restricted credit availability. It is related to

production and price risk in that low production or poor prices can precipitate financial problems.

4. *Institutional risks*: Occur from uncertainties about government actions. Tax laws, regulations for chemical use, and changes to quarantine and other trade barriers are examples of government decisions that can have a major impact on the farm business. They include the possibility that future governments may change the size or nature of assistance policies.
5. *Human or personal risk*: Includes factors such as problems with human health or personal relationships that can affect the farm business. Accidents, illness, death, and divorce can threaten a farm business.

There are other more subtle sources of risk for farm managers (Martin 2005):

- *Technological risk*: May arise where the value of current investments in assets may be reduced by technical improvements in the future. New technologies may impact on the profitability of farming systems, and new practices may be adopted at the wrong time. Examples include purchasing a new piece of equipment just before the release of an improved model, or release of a new variety which may lower the value of seed produced of an existing variety.
- *Scale risk*: This can occur where the farm is too small and if the economic size of a farm unit grows larger than the current managers can cope with. The 'cost-price squeeze' means that small farms tend to become uneconomic, and they may not have the capacity to grow. Generally as a business grows it becomes more complex. This may require more specialised knowledge to run it, and the current managers may not have the ability to learn. An example could be that the business grows to an extent that additional staff must be employed, but the manager may not have the skills to effectively manage them.

Producers can use various strategies to adjust and manage their risk. These include diversification to spread risks (i.e. not 'putting all your eggs in one basket' and having a range of crops or a mixture of crops and livestock), minimising areas of 'risky' crops and adopting farming practices that reduce risk. Other strategies, apart from maximising income and minimising costs, are off-farm investment and income. Many families survive on small farms only because family members work outside the farm and bring in additional income. Marketing strategies such as forward selling and hedging are sometimes available but some farmers prefer to 'leave it to the experts' and concentrate on the production at which they are more skilled (Martin 2005; Nguyen et al. 2005).

12.2.4 Whole-Farm Planning and Systems Approach to Managing Farms

During the 1950s and 1960s, researchers, farm managers and their advisers began to develop systems thinking and the 'whole-farm approach' to the management of farms, i.e. they began to see the organisation as a collection of interacting parts that need to be viewed as a whole. The internal and external environment of the farm business was also seen to be important. The systems approach encouraged researchers to consider all the components of agricultural science (such as soil science, plant science and animal science) together as part of the one business. It also led agronomists and other advisers to consider the whole farm, including economics, rather than just a specific technical problem. Initially, there was a 'hard systems' approach based on quantitative science and economics but this has developed to add a soft systems approach that includes the more qualitative aspects including the influence of the farm family, wider community and environmental issues (Shadbolt and Bywater 2005).

What economists term the 'marginal principal' provides a useful perspective when considering changes to a farm system. 'Marginal' here means additional in that the additional returns or benefits of a change to the system exceed the additional (marginal) costs (Shadbolt and Bywater 2005). A systems approach ensures that all the costs and benefits are included in the analysis.

12.2.4.1 Levels of Decision Making

Farm decision makers have to operate on a number of levels and time frames. Usually these are divided into operational, tactical and strategic. Management at an **operational** level is concerned with the efficiency of implementation and control of everyday operations.. These include planting or fertilising a crop, animal husbandry, and harvesting. Operational decisions require technical expertise and tend to be well-structured, i.e. the desired outcome is known and the information is available from within the business. The required information may be detailed and usually known with some certainty, as in applying a particular herbicide at the recommended rate to kill a problem weed. However, interactions with other parts of the system and the need to prioritise activities should also be considered.

Tactical decision making involves what needs to be done in the short to medium term to achieve the aims of the business – such as the detailed planning of production to achieve sales in a specific market. It is about efficient acquisition and allocation of resources. Time frames for tactical decisions in farming tend to be associated with the biological cycles of the crops and livestock. They may range from weeks in the case of vegetables and chickens to years for beef production or fruit trees. Annual cycles are common. Problems and their solutions are relatively well defined but there is a greater degree of uncertainty than in operational decisions, arising from the nature of biological processes, the unpredictability of climate and markets, and the limitations of our knowledge of how the farm system will respond to particular conditions or actions.

The **strategic** level is about the overall vision for the long-term future and includes decisions on the size and scale of the business and whether to diversify or intensify. Strategic decisions are quite different from operational and tactical decisions. They are made infrequently but can have a very large impact on the future of the farm. The purpose of strategic planning is to achieve a sustainable long-term excellent fit for the farm business with its physical, social, economic and political environments (Shadbolt and Bywater 2005). Operational and tactical decisions derive from this overall strategy for the farm business. The time-frame for strategic decisions is long and the information required less precise and more difficult to acquire than for other decision making.

12.2.4.2 Processes of Decision Making

The process of decision-making has been studied extensively. McGuckian (2006) has applied Snowden's (2003) theories of decision-making to mixed farms. Mixed farms, i.e. those with crop and livestock enterprises, are predominant in Australia and common in most rainfed agriculture. McGuckian classifies decisions as simple, complicated or complex.

Simple decisions are ones where there are few variables and a clear right or wrong answer – for example how much drench to give a 45 kg wether.

Complicated decisions are defined as those where a number of variables are involved, but the relationships between the variables are 'clear and well documented'. Deciding on a disease management program for a crop would be considered complicated. Complicated decisions require expertise and experience, but information and advice is usually readily available.

Complex decisions arise when 'a number of complicated decisions come together and interact, and trade-offs cannot be quantified or weighed against each other'. For example, deciding what type and how many livestock to run on a farm which also has a range of crops is a complex decision. Decision-making theory (Snowden 2003) suggests that farmers improve their complex decision making by 'story telling' – they learn by discussing options with others. Decision theory also suggests that individuals establish a set of boundaries or principles within which they make their decisions, for example 'not putting all my eggs in one basket', and then adjust their systems to suit. Past experience is important in making complex decisions, and this tends to lead to a conservative approach. Chapter 30 has more detail on farmer decision making

12.2.4.3 Dimensions of Management

'The management cube' (Fig. 12.1) indicates that there are at least three 'dimensions' to management.

1. The first dimension comprises the areas of business expertise or 'fields' of management that are required. These are generally defined as production, finance, marketing and human resources.

   - *Production management* involves making decisions on technical management to ensure a high-quality, saleable product while maintaining farm resources.
   - *Financial management* is critical for any business. It requires analysis of the financial effects of any decision and requires good record keeping.

- *Marketing* involves understanding the customers and managing the marketing mix (Product, Promotion, Place and Price).
- *Human resource or labour management* is becoming increasingly important, especially on larger farms (Martin et al. 2005). Issues relating to these fields can apply at any of the three levels of management.

2. The second dimension is the management process or the functions of management – planning, implementing, controlling and responding. Planning involves defining goals, establishing strategy and developing plans to coordinate activities. Implementing is determining what tasks are to be done, who is to do them, how the tasks are to be grouped, who reports to whom and where decisions are made. Some authors also include leading, which involves motivating subordinates, directing others, seeking the most effective communication channels, and resolving conflicts. Controlling is monitoring activities to ensure they are being accomplished as planned and correcting any significant deviations. Responding (not included by all authors) is the capacity to consider changes due to changed circumstances while doing any of the above.
3. The final dimension is the management life cycle. A number of aspects of a farm business can be said to have a 'life cycle'. These can range from a particular product through to the business itself. The stages of a typical life cycle of a business or product are indicated in Fig. 12.1 as entry, growth, maturity (or consolidation) followed by boost – to restart the cycle or exit (disinvestment).

Most rainfed farms are owned or managed by farm families which also have their own life cycle which adds a further complicating factor to the decision making. A third 'life cycle' relates to ownership. As mentioned, farm business may span several generations and the process of handing over (succession) can have a large impact on the life cycle of both the family (e.g. its cohesiveness) and the business (dispersion of assets) (Davis 2001; Shadbolt and Bywater 2005)

The **entry stage** of a life cycle involves the decision to enter an industry. This could be a new enterprise or product for an established business or a new entrant who has to accumulate net worth and experience, perhaps through share-farming or contracting.

The **growth stage** is where the resource base is expanded and productivity and efficiency are enhanced. This stage is the most vulnerable for the business (Nicholls 2007). There are a number of critical points during growth, as illustrated in Fig. 12.3.

Farmers considering adding a new enterprise to their farming system frequently try it on a small scale first, to test both production techniques and the market for the product. This is sensible, as an untested market is the first stumbling block for new enterprises. The second problem is likely to be that rapid growth causes a shortage of cash. Unless backed by existing financial resources and handled correctly, this can also lead to the demise of a new enterprise. A third crisis is associated with lack of business, legal, accounting, and human resource management skills. Managers entering a new enterprise need to gain or hire these skills to ensure success. The final possible hurdle to a new enterprise is simply growing too fast, out-growing the business' borrowing capability, staff and other resources, and management ability.

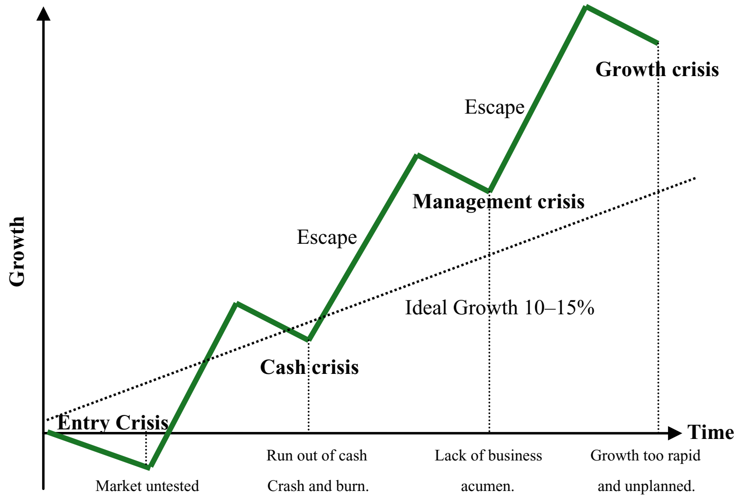

Fig. 12.3 Entry and growth stages of the business lifecycle (Nicholls 2007)

The growth stage often involves expansion in the size of the farm, typically by purchasing or leasing additional land. Borrowing is often needed to finance the expansion and requires good financial planning and management.

Following the growth stage is the **maturity** or consolidation stage. In this stage, debt reduction usually becomes a priority, and increased efficiency may be preferred to increased size.

Following the maturity stage, the options are to boost or exit. As the farm operator nears retirement, attention turns to reducing risk, liquidating the business, or transferring the property to the next generation. The tax consequences of liquidation or transfer must be considered along with the need for adequate retirement income. Some of the factors to be considered in handing over the farm have been considered previously.

The life cycle stage of the farm and the farm family is an important consideration in regard to a number of decisions regarding the operation of the farm system. It will affect the form of business organisation chosen, the attitude to risk, and the willingness to try new ideas. The goals of the operators, total capital invested, size of debt and other factors are likely to be different in each stage. These are all important in devising an economically and socially sustainable system.

12.3 Systems Thinking as a Tool of Land Managers

From the point of view of the farm family, the successful outcome of whole-farm management is the achievement of their goals and objectives. These can be both profit and non-profit targets, and may be conflicting. These goals are a reflection of the expectations the family has for the family and the farm. In turn, these expectations are influenced by the conditions and pressures of the society of which they are part. Changes in the community will affect the goals of the farm family (Kelly and Bywater 2005).

Successful farm managers have to continually rethink their decisions in the light of these changes in their social, political and economic environment. Making the best choice of the known options with less than full information requires both skill and appropriate tools. One of these tools is the whole-farm systems approach advocated in this book. A systems approach assists managers to comprehend the relationships between various parts of their business and their importance in successfully achieving the goals of the farm family.

In Chap. 1, we defined a system as 'A group of interacting components, capable of reacting as a whole to external stimuli applied to one or more components and having a specified boundary based on the inclusion of all significant feedbacks'. However, systems do not exist *per se*, but are defined as a consequence of the objectives of the analyst. Systems and systems thinking are tools used by a manger to impose meaning (Wilson and Morren 1990).

An important concept in defining a system is its boundary. Systems are a construct of the person conducting the analysis and so the boundary is defined by the purpose of the analysis. In many cases where the focus of the analysis is the technical aspects of the production system, the boundary will be the boundary of the farm. However where the focus is on the business aspects of the system, the boundary may include off-site processing of the farm products or even the supermarket that sells the products. How a system is defined depends on the reason and the purpose of the system. The purposes for defining a system can be varied. We may simply want to describe or learn about a system; we may want to improve its productive performance; or we may want to redesign the system because of changing circumstances or goals. In each case, the 'same' farming system will be defined differently (Kelly and Bywater 2005).

The managers of a farm system must consider what it is they are managing and how they will define the system. They need to consider the 'big picture' while keeping it as simple and manageable as possible. From a management perspective, there will be at least three main parts: people, physical resources and money. The people are those directly involved in the management and decision making. Recognising and understanding the attitudes, beliefs and values of these people is essential to an understanding of the system. Resources include the land and other physical resources and the people who can assist – those that can influence or are influenced by management decisions. These might include advisers, neighbours, suppliers, customers and clients. Money refers to the sources of money available to the managers of the system and includes cash, potential for borrowing and potential earnings generated from the resources (Kelly and Bywater 2005).

A clear understanding of the system that is being managed requires an understanding of how the components of the system relate to each other, the effect of external influences and what properties of the system emerge from these interactions, along with their relative importance.

As outlined in Chap. 1, the elements of a farming system include components, external influences, inputs, outputs, a boundary, an external environment and a process for making inputs into outputs. Outputs of the system include products of economic value. During their production, by-products are also generated. These can create benefits (for example, enhancement of the rural landscape) or disadvantages (for example, animal effluent or pesticide run-off) but are associated with a value or cost. Some of these have a direct impact on the farm business (for example, cost of effluent disposal facilities), but others impact on future generations or neighbours. A systems approach to viewing the farm within a wider ecological system such as a river catchment could better account for the costs and benefits of farm technology.

As discussed, the system boundary is a product of the purpose for defining the system. In some cases, the boundary may distinguish what is under some influence of the farm manager as opposed to those elements which are not, and may be said to be part of the system environment. In many cases, the surveyed boundary of the farm may best represent the system boundary. However, this may not be appropriate for the study of some problems or opportunities related to the farm such as those related to the surrounding landscape or pollution. Decisions in relation to the social and financial aspects of the farm household (schooling, off-farm employment, support services) will lead to a different definition of the system boundaries.

Anything not specifically included in the system but that may have an influence on it is part of the system environment. Normally the system manager has little or no control over the environment factors. The first part of this chapter considered many of these factors and they need careful consideration by the decision makers of the farm system.

12.4 Conclusion

This chapter has attempted to explain the complexity of the economic and social influences on the goals and decision making of those managing a farm system. Internal and external physical, technological, social, political and economic factors need to be considered along with risk management. The best way to successfully manage this complexity is through a whole-farm planning and systems approach. Many farmers are quite good at viewing their farms holistically in terms of production; however, fewer are successful at understanding the implications of their management with regard to marketing and finance. Greater understanding of a whole system approach which includes both the complexities arising at the farm level and the multiple hierarchies of the agrifood chain will improve the chances of success in the future.

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Chapter 13
Farming Systems Design

Craig Pearson

Abstract Innovation in cropping systems has been largely through changes in a single aspect of the system, but this cannot provide the outcomes desirable for the future. In future, many players with different and often irreconcilable perspectives may use tools such as multi-criteria analysis and perhaps government intervention in the design process. It is also desirable to join the 'two solitudes' of (1) conceptual analysis based on sustainability and resilience, and indices of these; and (2) farmers' and public perceptions of how systems need to be designed to meet the bigger issues of society such as farmer profitability, markets, creating health-full products, value-adding for the bio-economy, rural-urban juxtapositioning, and climate change.

Keywords Profit • Markets • Health • Bio-economy • Regional cities • Climate change

13.1 Introduction

While the history of innovation of rainfed farming systems has yielded marked successes, this background should not provide the model for future innovation. This chapter describes 'two solitudes' – currently irreconciled perspectives – on cropping system design: (a) the analytical assessments of performance based on concepts such as sustainability and resilience, and indices of these; and (b) perceptions of how systems need to be designed to meet the 'big issues' of society such as farmer profitability, markets, creating health-full products and value-adding. This leads to consideration of more holistic design approaches, including advocacy for more closed or **'regenerative' farming systems**. The chapter concludes with an overview of the players who will influence the design of future systems and the tools they will use which could include public policy.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_13,

13.1.1 Background

Farming systems have evolved through innovation, almost always by trial-and-error or by deliberative, designed changes in a single aspect of the system. For example, since the eighteenth century, the introduction of machinery has led to systems on a much larger scale, more timely sowing and harvest with less wastage. Since the 1960s, innovations have been in areas such as pesticides[1] and inorganic fertilisers, which have sustained an enormous amount of research into the type, timing and rates of application in infinitely-variable conditions. Since that time also, shorter, more uniform, higher-yielding cereal cultivars adapted to rainfed cropping have been developed, for example, dwarf sorghum (e.g. Quinby 1974, 1975), rice, maize and wheat (e.g. Borlaug 1983). Such improvements have been coupled with the introduction of a range of grain legumes (pulses) and oilseeds as part of crop rotations (see Chap. 29), and minimum or zero tillage (see Chap. 39). To cite just two summaries of these innovations in system design and their consequences, Perry (1992) describes rainfed cereal–legume systems in Australia and Smika (1992) describes the range of cereal-based systems, with varying emphasis on legumes and no-till, in the north American Great Plains.

While single-aspect innovation by farmers and researchers continues, in the last decade there has been increasing involvement in the design of cropping systems by the suppliers of inputs e.g. germplasm, and by the purchasers of the output, usually grain, the processors and multinational food retailers. Companies, through forward contracts, may specify the design (e.g. crop rotation), inputs (e.g. timing and type of fertiliser and pesticide). They may also breed and provide the crop germplasm to the farmers.

Both non-agriculturists (e.g. Brown 2003) and agriculturists (e.g. Tilman et al. 2002) are calling for more purposeful design of our systems, to address broad environmental concerns.

In some cases, the call is for not only greater purpose in design but also for government intervention. This intervention is justifiable especially in areas where governments may pay for ecosystem goods or services – that is pay farmers to deliberately manage their systems to provide goods, such as clean water, and services, such as habitats for birds and aesthetic landscapes, for the benefit of the general public. Of the 23 ‘ecosystem functions, goods and services’ which semi-natural and farmed ecosystems may supply (de Groot et al. 2002), only food, raw material (e.g. biomass for building materials) medicinal and ornamental crops are produced predominantly as direct, intentional outputs from farming systems. Payments for the other goods and services may be made directly for measurable outputs (e.g. clean water or carbon credits associated with carbon storage in growing tree-lots) or they may be by indirect payments (e.g. for farmers not planting an area to crop in order to maintain greater plant and insect biodiversity in a mixed-species

[1] In this chapter ‘pesticides’ includes fungicides, insecticides and herbicides.

grassland). Tillman et al. represent an opinion which is broadly held in north America and Europe when they posit "New incentives and policies for ensuring the sustainability of agriculture and ecosystem services will be *crucial* (my italics) if we are to meet the demands for improving yields without compromising environmental integrity or public health."

The extent to which farmers, and their organisations, are aware of terms such as '**ecosystem services**[2]' varies among regions. In Canada for example, a survey (Wildlife Habitat 2006) found that three-quarters of farmers 'would consider' taking action to improve water quality or soil productivity, but only one-quarter were familiar with the term 'ecological goods and services' and could explain its purpose. Nonetheless, local farm community groups, such as LandCare in Australia, have records of making substantial investments to address their environment. There is also widespread recognition among farmers that their well-being depends on community support, based on positive interactions between farmers and non-farm communities; for example, the South Australian No-Till Farmers Association (SANTFA) has launched a program called 'Community FarmLinx – Pathways to rural and urban co-existence'. It aims to identify pathways of change for all farmers to adopt best practice conservation farming methods (including no-till, retention of crop residues rather than burning, and low-drift spraying technologies), in order to minimise the impact of dust, smoke, water and pesticide pollution in outer metropolitan communities" (Craddock 2008).

13.1.2 Measures of Future Success

Chapter 1 defines and describes a number of attributes, or measures of success, of rain-fed cropping systems; Table 13.1 summarises these measures.

While the terms have altered marginally, these attributes align quite closely with the previously described properties of agro-ecosystems and suggestions for how they might be simply and realistically measured (Pearson et al. 1995, p. 2).

Table 13.1 Measures of success of rainfed cropping systems

Purpose
Productivity and profitability
Stability
Sustainability
Equity
Flexibility and adaptability
Resilience
Efficiency

[2] Natural ecosystems provide a number of benefits are known as ecosystem services. These include products like clean drinking water and processes such as the decomposition of wastes.

There appears to be good, relatively long-term agreement about the theory of how to define and evaluate cropping systems.

However, agreement about how to describe retrospectively the success of a system, either in concrete terms (profitability) or more abstract terms (e.g. resilience) conceals considerable discomfort as to whether our farming systems are becoming more successful in addressing some of the 'big issues' of our various societies. There is a lack of communication or common-ground between the analyses carried out by farming systems experts (as in Table 13.1) and the perception of failure held by farmers and the urban public. The two perspectives are currently not reconciled; we have unwittingly created '**two solitudes**' due to differences in world view, profession and language. In one solitude, analysts have spent 30 years proposing and refining measures of systems performance (e.g. Hamblin 2001) while recognising that there are problems in transferring these indices between sites and across scales (Pearson 2003). In the other solitude, farmers and the public are concerned with a complex mix of goals, not indicators or abstractions, for our next generation of farming systems.

13.2 Goals for Next Generation Systems

Lester Brown's (2003) overview of 'civilization in trouble' (his terminology) is well-publicised. His response (Plan B) involves four programs: (1) raising water productivity; (2) raising land productivity; (3) cutting carbon emissions (carbon-dioxide losses from soil and crops due to tillage and breakdown of organic matter, and agricultural use of fossil fuels in machinery); and (4) responding to social challenges such as population growth and HIV. Three of these involve farming systems and create high-level purposes for their future design. Brown's specifics of water and soil might be aggregated into 'depletion of resources' to which we could add four other concerns, drivers for change or goals which might be addressed through the design of the next generation of cropping systems. These are:

- Depletion of resources: the opportunity cost of cropping to the environment
- Food as a source of health
- Low farm efficiency and income, leading to a need for value-adding
- Rise of regional cities
- Climate change.

These five points are discussed at length below. They are important because consideration of them leads to the conclusion that we need to adopt a more purposeful and holistic approach to the future design of farming systems. Further, consideration of what is needed to address four of the five issues (resource depletion, farm efficiency, regional cities, and mitigation of climate change) leads to advocacy for more closed farming systems – what I have elsewhere called semi-closed or regenerative agriculture (Pearson 2007). Interestingly, the five issues transcend geography, they are as relevant to developing, agriculturally-based economies as they are to the developed, industrial countries from which this chapter draws examples.

13.2.1 *Cropping Systems to Meet Both Profitable Food and Environmental Resource Objectives*

Concerns voiced by Brown, Wackernagel and Rees (1996) and others have led to studies comparing the value of food production per hectare in terrestrial (crop and rangeland) systems with the value of natural capital.[3] Natural capital is the aggregate value, computed on a yearly basis, for goods and services provided by a natural ecosystem; for example water, biodiversity, soil and erosion control, aesthetics and recreation. For example, Constanza et al. (1997) have made this calculation for the world and Olewiler (2004) for specific catchments across Canada. Ecological goods and services are generally calculated to have greater value than food production from the same land (Constanza et al. 1997; Balmford et al. 2002), thus, in Cameroon a tropical forest was calculated to have a value (using net present value techniques calculated for the life of the forest of 32 years) of about $5M per hectare, whereas plantation-farming the same land diminishes the total long-term value by some $2M per hectare (Balmford et al. 2002).

The finding that, at least in those few areas which have been studied, the value of ecological goods and services is about the same as or greater than the value of food produced when the land is used for agriculture could be turned on its head as justification for the full costing of food. However, the real cost of food (as compared with the retail price) continues to receive little attention. Instead, these studies provide quantitative justification for government support (both financial and in preservation policies) for environmental goods and services. The logical consequence is that we should set goals for future research into farming systems to enhance value, and account for the impact of innovative technologies, in terms of *both* food production and environmental services. Such aggregate values are likely to be optimised by regenerative systems (see Sect. 13.3), which may not necessarily produce the highest food yield (see also the supplement to Chaps. 1 and 21).

Additionally, there are studies which quantify the off-farm impacts of agriculture or externalities[4] on the environment, and the costs of these external impacts to society. For example, Pretty et al. (2000) estimated the costs of the external impacts of agriculture in the UK to be of the order of £208 per hectare. About half of this was related to gas emissions, mostly methane and carbon dioxide, while another major item was contamination of groundwater by pesticides. Pretty et al. (2005) estimate that the real cost of the UK food basket is increased by £2.91 per person per week when the negative external costs from farm to consumer are incorporated.

Agriculture also creates numerous beneficial impacts as addressed by Hanley and Oglethorpe (1999) and others. In the main, while the negative impacts of agriculture are fully related to 'leaky[5]' or open agronomic systems, the positive externalities

[3] See also Glossary.

[4] See Glossary.

[5] That is, substances intended for use within a farm system 'leak' into the environment.

can be designed-in. An example of reduced leakiness and negative externalities is changes in the (original European Community countries, where regulations for groundwater quality introduced in the 1990s have reduced rates of application and made farmers manage their systems in a less-leaky manner. They have minimised the export of undesirable externalities such as pesticides and unused nutrients. As a positive externality, in the mid-west United States corn belt in the same decade, farmers grassed their drainage-lines within fields to achieve run-off of clean water, (ultimately used for human consumption), and reduced soil erosion.

Chapter 1 emphasises the opportunities to create inter-connected sub-systems to maximise the use of all above-ground parts of crops. To the present, the non-grain part (stover or crop residue) has been valued as relatively low-quality animal feed. If livestock are not part of the system, the stover (stubble) has been burned or, more recently, incorporated into soil organic matter either relatively quickly through minimum tillage (which mixes the stover into the soil) or more slowly through zero tillage (which leaves residues on the surface to be incorporated slowly). These are low-value uses for by-product. Enhancing the quality of the stover, e.g. by treatment with alkali, has not been economic because the end-use (animal roughage) does not justify the cost of treatment when added to the cost of handling and transport to the livestock. Valuing the organic matter incorporated into soil through minimal tillage seems to have escaped economists' attention and, even when it has been analysed; it again equates the value of the stover to the opportunity cost of using less of an input, e.g. nitrogen fertiliser. Next-generation cropping systems need to be designed with the objective of making maximum value, in terms of whole-of-life, of all above-ground parts of the crop, valuing the organic matter when it increases soil carbon (e.g. through carbon credits) and leaving roots in situ to contribute to the maintenance of soil productivity.

In 2007 the European Community (EC) announced aggressive targets to reduce energy consumption and increase the proportion of its energy which will be sourced from plants, the EC has proposed a binding minimum target for domestic biofuels of 10% of the vehicle energy consumption by 2020 (European Commission 2007). This will establish a market for plant-based stocks for biofuels, which will create clear design objectives for the next generation of cropping systems. It will also pose the interesting dilemma as to whether the EC, in seeking to become less reliant on foreign petroleum, will become more energy-secure at the cost of lower food security.

13.2.2 Markets, and Food as a Source of Health

After World War II, the bulk of food and fibre was produced locally and regionally, mostly as undifferentiated commodities. This was partly due to concern about 'food security', particularly in Europe where, for example, rationing of some foods extended to the 1960s. It was also associated with short, simple supply chains in the absence of cheap transport and sophisticated logistics, such as refrigeration and communications technology to support 'just-in-time' delivery.

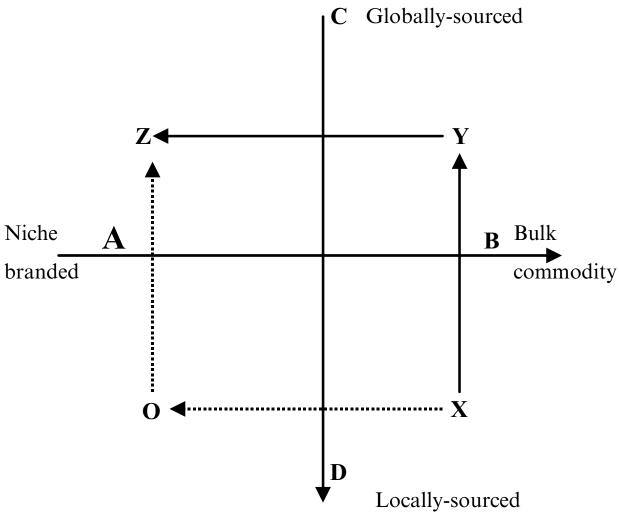

Fig. 13.1 Schema of changes in marketing, from locally-sourced foods treated as bulk commodities (*point X*) to globally-sourced commodities (*Y*) to globally-sourced but branded on the basis of quality or safety assurance (*Z*). The trend for mainstream foods has been paralleled by niche-products, e.g. certified organic foods. These have been created through conversion of local commodified products (*X*) to local niche-branded products (*O*) which have expanded through multinational supply chains to also involve global sourcing (*Z*)

The rise of multi-national supermarkets with sophisticated supply chains and increased wealth has resulted in consumers being able afford to import foods which were not in season locally. This shifted the bulk of fresh food sourcing from, say X to Y in Fig. 13.1, at least for affluent countries.

Branding of foods by the retailer has also become more common in the past decade. Further, as the public has increasingly sought reassurance about food safety and shifted to purchase on the basis of perceived quality, branding has shifted from a 'no frills' image (the label actually used by an Australian supermarket chain) based on low-priced commodities, to 'Presidents' Choice' (a current Canadian in-store brand) based on an image of quality. Branding which sells quality and reliability drives the creation of chains in which the retailer is a key and powerful player, and in which there is detailed specification of crop production practices and quality monitoring. Thus, in the last half-century, food-and-health were initially linked in the sense that food supply or security was paramount whereas now health is addressed throughout the marketing chain b specification and monitoring, and forward contracts between farmer and processor or, increasingly, retailer. First commodities became globally sourced, then differentiated products (e.g. organically-certified, and 'fair trade' registered) became globally sourced (see also Chap. 12).

Now there is a complementary trend – to respond to market growth in quadrant AD by creating differentiated or niche branded foods identified with location. This trend involves 'local food', 'food miles' and the 'slow food' movement. It will, in turn, create opportunities to differentiate food products according to the growing conditions – to design cropping systems for market niche product attributes, e.g. taste, and services bundled with the product. The farmer who sells Beefsteak tomatoes grown without pesticides directly to restaurants, where they are advertised on the menu according to farm-of-origin exemplifies the small end of this expanding market just as, at the large scale, HRH Prince Charles's organically-certified cereal grain from 'Dutchy Farm' creates a branded input for premium biscuits which are available on international airlines.

In addition to sourcing and branding, which are primarily to achieve market share rather than population health, the nexus between food and health creates opportunities to provide food which has enhanced health qualities (nutraceuticals). For example, Omega-3 unsaturated fatty acids (at high levels in flax) are used as a diet for poultry and cows to produce specially labelled eggs and milk. Omega-3 in flax and other grains may reduce the development of aortic atherosclerosis by 46% (Prasad 1997). Another example is the improvement in nutritional value of rice – the next-generation types being nicknamed golden rice – through increasing the content of the precursors of Vitamin A in the grain. Varieties released in 2005 have 23-times more beta-carotene than traditional varieties (Paine et al. 2005). This should overcome vitamin A deficiency, which will be particularly valuable for children in India where the incidence of deficiency is as high as 60%. Overcoming nutritional deficiencies, enhancing eyesight, delaying the onset of osteoporosis, are all examples of how specifically-targeted crop attributes can be introduced to provide greater profitability (value-adding), as well as addressing population health, provided the supply chains are segmented and the products appropriately branded.

13.2.3 Cropping Systems Designed for Value-Adding

The 'economic race to the bottom', wherein researchers respond to ever-lower grain prices (in real terms) by creating marginal increases in yield and farmers respond by reducing costs and increasing their scale of production, is not a model for the design of the next generation of cropping systems. Figure 13.2 illustrates where this has led. Currently in Canada (and in several other countries, irrespective of government subsidies) more than 50% of farmers fall in the lowest economic quartile, which is unprofitable. A further 20% or more are not profitable in a long-term view, eroding their capita and their systems are not economically sustainable.

The solution for many of the unprofitable farmers is to either exit the industry, or to be recognised as primarily managing an environmental resource, with profit as a minor, not primary, goal. These custodians of the landscape, usually semi-retired and/or earning off-farm income, have needs and constraints different from those of the larger-scale managers who depend on farming primarily for income. They therefore need differently-designed systems. Holistic design is desirable if we are to address the environmental needs of society (above) and the needs of lifestyle land managers, as well as the profitability of farmers remaining in the commercial sector of the industry.

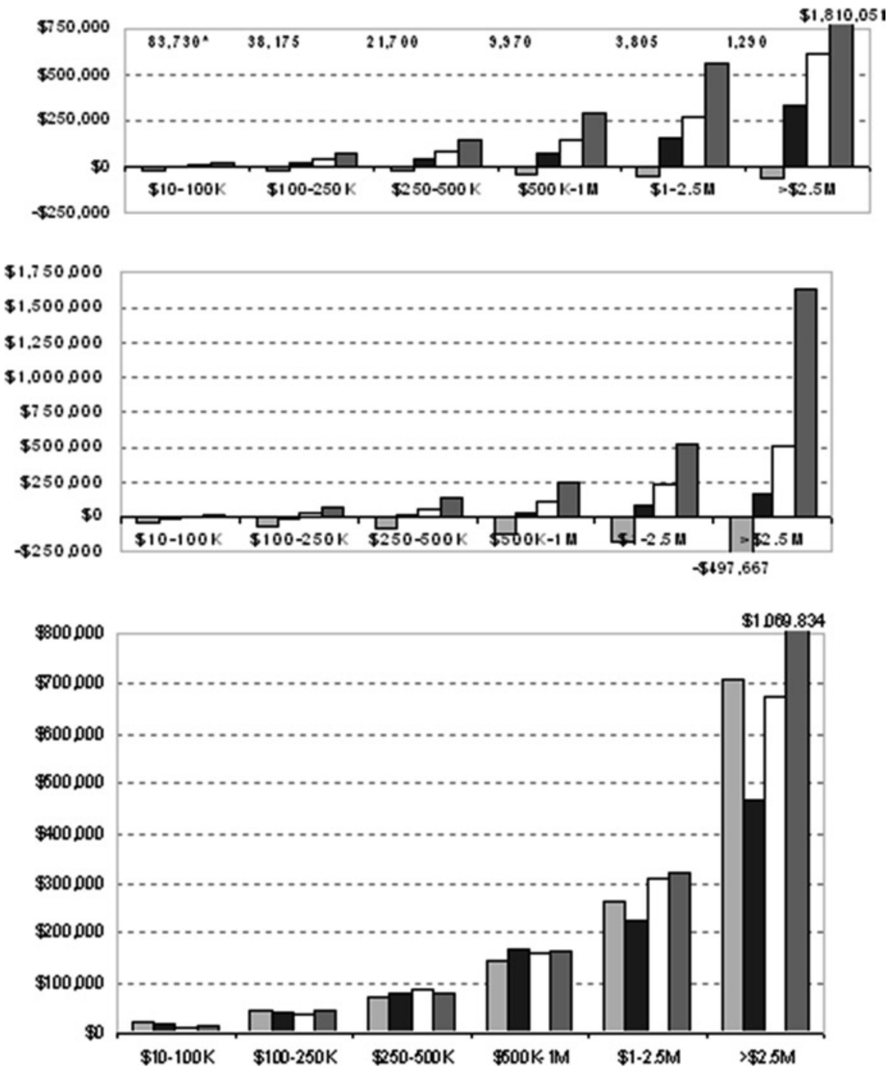

Fig. 13.2 Farm income with government support payments (*uppermost*), 'earned' farm income (*middle*) and gross investment (*lower*) for Canadian farms in 2004. Farms were grouped into six size classes according to gross turnover (farm receipts). *Within each size-class the number of farms are shown in the uppermost Figure (e.g. 83,730 farms are in the class which earns $10–100K p.a.). Also, within each size class, farms were split into four groups according to combinations of income, earned income, and investment, showing the variation within any group of farms of similar economic activity. The lowest and second-lowest classes of farm are not financially sustainable, either in farm income (if the purpose was viability based on farm income alone) or capacity to invest for innovation (Source: Sparling 2006)

As indicated in the previous section, there are reasonable environmental objectives, such as decreasing our impact on the environment and our consumption of non-renewable resources – our ‘ecological footprint’ – which might provide incentives to use more, or all, of the crops we currently grow. Stover collected and processed for building materials is but one example. There is a potential conflict – how much stover should be removed for value-adding and how much should be left to improve soil organic matter and carbon content.

This thrust to optimize the use of plant material and maximise recycling within more regenerative systems (see Sect. 13.3) will stimulate a new generation of plant breeding and bio-engineering. For example, the bioplastics market was estimated to grow to between $50 and $210 billion by 2010 (Daynard, pers. comm. 2001). Bioplastics wrapping, impregnated with enzymes which change color as *E. coli* grows in the contained food, provides yet another example of how conventional crops can be processed to provide more ecologically-friendly and health-full products, in addition to just food. These value-added products might create large markets. They appear to be driving large-scale but relatively low value change to cropping systems, such as providing building materials, and ethanol and biodiesel; or they may create small, high-value markets, such as those for the enzymes for impregnated wrappers.

While advocating the holistic design of cropping systems so as to use the products of the crop more fully and to use crops to substitute for petroleum and petroleum-derived products such as plastics, there is also a need for caution about the widespread adoption of new practices, collectively called ‘moving to the bio-economy’. Design of new systems for the bio-economy might desirably arise from debate among scientists and community groups. These will identify the potential dangers of widespread shifts in cropping system design to address worthy environmental objectives (e.g. our ecological footprint) and farm profitability. The likely demands of the bio-economy may create dangers which include the expansion of cropping into marginal lands, and removal of so much biomass that soil carbon is not maintained (see Chap. 14). By contrast, to meet internationally agreed targets for reducing greenhouse gases, there will likely be incentives to build carbon stocks (e.g. as trees and as soil organic carbon).

13.2.4 Rise of Regional Cities

Increasing population and city sprawl have an impact on agriculture. Mega- or regional cities are arising on every continent, creating challenges (with respect to agriculture) in: (1) how to create access to green-space, fresh food and water to maintain health, and (2) how to maintain cropping on the best land. Calthorpe and Fulton (2001) describe some examples of planning to create better environments despite the rise of regional cities. This planning, and the contribution farming can make to it, is nonetheless carried out in an intellectual environment in which the momentum is for further sprawl driven by developers’ desire to ‘repeat past successes’, governments' search for expanded tax bases, the myth that poor transport and community functioning can be addressed by more roads, and the belief that land remains plentiful.

The design of future cropping systems will need to address 'living with' and sometimes 'living in' regional cities. What government policy settings or interventions are desirable to maintain economically viable farming in urban settings? Does intensity of production, and perishability (or freshness) necessarily increase with proximity to the city? Will media campaigns for eating local produce, and 'reducing food miles' create price premiums such as in organically-certified foods? Already there is some increase in the popularity of local markets in north America, perhaps moving to the more locally- and fresh-sourced food which is more accepted in continental Europe.

13.2.5 Cropping Systems for Climate Change

Awareness of the need to address climate change has led various research groups to model ways of building up organic carbon sinks under alternative cropping systems. Shifting to forests and tree crops provides the greatest benefit although they do not address the increasing need for carbohydrate and protein for humans. Shifting to perennial crops, whose nutritive composition is enhanced through application of gene (not necessarily trans-genic) technology, is more realistic.

Crop management practices interact with each other and are almost unpredictably affected by weather and by environmental variation between sites. As Jarecki and Lal state (2003): "…no single practice guarantees enhancement of soil quality. (Nonetheless) according to the Inter-governmental Panel on Climate Change (IPCC 2000), improved crop management in the world can sequester (an additional) 125 million tonnes of soil organic carbon by 2010 and 258 million tonnes by 2040."

Shifting to perennial species will increase soil organic carbon, likely for up to 25–50 (e.g. Jarecki and Lal 2003) or even 60 (West and Post 2002) years until new steady-state levels are reached for carbon sinks. The long-term, but finite, nature of moving to higher levels in carbon sinks creates a goal for designing farming systems which reduce greenhouse gasses. While it is common for soil stores of carbon (as complex organic matter) to fall within 1–2 years when forests are cleared for farming, it should be a long-term goal to re-fill these stores through altering the farming system. This could be assisted by shifting to perennial crops or increasing the number of annual crops in a rotation, eliminating fallow and tillage, using cover crops (to protect the soil between periods of normal grain-crop production) and using green manure crops (which are incorporated into the soil without harvesting the grain). Thus, the future design of farming systems needs to consider the complex suite of management factors which can be optimised so that soil carbon stores are re-filled as rapidly as possible. It is also important to know whether there are practices which might increase the size of these stores beyond their original pre-farming capacity.

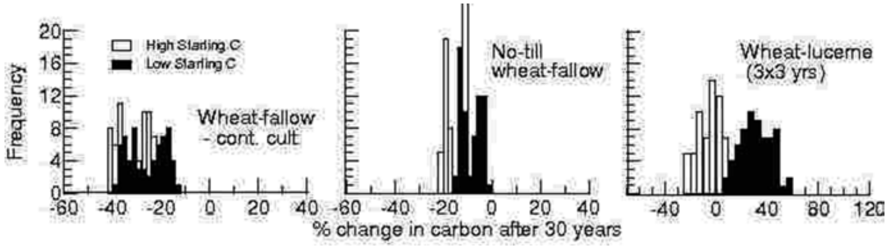

Fig. 13.3 Modelled frequency plots of the percentage change in soil organic carbon for cereal (wheat) and cereal–lucerne cropping regimes on a black earth (Source: Hill 2003)

Naturally, management shifts such as the use of perennial crops or more complex annual cropping systems have the caveat that they would first have to meet the primary requirements, or goals, of the system, such as being highly productive and resilient in producing profitable, highly nutritious food.

Within annual rainfed cropping systems, which include the vast majority of our food crops, the two variables most likely to impact on sequestering of carbon are tillage and the inclusion of legumes. In an elegant scenario analysis, Hill (2003) shows the likely impact of such variables on systems on three soil types. Figure 13.3 is an extract from this, for one soil (black earths) in Australia. Here, the final amount of soil carbon depends on the starting values; the open and closed histograms in the figure refer to high and low soil carbon starting levels respectively. However, cropping system and management have large impacts too. The notable changes in carbon sequestration relate to continuous cultivation (in which soil was cultivated four times each season – (left-hand figure), where soil organic carbon decreased by 20–40%. The same rainfed wheat system with herbicide application and no-till (middle) showed much less reduction in carbon. In contrast a wheat–lucerne (alfalfa) rotation with 3 years of each species – (right figure) accumulated carbon, at least where the starting soil carbon values were low (the black bars).

Field measurements also show that no-till can increase soil organic carbon by 44–117% relative to conventional tillage of crops of sorghum, soybeans and wheat in Texas (Wright and Hons 2005), or add about 60 g C/m^2 per year (West and Post 2002). However, the benefits of legumes in the design of cropping systems are more variable; for example, changing from continuous corn to corn–soybeans may not result in a significant accumulation of soil organic carbon (West and Post 2002). Despite these variable outcomes with respect to carbon, the large-scale inclusion of grain legumes in cropping systems, such as grain lupins in wheat–lupin systems on sandplains in Western Australia, and soybeans with corn, wheat and hay in Ontario (Hume and Pearson, Chap. 29, this volume) add value in other ways such as increased profitability and reduced use of pesticides and fertiliser N.

To address the goal of accumulating soil organic carbon, it is feasible when designing the system to estimate the amount of carbon retained in crop residues, roots and the rhizosphere, and to estimate how much crop residue needs to be left, to maintain or increase soil carbon (Johnson et al. 2006). This pro-active management or design will vary between climates, soil types, crops, and according to tillage and soil flora which, in turn, are affected by practices such as pesticide applications (see also Chap. 14).

While climate change should cause some reallocation of research resources to issues such as perennation and grain legumes, it will also stimulate research of plant physiology and adaptation. As an example, modeling of climate scenarios in eastern Canada suggest that growing seasons will lengthen but the incidence of drought during the season will increase. While these tendencies might more-or-less cancel out in terms of crop yield (e.g. Pearson et al. 2008), the crop genotypes most resilient in the new climate scenario will have characteristics different from current crops. In particular, low variability of yield, desirable for consistent, healthy food may become an attribute which is more valued than yield potential because of the need for consistent quality and yield under increasingly variable weather.

Crop adaptation to climate change will also necessarily require increased use of nitrogen fertilisers (or shifting to greater use of legumes). Porter and Semenov (2005) give two reasons: (1) the yield response to elevated atmospheric carbon dioxide inevitable for at least the next 50 years, requires higher concentrations of Rubisco, a nitrogen-rich enzyme; (2) elevated CO_2 on its own increases the ratio of carbon to nitrogen in the crop so that additional nitrogen will be needed to maintain the ratio, and the nutritive value of the food, at current levels.

13.3 Designing Future Systems

There are five groups of players who have contributed, and will continue to contribute to innovation in cropping systems. (1) Consumers. Demands e.g. for improved animal welfare have changed farming practices, while emerging market segments e.g. fair-trade and organic have changed practices and introduced stringent trace-back and third-party accreditation of systems. Lest we think such innovations are restricted to more affluent consumers, the food riots in 2008 in Bangladesh, Egypt, Indonesian and Senegal serve notice that consumers have the capacity to directly influence what, and how, food is produced and traded. (2) The farmers, whose motives are to maximise income and satisfaction while maintaining sustainability. They will hopefully employ (in 1980s terminology) the 'precautionary principle' so as not to endanger future generations through implementing practices for which we cannot currently foresee the consequences. (3) Groups in the private sector such as seed and chemical companies, machinery manufacturers, chain managers and retailers. Many have a direct influence on the welfare of the farming sector and its profitability, as demonstrated by, for example, Monsanto's advocacy of genetically-modified crops versus some farmer and consumer concerns. However, many in this sector have little direct knowledge of cropping systems and the consequences of changes within them. (4) Researchers, comprising molecular biologists, plant breeders, plant physiologists, soil scientists, modelers, cropping systems specialists, bio-engineers and others. These disciplines remain rather loosely connected with the consequence that, as in the past, there is a danger that innovation will be one-dimensional, arising from within one 'silo' and not necessarily addressing the large issues which face society. (5) Public policy-makers and politicians who are under pressure in most developed societies to find a compromise between farm lobbies which advocate greater 'safety nets' or insurance against poor yields or subsidies, and the goals of free trade, creating markets for less developed economies and the World Trade Organization.

As mentioned earlier, the issues and principles discussed in this chapter apply equally to farming systems in less- and more-developed economies, although the priorities will change regionally and nationally. *The overarching thesis of the chapter is that we need to move from simplistic, usually one-dimensional, technical innovations to an holistic multi-criteria approach.* Most of the issues can be addressed, albeit with trade-offs or optimisation between the various goals, if farming systems move to becoming less leaky and designed for greater recycling of resources. This shift from conventional design, which has been oriented to inputs and outputs, to semi-closed or '**regenerative**' farming systems (Pearson 2007) is illustrated in Fig. 13.4.

This figure illustrates the differences in cycling and use of energy and materials in conventional and regenerative systems. Conventional systems have evolved to consume relatively high levels of inputs with generally little or no recycling from processors and consumers. By contrast, the regenerative system relies less on inputs and more on recycling, eliminating waste from the agronomic system and minimising it from the processing and consumption systems.

To design future cropping systems, we have many tools. These involve both the social sciences, for example through focus groups and conflict resolution techniques, and the biological and mathematical sciences, using, for example, bioinformatics to accelerate breeding and computer modeling, to quantify likely ecosystem outputs and to help us choose between alternative goals. Computational tools to assist choice-making include decision-support systems and multi-criteria analyses. One judgment might be that such tools, when applied to the mix of needs and opportunities for capturing profit which are described above, would place priority on goals such as breeding for specific health outcomes, perennation, and tolerance to increasing climatic variability e.g. drought and high temperatures. Another judgment, espoused by agriculturists such as Tilman et al. (2002) is that the threats to society are so great, and the complexity so large, that government intervention is necessary, particularly to safeguard environmental goods and services.

Policy intervention or regulations are accepted in other agricultural systems, e.g. intensive livestock, so it is not inconceivable that municipalities could take a role in regulating the design of cropping systems. A less interventionist approach is to engage all stakeholders in discussion of design criteria and to build a mix of objectives and common language, which will unite farmers, stakeholders and the researchers who occupy the 'two solitudes' described earlier. It seems essential that we move towards semi-closed, regenerative systems in which fossil-fuel derived inputs are used sparingly and all products for example, the stover as well as the grain – enter markets, and are ultimately recycled into future cropping sequences.

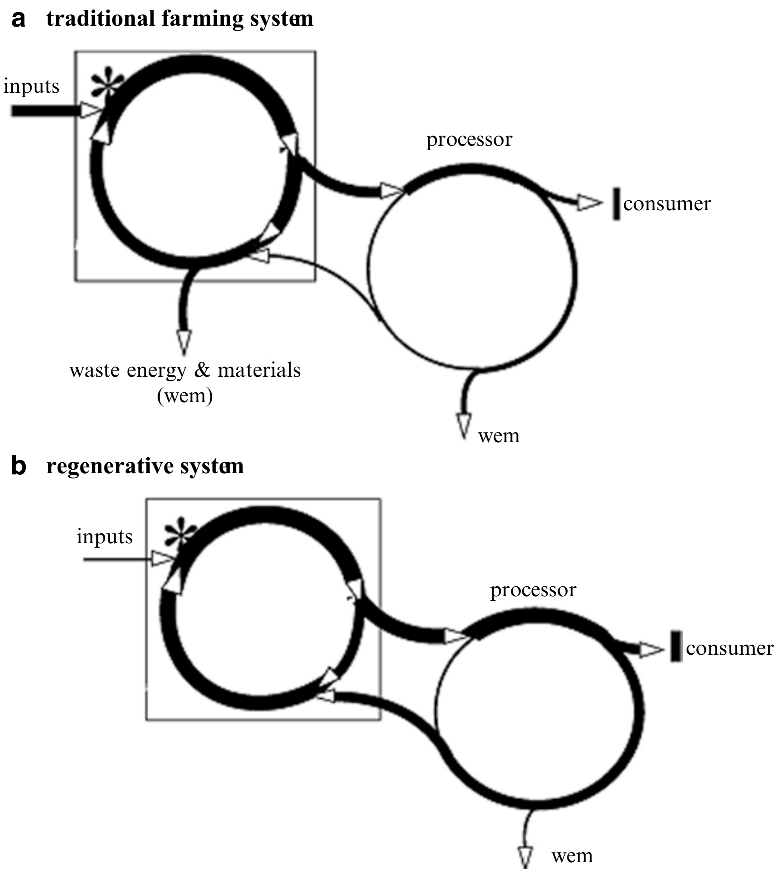

Fig. 13.4 Schema of (**a**) current mainstream, conventional or industrial rainfed farming, and (**b**) regenerative systems. The width of arrows is indicative of the flow of energy and materials, the asterisk representing energy capture within the agronomic system. In regenerative farming systems, inputs are much reduced because of direct *in situ* energy capture e.g. wind, biosolids fermentation, as well as photosynthesis. The percentage of production which is harvested and processed is increased (e.g. as biomaterials), leading to higher yields to the consumer, higher cycling back into the agronomic system and reduced waste energy and materials (wem) (Source: Pearson (2007))

It appears that we have moved from an era when innovation was driven by researchers and farmers, and involved mostly changes in single inputs to achieve incremental improvements, usually in yield, to a much more demanding scenario of deliberate design with accountability to the non-farming public. Design now involves many players with different and sometimes irreconcilable perspectives. Its objectives are complex and not usually incremental. These objectives will, whether through focus groups, multi-criteria modeling or government regulation, need to be identified and pursued after robust consideration of how best to optimise (or more realistically, improve) very complex systems.

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Chapter 14
Soil Organic Carbon – Role in Rainfed Farming Systems

With Particular Reference to Australian Conditions

Francis C. Hoyle, Jeff A. Baldock, and Daniel V. Murphy

Abstract As soil organic carbon is central to the functioning of all soils, we require a more fundamental understanding of the climatic and management factors which influence its storage and persistence. The interest in carbon storage and sequestration has focused attention on changes in soil organic carbon across different regions, climates and management systems. The major components of soil organic carbon have different physical and chemical properties. A greater understanding of the quantities and composition of these different components is required to gain an insight into the relative contributions soil organic carbon can make to soil productivity. Whilst the texture and structure of the soil has an overriding influence on the capacity to store soil carbon, management options more often influence the actual soil organic carbon content. This chapter addresses the function of soil organic carbon in farming systems, including the role of specific fractions in key soil processes.

Keywords Soil function • Organic carbon fractions • Carbon balance • Carbon sequestration • Carbon management

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_14,

14.1 Introduction

Soil organic carbon (SOC) is central to the functioning of many physical, chemical and biological processes in the soil ecosystem. Soil organic carbon is a term used to define the total amount of organic carbon present in those fractions of soil under 2 mm diameter. Soil organic carbon is not the same as soil organic matter (SOM), which includes roots and other organic particles, and contains other elements such as hydrogen, oxygen, phosphorus, sulfur and nitrogen that are associated with carbon in organic molecules. On average, values of SOM are 1.72 times greater than SOC. While SOC contributes little to the total soil mass (typically less than 10%), it does contribute positively to a range of soil processes (Fig. 14.1).

These soil processes interact and are often positively correlated. For example, SOC provides the dominant energy source for microorganisms (Chap. 6) allowing them to perform the following functions that are considered important in defining soil biological health:

1. Decomposition of plant and animal residues to form new SOC, which improves pH buffering capacity and cation exchange capacity (CEC).
2. Transformation of nutrients from organic to inorganic molecules (e.g. from organic N to NH_4^+ and NO_3^-), thus increasing nutrient availability to plants.
3. Formation and stabilisation of soil structure through bacterial polysaccharides that 'stick' soil particles together and through fungal hyphae enmeshing soil particles.
4. Degradation of pollutants and pesticides which otherwise would persist.
5. Production of gases (CO_2, N_2O, NH_3, N_2, CH_4), some of which contribute to the greenhouse effect and global warming.

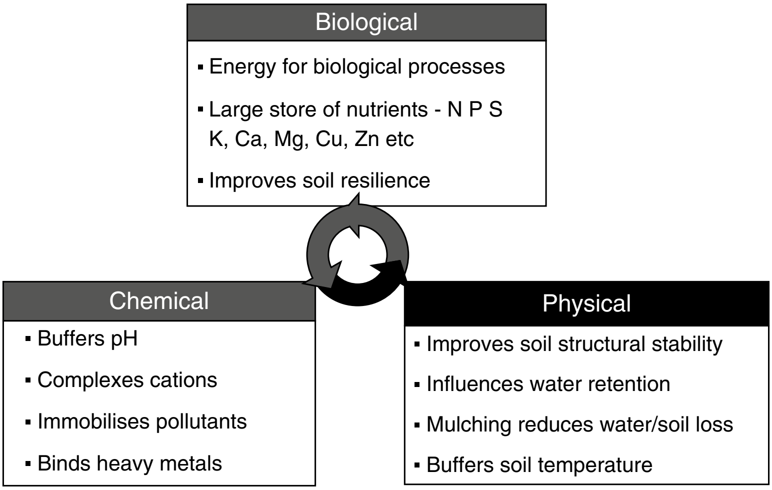

Fig. 14.1 The central role of soil organic matter in contributing to key soil functions and overall soil fertility

In addition to benefits related to soil biological health, the presence of SOC and its associated nutrients also contribute positively to **soil resilience –** defined as the ability of a soil to recover to its initial state after a deterioration event (see also Chap. 1). For example, under conditions of prolonged drought accompanied by crop failure and little return of crop residues to the soil, a soil with a high initial content of organic carbon will return to its former state of soil health[1] more rapidly when the drought breaks than a soil with a lower SOC content.

The optimal level of SOC required for these functions in any particular soil is difficult to quantify because different amounts and types of SOC may be required. Irrespective of soil type, if SOC content is below 1%, water-limited yield potential may not be achieved (Kay and Angers 1999) as the soil's capacity to perform key functions (Fig. 14.1) is constrained. Soil organic C contents of Australian soils have been shown to vary from greater than 81 g C/kg soil (8.1% carbon) for alpine humus soils (Organosols[2]) to less than 3 g C/kg soil (0.3% carbon) for desert loams (Chromosols) (Spain et al. 1983). Australian soils under rainfed farming typically have SOC contents in the range 0.7–4%. Enhancing the grain yield and harvest index of agricultural crops often results in increasing proportions of the carbon fixed by photosynthesis being exported from the site as grain, rather than returned to the soil as residues. If the rate of carbon return to the soil is less than that being lost through export, microbial decomposition and erosion, the SOC content will decline.

14.2 The Carbon Balance in Agricultural Soils

Carbon balance is used to refer to the net result obtained when all processes of carbon addition and loss from a soil are summed. The soil carbon balance can be thought of as a tipping scale. When the amount of carbon input into soil matches the loss of carbon from the soil, the scale is balanced, and there is no net change in SOC content. It is only when inputs outweigh losses (i.e. positive carbon balance) or losses are greater than inputs (i.e. negative carbon balance) that SOC contents will change.

CO_2 removed from the atmosphere and stored as either organic or inorganic carbon for long periods of time (greater than an annual time scale) is considered 'sequestered'. Places where carbon is stored are called carbon 'sinks' whilst places where carbon is emitted or lost are termed carbon 'sources'. As soil can store carbon, it represents a large potential sink but additionally it is also a potential source of CO_2. If the rate of input from plants and animals exceeds the rate of loss, SOC accumulates (i.e. positive carbon balance), and the soil acts as a CO_2 sink. If the rate of loss is greater than the rate of input, SOC declines (i.e. negative carbon balance), and the soil becomes a CO_2 source. Thus, at any given time, the amount of carbon retained in a soil is a reflection of the net difference in the carbon balance between

[1] See Glossary.

[2] This chapter uses the Australian Soil Classification see http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm.

historical inputs of organic carbon (e.g. photosynthesis/net primary productivity, animal manure, compost) and the sum of organic carbon losses associated with microbial decomposition (i.e. CO_2 evolution), leaching of dissolved and particulate carbon and wind or water erosion. Even a small loss of surface soil by erosion can have a large impact on SOC sinks as this surface layer holds much higher SOC concentrations than the deeper layers, and the smaller and lighter carbon-rich particles are preferentially lost.

Erosion is greatly influenced by the percentage ground cover. The risk of wind erosion, for example, can be decreased by covering a minimum of 50% of total ground area with stubble or other residues. In Australian agriculture, typical soil losses in a single year can be 60–80 t/ha from bare fallow, 8 t/ha under a crop and 0.24 t/ha under pasture; single, high-intensity storms can erode 70–300 t/ha through both wind and water erosion. Since 1 mm depth of soil weighs approximately 10 t/ha, erosion events in cropped soils represent a significant loss of topsoil with its associated smaller and lighter carbon- and nutrient-rich fractions.

14.2.1 Potential SOC Content

The potential to store SOC is rarely achieved as sub-optimal climatic conditions and soil management often restrict plant growth and return of plant residues (Fig. 14.2).

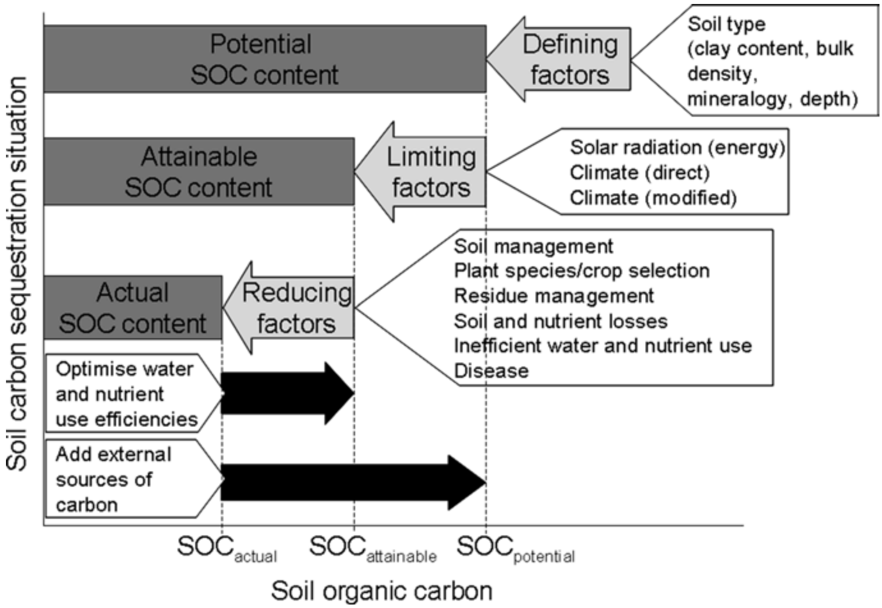

Fig. 14.2 The influence of soil type, climate and management factors on the level of soil organic carbon (SOC) that can be attained in a given soil (after Ingram and Fernandes 2001)

The potential ability of a soil to retain organic carbon is based on its capacity to protect (i.e. stabilise) SOC. Organic carbon is thought to be protected against microbial decomposition by adsorption of organic compounds onto the surfaces of mineral particles, by being within pores of less than 0.2 μm in diameter and by the burial of organic materials within aggregations of mineral particles. In heavier textured soils, aggregated clay particles physically protect organic particles from microbial decomposition. Mechanisms of protection of SOC operate at soil aggregate size scales ranging from micrometres (μm; i.e. one thousandth of a mm) to centimetres (cm) and depend on the chemical and physical properties of the mineral constituents and the 3-dimensional arrangement of mineral particles. Well-aggregated soils are also less prone to erosion.

In contrast, a more rapid turnover of SOC occurs in soils with little or no clay content; hence it is more difficult to increase the SOC content of coarse-textured, sandy soil from crop residues alone. An example of the influence of clay content on SOC is demonstrated in Fig. 14.3. This shows the range of SOC values measured in a 10-ha area under a cereal–legume rotation, where the clay content varied from 3% to 52%. Soil organic carbon values increased with clay content, over a fivefold range in values (min. 0.7%, max. 3.4%), reflecting differences in the amount of plant growth (and thus residue returns) as well as physical protection as clay content increased.

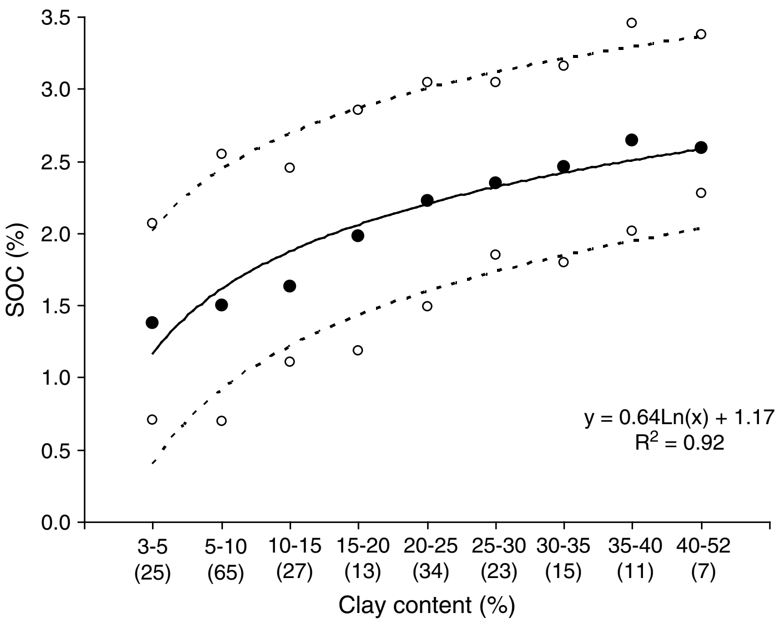

Fig. 14.3 Influence of clay content on the range of soil organic carbon (SOC) values in a 10 ha area of a paddock under cereal–legume rotation in the central agricultural region of Western Australia. Solid circles represent the average SOC value for each clay content whilst open circles represent the upper and lower SOC values for each clay content. The numbers of samples within each clay content are shown in brackets (n = 220 in total). The soil contained no gravel

Although soil bulk density and depth are not directly important to the stabilisation of SOC (protection against biological decomposition), they can define the amount of mineral material and/or surfaces that may interact with SOC, as well as the aeration status of the soil which directly influences the rate of microbial decomposition. The potential SOC content that a soil can achieve is a function of these defining factors (Fig. 14.2). Thus for a soil to reach its potential SOC, inputs of carbon from plant production must be large enough to fill the protective capacity of a soil as well as to offset losses due to microbial decomposition.

14.2.2 Attainable SOC Content

The SOC content that can be achieved depends not only on the potential of the soil to protect organic carbon but also on the productivity of the crop or pasture (net primary productivity). As productivity depends on water supply, temperature and solar radiation, attainable SOC may be less than potential SOC. These limiting factors are largely outside the control of rainfed farmers. Where plant residue returns are equal to or greater than those required to achieve the potential SOC, the attainable SOC content equals the potential SOC. However, under most rainfed agricultural conditions the availability of water will define an upper limit of plant productivity below that required to attain the potential SOC, resulting in a lower 'attainable' SOC (Fig. 14.2).

Capture of CO_2 from the atmosphere by photosynthesis contributes to carbon sequestration through the return of plant shoot residues, root exudates and root biomass to the soil. Some of this carbon will return to the atmosphere as CO_2 through biological decomposition, but a component is likely to be sequestered within the more stable fractions of SOC that are resistant to biological decomposition. Therefore carbon losses as CO_2 to the atmosphere can be reduced by increased movement of organic carbon into stable SOC pools or the microbial population. This could be achieved by increasing plant growth (and the amount of photosynthetically-fixed CO_2) or through improved agronomic and soil management options that reduce losses through decomposition and erosion.

The positive relationship between annual rainfall and net primary productivity (total dry matter production as defined using the equation of Lieth 1975), which occurs where water is the major constraint to plant growth, is shown in Fig. 14.4 by the sloping solid line. Since productivity directly influences the potential return of carbon to the soil in the form of roots and shoot residues, a positive relationship between SOC and rainfall might be expected. However, none is evident for a range of soil types used for grain production in Western Australia (Fig. 14.4). Instead SOC data (collated from between 40 and 220 individual fields) reflect the trend in actual productivity as determined by annual wheat yields estimated as shire averages from 1960 to 2002 (Fig. 14.4). Altered cropping and management strategies that improve crop productivity are therefore required to increase SOC contents.

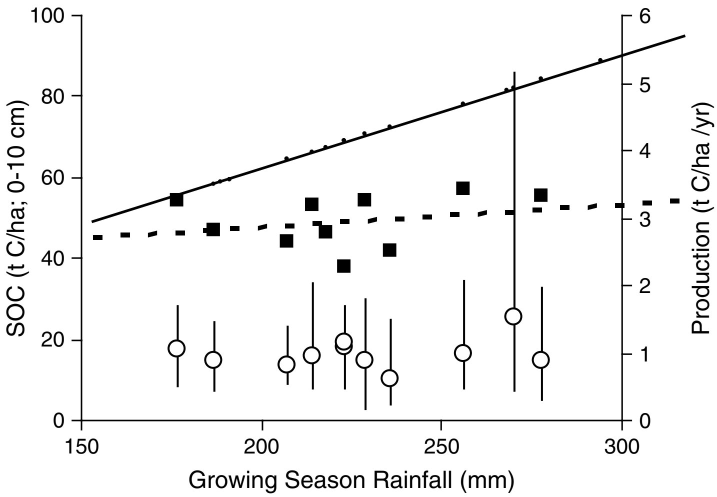

Fig. 14.4 Soil organic carbon (t C/ha; open circles with vertical lines indicating upper and lower values; *primary y-axis*). Calculated net primary productivity (DM t C/ha/year; solid line; *second y-axis*). Actual above-ground plant biomass (t C/ha/year; squares with dashed line indicating linear trend; *second y-axis*). Data are plotted across a range of growing season rainfall (mm) in Western Australia

14.2.3 Actual SOC Content

Reaching the attainable SOC is generally the best possible outcome for many rainfed farming systems. But to achieve this, there must be no constraints to productivity and associated carbon inputs such as low nutrient availability, weed growth, disease or soil physical constraints. Such a situation virtually never exists, and the lower plant productivity is reflected in the actual SOC.

Even where rainfall is deficient, many of the factors that restrict build up of SOC are under the farmers' control (Fig. 14.2). For example, rotational sequence may alter the actual SOC as plant species vary in their efficiency at converting water to plant biomass, in the amount and distribution of roots below ground (Fig. 14.5) and in their tissue composition (i.e. lignin content). Soil constraints to plant growth may be considered as factors limiting the actual SOC. Some soil constraints (e.g. compaction) can be ameliorated through management. While other constraints may be due to soil factors less readily managed – for example saline conditions at depth.

Farmers may be able to regulate agricultural management to maximise organic inputs and retain them. However, if the attainable SOC is much lower than the potential SOC, only the addition of an external source of organic matter to the soil will improve the situation (Fig. 14.2).

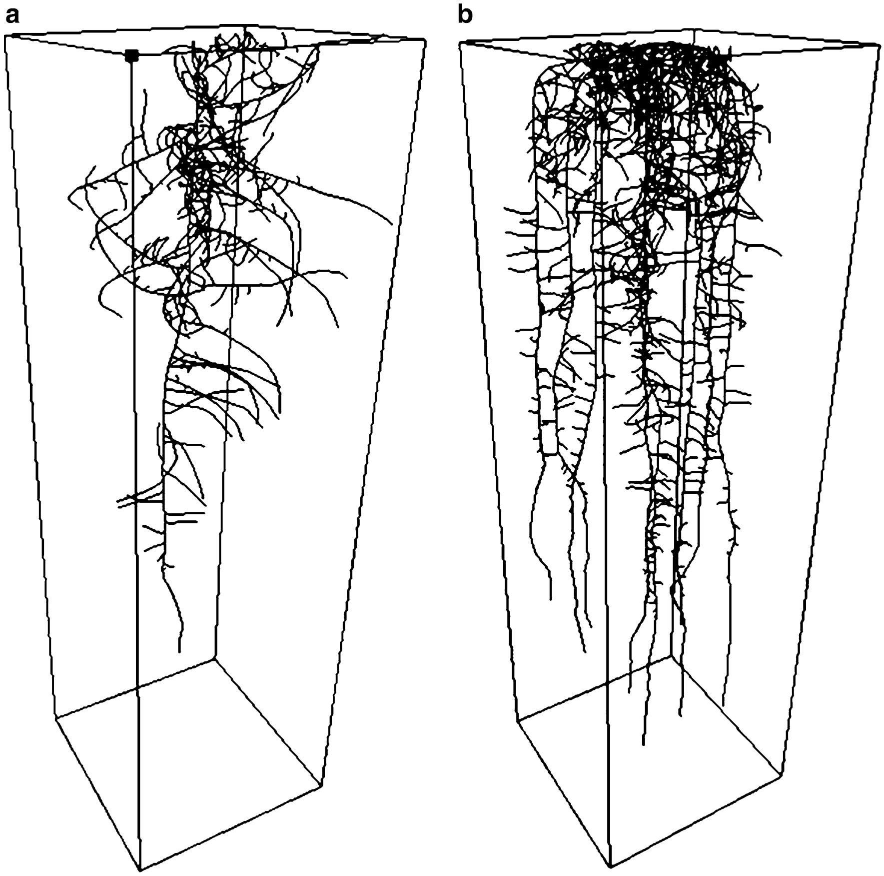

Fig. 14.5 Differences in below ground plant root architecture and biomass of (**a**) lupin and (**b**) wheat plant simulated using ROOTMAP (produced by Vanessa Dunbabin, University of Tasmania)

Variations in land use and agricultural management with respect to crop type, rotation sequence, soil management, stubble management, and green manure incorporation can influence the actual SOC. In general, soils under pasture have a higher SOC content than those under cropping (Blair et al. 2006), while minimum tillage and stubble retention may improve SOC content in cropped soils (Chan and Heenan 2005). The addition to and retention of organic matter in soil represents one of the primary input pathways, whilst the adoption of no-tillage is primarily a protection pathway which contributes to increased soil aggregate stability. Increased soil disturbance breaks down the physical protection provided by soil aggregates, and exposes plant and animal residues and other SOC to microbial decomposition, thus accelerating the rate of SOC decline. Extreme climatic conditions such as drought or episodic events such as disease prevent farmers from improving SOC status because there is less organic input and these provide real challenges within a rainfed agricultural system (Table 14.1).

Table 14.1 Management options for improving the potential for sequestration of organic carbon in soil

Option	Source	Example	Benefits	Factors addressed
Increase C inputs	Increase active plant growth, longevity and diversity; increase ground cover	Pastures Perennials Pasture cropping Inter-cropping Reduce fallow periods	Increases C inputs through longer active growth and reduced fallow periods Provides range of residue quality Increased root biomass Decreased erosion	Much of the historic C loss in Australian soils has been associated with the clearing of native vegetation for agricultural production. Land converted to an agricultural system often experiences changes in the amount of SOC; typically, agricultural soils experience organic carbon decline of between 25 and 75% with continued cultivation
	Add stable organic amendments	Compost Processing wastes Charcoal and char Other	Increases C inputs Contributes to stabilising soil aggregates and pore structure	Animal manure, composts and bio-solids added to the soil can contribute both organic matter and nutrients where structural integrity of the soil is maintained. Increasingly, by-products from other industries are being considered (charcoal, canola meal, compost etc). However, there may be insufficient evidence to establish their impact on soil properties or crop production on a broadacre basis. Management of humus provides some potential for altering CEC, but almost all of the charges on organic colloids are pH dependent (CEC increases as pH increases). Thus increases in CEC are limited on acid soils
	Increase plant biomass	Manage soil for constraints Increase water use efficiency Agronomy management	Increases C inputs Increases profitability	Appropriate soil and plant management to increase water and nutrient use efficiency can result in higher plant biomass and residue inputs to the soil where retained. The most limiting factors must be assessed to determine the cost/benefit return and end profitability of any specific management approach

(continued)

Table 14.1 (continued)

Option	Source	Example	Benefits	Factors addressed
Improve soil structure	Retain stubble and maintain ground cover	Zero tillage Pastures Cover crops Do not burn	Decreases loss of organic residues from soil Protects soil from erosion Promotes water conservation	Generally the potential for increasing water-holding capacity of soils is less than 5 mm. Increasing ground cover and intact roots will help protect the soil surface from raindrop impact, minimise the risk of both wind and water erosion, reduce evaporation and buffer the soil against extremes of temperature
	Manage livestock	Controlled grazing Reduce stocking rate Rotational grazing	Limits soil compaction Protects soil from erosion	Near-surface soil compaction can occur with grazing livestock. However, when the soil is moist and most prone to damage, stock can be moved to parts of the farm where there is less risk of soil compaction or where it is most easily rectified at a later date. Removing or reducing stock (particularly cattle) when the soil is wet and shortening the duration of high stocking rate will help reduce the risk of compaction
	Reduce tillage	Zero tillage Reduce number of workings	Decreases erosion risk Protects stable SOC pools Promotes water conservation	Increased soil disturbance breaks down the physical protection provided by soil aggregates and exposes plant and animal residues and other SOC to microbial decomposition, accelerating the rate of SOC decline. Reduced or zero tillage options will promote soil aggregation and provide greater physical protection of SOC (tillage is likely to result in continuing decline in SOC)
	Control traffic	Guidance systems Match wheel tracks	Reduces area of land affected by compaction	Using controlled traffic is an essential partner to soil loosening for minimising or repairing compaction. Compaction can be minimised by confining all or most tillage and traffic operations to designated fixed vehicle pathways
Supply optimum nutrients	Inorganic fertiliser	Urea Superphosphate NPK	Enables rapid supply and timing of nutrient availability to increase plant biomass	Soil nutrients need to meet crop demand and maximise profitability without causing off-site pollution. Nutrient replacement should equal nutrient removal. An understanding of which nutrients are important, nutrient form and availability, and soil testing are required

Add organic amendments and wastes high in nutrients (low C/N)	Animal manures Oilseed wastes Legume green manure	Enables longer term supply of nutrients and contributes to biological turnover	Soil organic matter is a major storehouse of nutrients. A decline in soil organic matter will reduce the ability of the soil to provide adequate nutrients for crops over the long-term. Efficient recycling of nutrients within the soil can offset the cost of inorganic fertiliser, reduce energy costs, cut waste, reduce potential environmental impacts and improve soil health. Nutrient content varies greatly depending on the fertiliser source, making it difficult to predict their effectiveness or cost per unit of nutrient
Use appropriate rotations	Crop and pasture legumes	N fixation contributes to N release in soil	Legume crops fix N and generally result in increasing levels of soil N which benefit subsequent non-legume phases. These residues decompose more rapidly than those of cereals and release N in subsequent seasons, but contribute less to building SOM than plants with more stable residues such as cereals and grasses

14.3 Soil Organic Carbon Fractions and Their Function

Soil organic carbon exists in a range of different types of materials that vary in size, chemical composition, stage of decomposition and age. Newly incorporated organic material is approximately seven times more decomposable than inherent SOC (that present prior to addition of the new material). However, inherent SOC is usually a much larger pool (15–225 t C/ha for the 0–30 cm soil layer). Though the decomposition rate of inherent SOC may be low, it can result in significant mineralisation of both carbon and nutrients (Shen et al. 1989).

SOC should be considered as a continuum of different forms with turnover times ranging from minutes for soluble root exudates (Jones et al. 2004, 2005) to hundreds or thousands of years for highly resistant material (Anderson and Paul 1984). Soil properties and processes are therefore influenced by the size and quality of the SOC fractions.

A number of SOC fractionation schemes are in use (see Sollins et al. 1984; Sohi et al. 2001), and these differ in the means by which separate components of SOC are recovered. One such fractionation scheme (Fig. 14.6) involves the separation of SOC based on different size classes and chemical composition:

- Surface Plant Residues (SPR) and Buried Plant Residues (BPR) comprise leaf litter, plant stems or stubble and below-ground root matter. They represent the main source of plant C inputs into broadacre rainfed farming systems where the importing of composts and animal manures is uneconomical unless a source is located nearby.
- Particulate Organic Carbon (POC) represents the initial stages of organic matter decomposition; it still contains considerable energy ‘locked up’ within the bonds of organic molecules.
- Humus (HUM) is decomposed organic matter that is more biologically stable and turns over more slowly than POC. Changes in soil management or farm inputs typically alter this fraction over a period of decades.
- Resistant Organic Carbon (ROC) is the most biologically stable form of organic carbon and, in Australian soils, is dominated by char-type material derived from plant residues after incomplete combustion. The size of the ROC fractions is thus dependent on historical fire frequency. In Australian soils, Skjemstad et al. (1999, 2001) determined that between less than 1% and 57% of SOC is composed of fine char carbon, most of which is located in the less than 53 μm fraction (Skjemstad et al. 1996, 1999).

The composition and size of different SOC fractions will influence the contribution that each type of SOC makes to the various functions typically ascribed to SOC (Fig. 14.1). A conceptual representation of the contribution that SOC and its component fractions make to a series of soil properties and processes is given in Fig. 14.7. In Fig. 14.7, the width of the shape reflects the relative importance of SOC to the function or process identified. For example, SOC will be most important for defining CEC in soils with low clay content. As clay content increases the

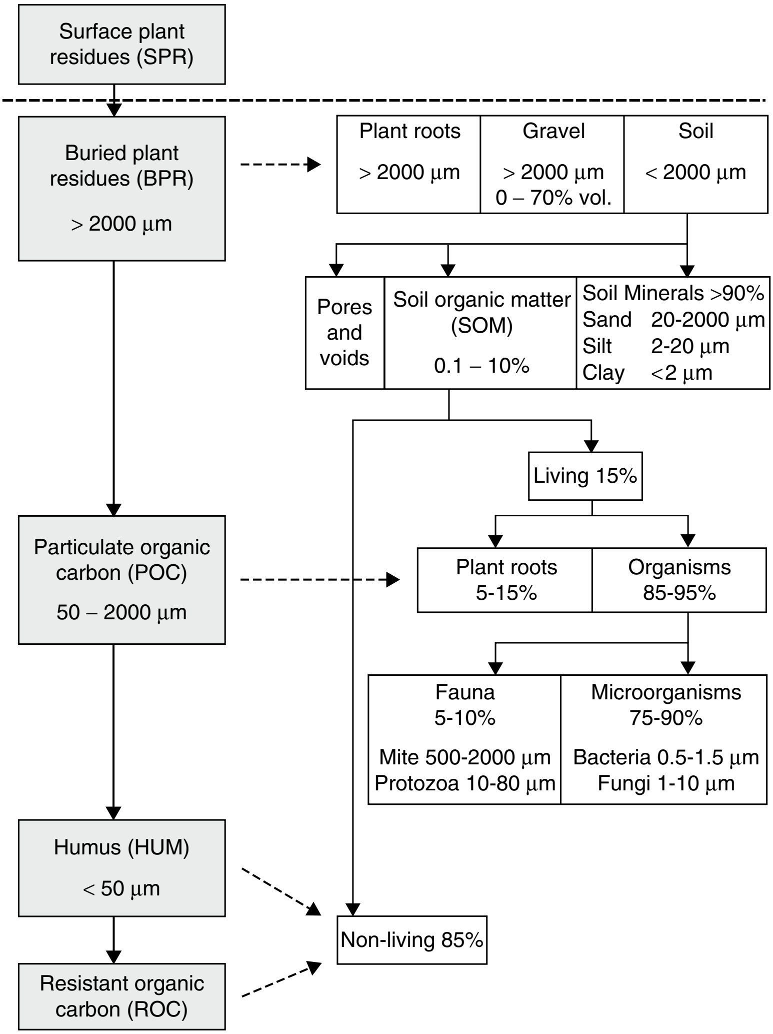

Fig. 14.6 Schematic of soil organic matter fractionation scheme that represents different stages of soil organic matter decomposition. Measurements refer to particle sizes

contribution of SOC to the total CEC of the soil will diminish. At high clay contents (greater than 60%), SOC is not required to attain acceptable levels of CEC and thus the CEC shape in Fig. 14.7 does not extend past 60% clay. Within the shapes, the width of each shaded area reflects the perceived relative contribution that the different fractions of SOC will make. For the structural stability shape, at low clay contents, the POC fraction would be expected to be the most critical form of SOC;

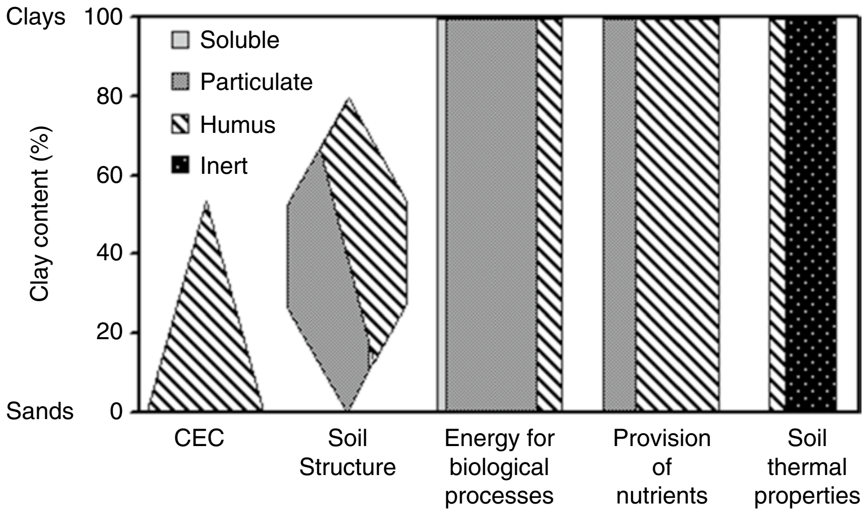

Fig. 14.7 Conceptual role of different soil organic carbon fractions (soluble, particulate, humus, inert) on a range of soil functions

while, at high clay contents, the humus form would be expected to be most critical. It should be noted that the shapes presented in Fig. 14.7 are conceptual in nature, and further research is required to derive accurate quantitative relationships.

14.3.1 Cation Exchange Capacity (CEC)

Like clay particles, humus (HUM) can hold nutrients through adsorption reactions because of its large negative charge density at pH values greater than 5. This allows humus to make a significant contribution to the CEC of a soil. The soil fractions differ widely in their CEC, with HUM and ROC (see below) having the highest CEC of all SOC fractions. The CEC of freshly-made charcoal does not appear to acquire the same level of CEC as old chars extracted from soil. Thus, the addition of HUM-type materials from composts or well-decomposed organic waste provides some potential for altering CEC.

The impact of the HUM fraction on CEC is greater where the HUM fraction is dominant in providing the CEC (as on light-textured sandy soils), compared to clay soils which have a CEC associated with the clay complex. For example, in a soil with 25% clay and 1.5% SOC, approximately one third of the CEC (of topsoil) can be attributed to the SOC whereas in a sandy soil, with little or no clay content, SOC accounts for almost 100% of the CEC of topsoil. The ability of SOC to hold and release nutrients (that would otherwise leach deeper into the profile) in the upper layers of sandy soils – and make these nutrients available for plant uptake – is a key benefit of SOC.

However, almost all of the charges on organic colloids are pH dependent, limiting the benefits in acid soils since CEC decreases as pH decreases. It is also important to note that SOC-induced change is largely associated with the surface soil, and the mineral fraction will continue to provide most of the CEC within the rooting depth of a plant.

14.3.2 Soil Structure and Water Relations

Soil organic carbon stabilises soil aggregates and improves water infiltration into soil by contributing to the development of a more porous soil structure. In addition, surface plant residues, if present in sufficient quantities, can reduce evaporation and buffer soil temperature.

Different fractions of SOC can hold up to several times their own weight in water due to their porous nature. As SOC is likely to be concentrated in the upper layers of the soil profile, plant systems with a proliferation of roots in the upper soil horizon are more likely to access this moisture. Due to the energy required to extract moisture from small pores, not all of the water is plant available. The relative contribution of SOC fractions to soil water-holding capacity will decrease with increasing clay content. The additional water-holding capacity (WHC) provided by SOC, above that due to soil texture alone, will be of most benefit where rainfall distribution patterns result in low or variable soil water conditions. Dependent on the season, this additional water storage capacity may be of significant value.

Soil texture, soil structure, soil constraints and plant rooting depths are the crucial factors determining the amount of water available for plants to access (plant-available water or PAW). Although WHC tends to increase as clay content increases due to changes in the soil pore structure (higher number of small pores), a portion of the water remains unavailable to plants. This means that the influence of an increase in SOC on plant-available WHC is not a constant but is dependent on soil clay content. For example, in Fig. 14.8 it can be seen that the influence of an increase in SOC has a declining effect on plant-available WHC as clay content is increased.

In this example the amount of extra plant-available water holding capacity increased from 2 mm in soils with 30% clay, to approximately 5 mm in those with less than 10% clay. Although this may not be important in any one event, storage of this amount of extra water over ten rainfall events would amount to 30 mm – the equivalent of 600 kg/ha grain if a water use efficiency of 20 kg grain/mm water is reached. It is important to note that it will be more difficult to obtain an increase in SOC content of 1% on a sandy soil compared to a soil with higher clay content.

SOC can also influence plant-available water by stabilising soil structure and, in particular, the pore size distribution within a soil. Table 14.2 shows measured changes in the infiltration of water and its flow through the soil profile. In particular, it indicates the greater amount of water available under farming systems that incorporated green manure crops compared to a winter fallow.

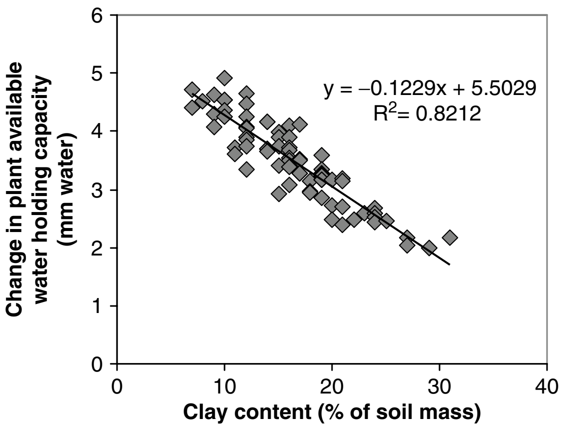

Fig. 14.8 The effect of increasing soil organic carbon by 1% in the 0–10 cm soil layer on plant available water holding capacity (mm) at a range of different clay contents (% of whole soil mass) on Chromosols of the mid-north region of South Australia

Table 14.2 Soil bulk density and water infiltration rates measured on a red sandy loam (Chromosol) at sowing time in 1999, after field pea green manure and fallow treatments were imposed in 1998 at Mullewa, Western Australia

Measurement	Fallow	Brown manure (green manure crop desiccated at flowering)	Green mulch (green manure crop slashed at flowering)	LSD (P=0.05)
Bulk density (mg/m³)	1.5	1.3	1.4	0.3
Sorptivity (mm/h)	13.6	16.7	17.4	3.4
Flow rate (mm/h)	47.0	27.3	30.1	8.8
Volumetric water (%)	7.0	11.3	12.1	6.3
Available water (mm/m)	69.6	113.2	121.3	

14.3.3 Energy for Biological Processes

When soil organisms break down organic matter they use carbon as an energy source and cellular building block, and use mineral nutrients for their growth and metabolism. In using organic matter (including other organisms) as food, they release CO_2. Depending on climatic conditions, between 50% and 75% of the carbon in fresh organic residues may be released as CO_2 during the first year of decomposition. Labile fractions of SOC (POC and dissolved organic carbon) are the predominant sources of energy for soil micro-organisms. In cropping soils of Western Australia, a strong positive relationship has been found between POC and the total mass of micro-organisms measured as microbial biomass carbon (MBC; Fig. 14.9).

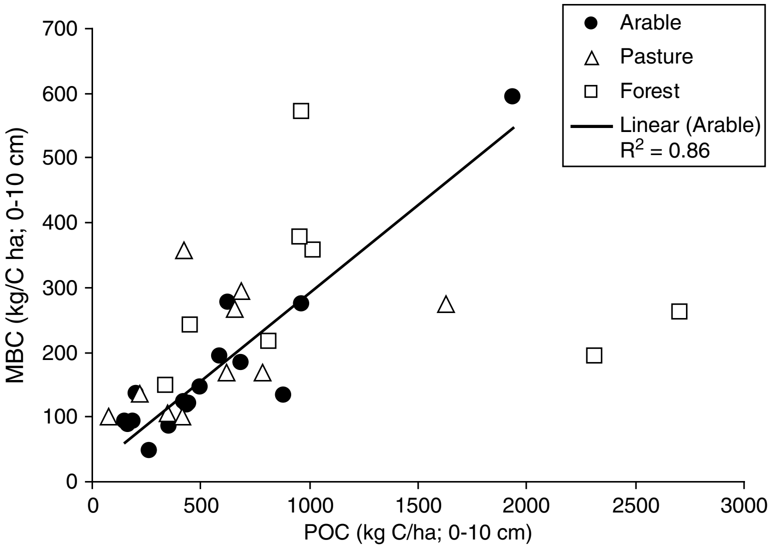

Fig. 14.9 The relationship between particulate organic carbon (POC) in organic matter and microbial biomass carbon (MBC) under a range of land uses in Western Australia. The line shows the strong linear relationship for the arable sites

Land use and agricultural management practices alter the relative proportion of labile SOC fractions, which in turn regulate microbial community composition and function (Grayston et al. 2004; Cookson et al. 2005). In arable systems, these labile fractions are often associated with rapid cycling of nutrients which can be correlated directly with increased yield (Stine and Weil 2002). In contrast, ROC is considerably less biologically available than other components of SOC (Baldock and Smernik 2002). With mean residence times in the order of several thousands of years, much of the ROC is more reflective of the historical conditions under which the soil developed rather than more recent agricultural management practices; it can be considered as an inherent fraction of the SOC that does not provide energy to microbial processes.

14.3.3.1 Provision of Nutrients

As organic materials decompose, nutrients can be released (mineralised) or taken up (immobilised) by soil organisms. Net nutrient mineralisation (the balance between mineralisation and immobilisation) provides a measure of the influence that decomposition processes will have on the supply of plant-available nutrients. A primary control over net nutrient mineralisation is the carbon to nutrient ratio of the organic materials being decomposed. As the carbon to nutrient ratio decreases, the potential for a net release of nutrients into the plant-available pool increases.

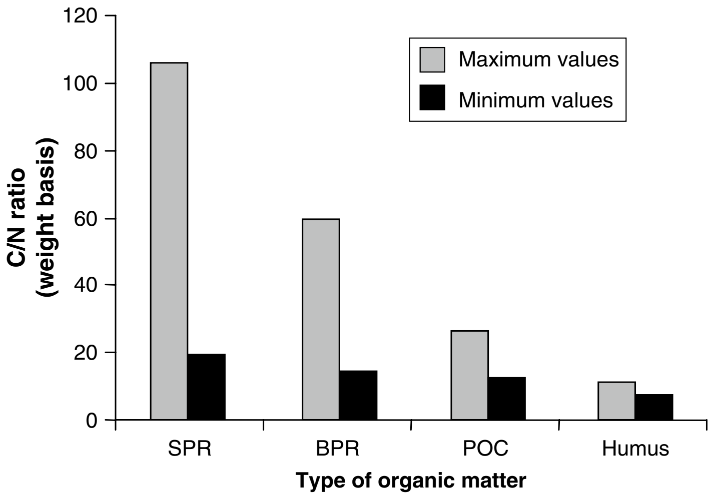

Fig. 14.10 The upper and lower boundaries for the C/N ratio of different SOM fractions measured across 29 south eastern Australian soils with total organic carbon contents ranging from 0.8% to 5.7%

As plant residues progress through the POC fraction to the more biologically stable humus fraction, the extent of decomposition increases, and the carbon to nutrient ratio decreases in magnitude and variability. Across 29 soils from south-eastern Australia with SOC contents ranging from 0.8% to 5.7% in the top 10 cm layer, C/N ratios of SOC fractions and their variance decreased from surface plant residues (SPR) (more than 100) through to humus (less than 10) (Fig. 14.10). The variations in C/N ratios measured for the SPR and BPR fractions suggest that nitrogen release dynamics will vary with the type of crops grown. High-N residues with narrow C/N ratio, such as those obtained from pulses or pasture legumes, will result in greater N release to the soil compared to low N residues (i.e. wide C/N ratio) such as cereal crops.

The influence of C/N ratio (determined from the combined POC and BPR fractions) on mineral N release (Fig. 14.11) illustrates that organic material with a C/N ratio below 22 released more mineral N. In this example, as the C/N ratio of these pools narrowed further, the availability of N increased rapidly. The N availability after three different green manure treatments (lupin, field pea and oats) reflects recent organic inputs, due to the chemical similarity between plant residues and POC (Fig. 14.11). In contrast, organic material with a C/N ratio above 22 did not supply additional mineral N to the soil–plant system. Residues with high C/N values (e.g. wheat stubble with a C/N of approximately 80:1) can immobilise or 'tie up' soil N in the short term.

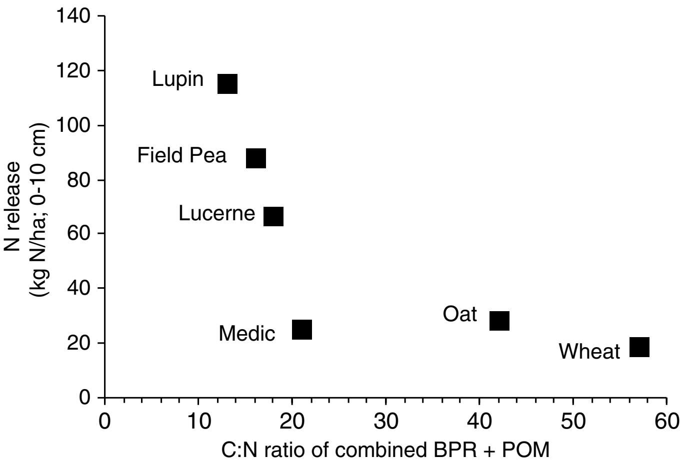

Fig. 14.11 The influence of the C/N ratio of the buried plant residue (BPR) plus particulate organic carbon (POC) fractions on N release (assessed as potentially mineralisable N) in soil

14.4 Monitoring Soil Organic Matter

Globally, the soil is a large sink containing approximately 1,550 Gt SOC, with an additional 750 Gt of inorganic carbon (0–100 cm depth; Krull et al. 2004). SOC accounts for more carbon than the combined total amount of carbon in the atmosphere (780 Gt) and vegetation (550 Gt). In Australia, soils and vegetation are estimated to contain 48 and 18 Gt carbon, respectively. Thus the carbon contained in soils globally and in Australia is approximately 2.7 times greater than that stored in vegetation.

Most Australian soils would be expected to contain more than 15 t C/ha in their 0–30 cm surface layer, which equates to a soil with a carbon content of 5 g SOC / kg soil and a bulk density of 1 t/m^3. Soil containing 50 g SOC /kg soil and a bulk density of 1.5 t/m^3 would have 225 t/ha C in the 0–30 cm layer. Using an average wheat yield of 2 t/ha grain, a harvest index of 0.37, a carbon content of 450 g C/kg residue, allowing for root dry matter and 50% decomposition, loss of crop residue, an annual addition rate of carbon to the soil of about 0.8 t/ha is achieved. This is approximately an 18^{th} of the minimum SOC value of 15 t/ha C ha and a 280^{th} of the 225 t/ha C value. Consequently it is often difficult to measure management induced changes in SOC on an annual basis given the small amounts of the C inputs relative to the amount of inherent carbon present in a soil. Long measurement times (more than 10 years) are usually required to detect significant management-induced changes in total SOC content unless considerable external inputs of carbon are also provided. Because of the continued decomposition of SOC, substantial amounts of

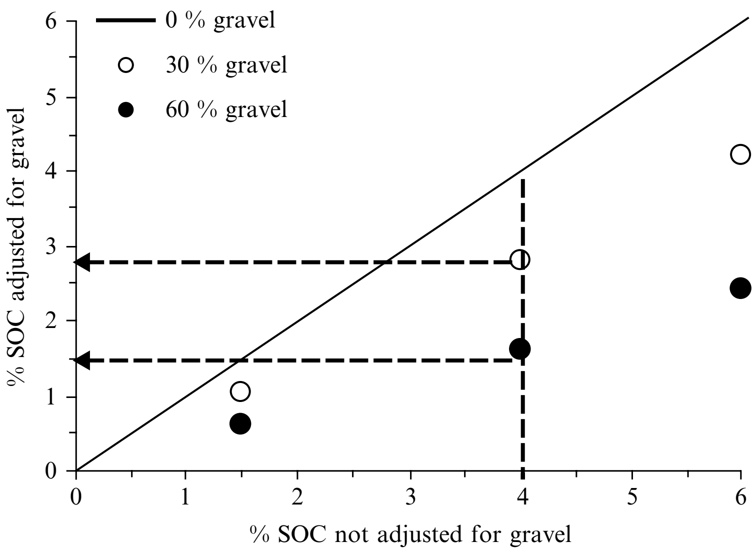

Fig. 14.12 Calculated change in soil organic carbon content (%) for soils not adjusted (*x-axis*) or adjusted (*y-axis*) for gravel content. The dashed lines illustrate that a soil test result of 4% SOC once adjusted for 30% or 60% gravel would equate to 2.8% SOC and 1.6% SOC respectively

additional organic material are required to have a measurable effect on SOC over the long-term (simulation modelling suggests an additional 2 t/ha of plant residues retained each year for 20 years may increase total SOC by only 0.5%). Where rapid changes in total SOC content have been reported in typical Australian farming systems these have often been associated with changes in gravel and/or soil bulk density not being taken into account. For example, as gravel content is increased, the mass of soil (i.e. less than 2 mm) in a given volume is less, resulting in SOC being concentrated in a smaller volume, within the <2 mm soil fraction (Fig. 14.12). Where SOC comparisons are being made between sites with different bulk density and/or gravel content (or at the same site in different years), a percent carbon value must be adjusted to t/ha to allow for changes in soil density and gravel content.

In Australian agricultural soils, SOC content is highest in the 0–10 cm soil layer, due to leaf drop, stubble return and the predominance of roots in the surface soil layer. This is generally between 30% and 50% of the total soil C within a soil profile. Because of its more biologically labile nature, the response time of this soil layer to changes in soil management or inputs is likely to be more rapid than that of SOC in deeper soil layers. SOC contents of the 10–30 cm and 30–100 cm layers tend to be lower and demonstrate smaller management-induced change, with the possible exception of soil under deep-rooted perennials. However, a study by Macdonald et al. (2007) in the northern wheatbelt of WA showed that total organic carbon (0–65 cm) did not differ significantly between adjacent native woodland and a mixed grass/lucerne pasture, whilst there was clear evidence of N enrichment

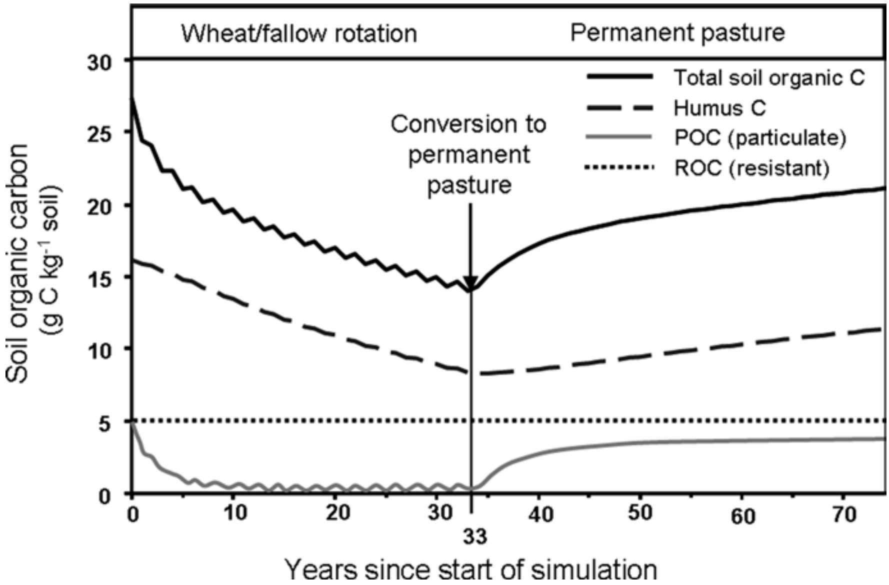

Fig. 14.13 The influence of changing from a wheat–fallow rotation to permanent pasture on soil organic carbon fractions simulated over a 75-year period

under the grass/lucerne pasture system. In both cases, the major portion of the soil carbon (about 80%) was present in the surface 15 cm.

Total SOC is unlikely to be a good predictor of the availability of C to microbial communities and thus the level of biological activity that can be maintained in a soil. Instead, the labile fractions of SOC that are sensitive to changes in land use and management practice are considered more important indicators (McLauchlan and Hobbie 2004; Haynes 2005; Hoyle and Murphy 2006). Quantifying management-induced changes to the more dynamic SOC fractions can provide a more rapid indication of the direction of SOC change. For instance, it can be seen from Fig. 14.13 that although the directions of change for the POC and humus forms of SOC were the same, the relative rates of response of the more labile POC fractions were initially greater than that of the more stable humus fraction both in terms of carbon loss (when the wheat fallow system was implemented at year 0) and in terms of carbon build-up (when the permanent pasture system was implemented at year 33).

14.5 Conclusions

- Soil organic carbon plays a central role in the functioning of all soils including providing an energy source for biological processes, improving soil structure and buffering chemical reactions.

- Clay content is a key determinant of the potential for soil to store organic carbon; however, in most circumstances the amount of organic carbon in a soil is limited by climatic and soil induced constraints to plant growth and thus organic matter returns.
- The level of SOC is the result of the balance between inputs (e.g. plant residue and other organic inputs) and losses (e.g. erosion, decomposition).
- Organic carbon stored in a soil exists in a range of different fractions that vary in their size, chemical composition, stage of decomposition and function.
- Greater insight into soil function can be gained by monitoring SOC fractions rather than considering only the total amount of organic carbon present.
- A primary challenge for farmers is to sustain a profitable farming system for the long term, which requires continued addition and maintenance of organic inputs.
- Monitoring is essential to assess whether management induced changes are depleting or restoring the soil resource, and in understanding the impact of changing land use and climate.

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Part II
Rainfed Farming System Worldwide - Operation and Management

Following the principles discussed in Part I, Part II examines and integrates the diverse features of some important rainfed farming systems throughout the world. It defines the structure, operation and management of these systems as determined by environmental, biological, economic, social and political factors.

Part II comprises 12 chapters which introduce the reader to a number of rainfed farming systems (as defined in Chap. 2) in countries in southern, western and eastern Asia, northern and southern Africa, North and South America and Australia. These systems cover a range of rainfed agricultural development—from low to high levels of farm productivity and intensity. They are restricted to non-irrigated systems although some reference may be made to the use of supplementary irrigation from water harvested by farmers. Some examples of farming systems with generally adequate water in parts of the USA, South America, south Asia and Tibet are briefly discussed.

While each chapter of Part II presents its system(s) in ways that are molded by their history, environment, structure and operation, all include the essential system features in terms of:

- components and external influences—their elements
- structure—enterprises, rotations, machinery use, labour use
- operation—production of crops and livestock; control of pests; distribution and efficiency of utilisation of resources including water, energy, nitrogen and time
- response to external change.

This enables some assessment of the systems in terms of their productivity, profitability, efficiency, flexibility and sustainability, but also their weaknesses and opportunities for improvement.

Part II chapters may also provide case examples which show how farmers manage their farm systems to make best use of available resources in order to achieve their goals. They sometimes also reveal principles concerning whole systems that are additional to those expounded in Part I.

Chapter 15
Rainfed Farming Systems in the West Asia–North Africa (WANA) Region

John Ryan

Abstract In dry, rainfed lands of the world crop yield potential is usually limited by both low rainfall and degraded soil, as well as social and economic constraints. Though the Mediterranean region is the site of the origin of modern agriculture, the Mediterranean climate, with its characteristic relatively cool, moist growing season followed by a hot, dry period, imposes severe limitations on agriculture. The rainfed cropping systems that have evolved in response to climate are also influenced by regional and global socio-economic forces, which contribute to increased land-use pressure. This chapter gives an overview of rainfed farming in the WANA lands bordering the Mediterranean Sea, the climatic environment that governs and the soil resources that sustain it. Emphasis is given to specific cropping systems, soil fertility and crop nutrition, water-use efficiency, cereal-based rotations in relation to cropping sustainability and to soil quality. While most of the studies cited are from the International Center for Agricultural Research in the Dry Areas (ICARDA) based in the northern rainfed zone of Syria, the findings are generally applicable to the medium-range rainfall zone (300–500 mm/year) throughout the Mediterranean region. These studies also reflect the contributions of various national agricultural research systems and organisations that have cooperated with ICARDA especially in Morocco, Turkey and Pakistan. The chapter highlights some of the major changes that have impinged upon the region's rainfed farming systems in the past few decades, with implications for the future of rainfed cropping sustainability in the Mediterranean region.

Keywords Mediterranean agriculture • Rainfed cropping systems • Cropping intensification • Plant nutrition • Water use efficiency • Cereal–legume rotations • Soil organic matter

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_15,

15.1 Introduction: Background to Agriculture in WANA Region

Many regions of the world still fail to meet the nutritional needs of their people despite the scientific advances that have been made globally in food production. With continuing population growth, the energy crisis and escalation of oil and natural gas prices, the spectre of malnutrition looms for many in the Third World. Food security is now firmly on the world's political agenda and the discrepancies between the developed and 'developing' countries have become more apparent.

The semi-arid to arid conditions in some areas pose severe constraints on agricultural production, but there has been a resurgence of scientific interest in rainfed (dryland) agriculture (Rao and Ryan 2004: Peterson et al. 2006). Indeed, Lal (2000) considered the sustainable use of the world's soil and water resources to be a major challenge to mankind.

The lands bounding the Mediterranean (Fig. 15.1) are largely characterised by limited rainfall, with local modification of rainfall amount and patterns due to elevation and distance from the sea (Kassam 1981). As a consequence, the region's agriculture is dominated by rainfed cropping; indeed, much of the land as a whole is desert, where rainfall is too low to permit any cropping, allowing only limited nomadic pastoralism.

The Mediterranean Basin has two contrasting areas in terms of economic development: the north (Europe, Turkey and the some of the newly independent countries of central Asia), which is relatively affluent, and the south (North Africa) and

Fig. 15.1 Map of WANA region showing the countries under the mandate of the International Center for Agricultural Research in the Dry Areas (ICARDA), including the West Asia-North Africa region with a mainly rainfed agriculture

west (West Asia) which is poorer. This chapter focuses on the West Asia-North Africa (WANA) region. The WANA lands that border the Mediterranean are steeped in the history of mankind and its struggles since the beginnings of settled agriculture (Dregne 2006). The 'Fertile Crescent', extending from Lebanon to Syria, eastern Turkey and northern Iraq, is one of the major sites of evolution of human civilisation (Damania et al. 1998). The earliest settlements were in valleys and flood plains where water and deep, fertile soil were plentiful. The cultivation of crops and the practice of animal pastoralism marked the beginnings of agriculture with the domestication of many of the world's major cereal and pulse crops and also livestock, notably sheep and goats (Harlan 1992).

These lands are prone to food scarcity, because the rainfall-limited productivity is inadequate to feed their increasing human populations. Food supply is also being influenced by new driving forces (Von Braun 2007). These include: income growth, globalisation, high energy prices, urbanisation and climate change. In response to these concerns, Von Braun (2007) stressed the need for policymakers to mobilise the required resources at local levels to deal with the issue of food in its broadest context, including research in agriculture, nutrition and health.

Meeting future food demand while avoiding expansion of cropping into marginal and environmentally sensitive land areas will require intensification of production of basic cereals such as wheat, rice and maize (Cassman 1999). Cassman (1999) argued that this increased output could be sustainably achieved only by *changes involving improved germplasm*, *adequate crop nutrition and commercial fertiliser use*, *cropping intensification and irrigation.* Ecologically, such intensification must achieve both improved yield, and maintenance or improvement of soil quality.

While environmental concerns are becoming of equal importance with productivity in farming systems in developed countries, the dominant concern in developing countries is still to produce food, often at the cost of environmental degradation. This dichotomy is particularly evident in rainfed, semi-arid areas of the world.

With low and erratic rainfall a dominant constraint in the WANA region (Smith and Harris 1981; Kassam 1981), recent research has focused on improving water-use efficiency (WUE) and other aspects of the region's traditional farming systems (Cooper et al. 1987a; Pala et al. 2007). Since the establishment of the International Center for Agricultural Research (ICARDA) in 1977 in Aleppo, Syria, a major thrust of its research, especially in the early years, focused on water and nutrients to enhance crop production (Monteith and Webb 1981; Van Duivenbooden et al. 1999). The international Center collaborates closely with the National Agricultural Research Systems (NARS) in most countries of WANA, as well as with regional and international organisations dealing with agricultural development. Rainfall has sometimes been supplemented by use of groundwater for irrigation; but this resource is limited and over-exploitation of groundwater has raised concerns about the sustainability of expanding irrigation in such a water-limited environment (Ryan 2002).

The ravages of man on the soil and vegetative resources of the region over the millennia have greatly altered the landscape. Soil degradation followed the destruction of the region's original forest cover for fuel and construction, and overgrazing of the native vegetation by sheep and goats, was inevitable (Carter 1974; Clawson et al. 1971). Evidence of soil erosion is everywhere, but particularly in mountainous and hilly areas where the original soil cover overlying the limestone bedrock was shallow – much of today's landscape is almost completely devoid of soil (Ryan 1982). Archaeological sites in North Africa and the Near East have unearthed cities buried under metres of sediment and dust. These 'buried cities' with once thriving populations now bear testimony to the power of man to destroy the basis of his existence, through ignorance of the consequences of his interactions with the environment.

Despite the antiquity of the Mediterranean region, the complex system of integrated crop and livestock production mentioned in Biblical and other early records is still in evidence (Grove 1996), and the agricultural sector still controls the economic and social lives of a majority of people. However, many changes have occurred in the last three or four decades (Ryan 2002) with intensification of inputs and cropping frequency, increases of mechanical power for cultivation (mouldboard ploughs, 'ducksfoot'[1] cultivators, offset disc harrows,), planting (seed drills that work in stubble) harvesting (combine harvesters) and irrigation. Despite migration towards the large urban areas, the rural population is still large, due to high birth rates, with consequent increases in land-use pressure.

The extent to which any ecosystem can withstand land-use pressure, or its resilience to recover from a degraded state, is a characteristic of that ecosystem. Semi-arid or arid areas are often overgrazed and irreversibly degraded – lacking resilience. Sloping land, which is representative of much of the region, is particularly vulnerable to erosion and declining quality. In dry areas of the world such as WANA, the extent to which economic development, political stability and human well-being can be assured will depend greatly on improvements in the agricultural sector (Steiner et al. 1988). But only a vast improvement in this sector can sustain current and projected populations.

In contrast to developed countries, most countries of the WANA region are characterised by low agricultural output This is due to low per capita production, related to various socio-economic constraints such as weak to non-existent extension systems, limited credit facilities, low levels of the normal production inputs (fertiliser and crop protection chemicals), weak road and marketing infrastructures, and small, frequently fragmented holdings (Ryan 2002). The conditions described by Shroyer et al. (1990) for Morocco in North Africa provide a general indication of the conditions that prevail throughout the whole Mediterranean region.

The successful operation of Rainfed Farming Systems in the Mediterranean region is dependent on positive interactions between soil, climatic and socio-economic factors, some of which have features common throughout the region.

[1] See Glossary.

15.2 Climatic Environments

Rainfall and the agricultural growing season are concentrated into the cooler months, as illustrated in Fig. 15.2. The precise length of the rainfall season varies with proximity to the sea and with altitude. During this wet season, with only moderately low temperatures, rainfed cropping of temperate species is possible (Harris 1995). The cool, wet winter is followed by a hot, dry summer. Temperate crops can make good use of the limited rainfall with the help of low cool season evapotranspiration rates. The higher rainfall efficiency under lower temperatures and evaporation in winter (see Chap. 1) enables crops to be grown in the Mediterranean region at lower rainfall than in summer-rainfall areas of the world.

Details of the Mediterranean climate are found in many sources, e.g. Kassam (1981) who described climate, soils and land resources of the region, and Smith and Harris (1981) who examined the constraints of a Mediterranean climate for cropping. Brief descriptions of Mediterranean climatic conditions are found in Matar et al. (1992) and Ryan et al. (2006). The latter publication, along with an earlier one of Emberger et al. (1963) provides bio-climatic maps and length-of-growing period figures for various locations in the region based on rainfall, temperature, and evaporation. Mediterranean-type climates are also found at similar latitudes on the west coast of the USA, and in parts of Chile, South Africa and southern Australia.

In the WANA region, rainfall is mainly in the range of 150–600 mm/year, although with higher precipitation as rain or snow in mountainous areas. Mean daily temperatures are cool (5–18°C) to cold (less than 5°C) in winter (coldest in December–January) and are hot (greater than 20°C) in summer (Harris 1995). The typical Mediterranean climate is found in all lowland areas around the Mediterranean Sea but develops continental features (greater temperature ranges) in inland areas. The Mediterranean region is bounded on the north by countries with temperate climates and, to the south by tropical and subtropical climates.

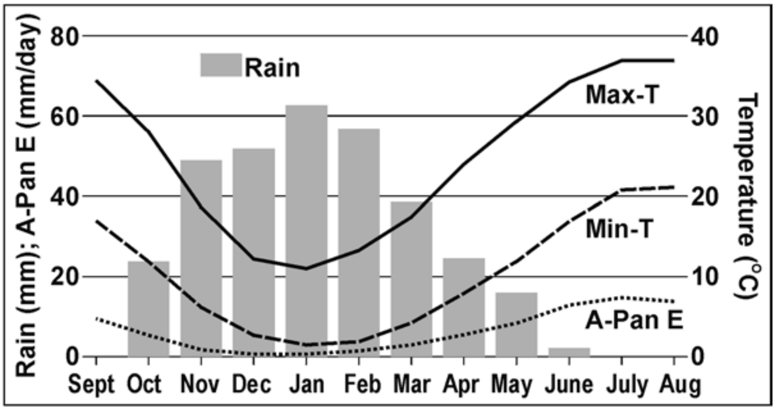

Fig. 15.2 Typical Mediterranean rainfall and temperature pattern – Tel Hadya, near Aleppo in northern Syria (mean annual rainfall: 340 mm, 284 m above sea level)

Two major climatic zones in the winter rainfall area are recognised: ‘lowland’ areas of less than 1,200 m in altitude, and ‘plateau’ areas above that. These two areas have distinctly different moisture and thermal regimes and therefore different crop and land use patterns. In higher-elevation areas, frost damage to crops is common while colder conditions, allied to snow cover and frost, extend the period of crop dormancy and thus limit the cropping season. Cold tolerance is a trait of varieties adapted to higher elevation areas and heat tolerance for those in lowland areas.

Based on calculations of Kassam (1981), rainfed cereal cropping is feasible on 53% of the land area in North Africa and on 61% of that in West Asia. Even within any relatively small area, considerable climatic variation exists, which greatly influences cropping systems and their output. For example, in the northern area of Syria, there are three sub-zones across a short rainfall transect: rainfall ranges from 476 mm at Jindiress, 340 mm at Tel Hadya to 286 mm at Breda (Ryan et al. 2008d). Despite their low elevation (Ryan et al. 1997), the sites experience variable (20–50 days) frost, increasing inland as the rainfall decreases. Though Morocco is a relatively uniform land area, it exhibits the same climatic variation as northern Syria, with rainfall decreasing from 500 to 600 mm/year in the north at Meknes to 460 mm at Merchouche about 100 km south, to 386 mm further south at Settat. Another further 150 km south in Abda Province, rainfall can be as a low as 200 mm/year. While distance from the coast is a factor in the rainfall decline, the main reason is the significant decrease in latitude into the drier Saharan climatic belt. Crop yields are linked to seasonal rainfall; in the drier part of the spectrum, where barley is more adapted, crop failure due to drought is common and the barley is then grazed in the early stage of vegetative growth. The wide variation in agro-ecological zones throughout WANA gives rise to similar variation in cropping systems and patterns. The implications of such variation are illustrated (Fig. 15.3) for the case of northern Syria (See also Section 15.4).

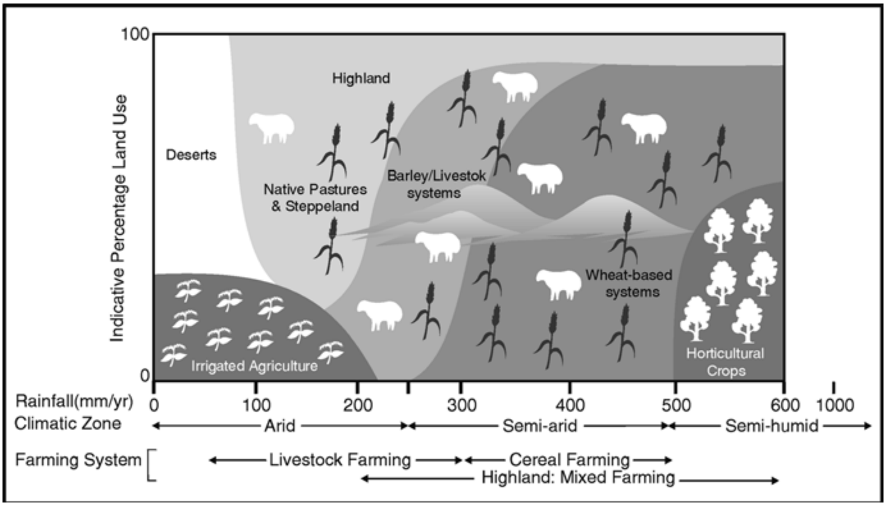

Fig. 15.3 Schematic representation of the farming systems across the rainfall transect in the West Asia-North Africa region

As expected, there is a positive relationship between seasonal rainfall and crop yields. This relationship is modified by the variation in seasonal rainfall distribution, and becomes more variable as the mean annual rainfall decreases (Keatinge et al. 1986). Solar radiation and temperature also influence the effectiveness of rainfall for crop growth, as sporadic showers have little influence on soil moisture due to immediate evaporation if ambient temperatures are high (Harris 1995). Some of the rain may be lost by runoff if intensities exceed the infiltration rate or quantity is greater than storage capacity of the soil (Smith and Harris 1981).

15.3 Soil Resources

Over the ages, societies in the region have flourished only when they occupied land with fertile soils and plentiful water. However, even with limited rainfall, high yield potential was possible if the soils had good structure, texture and depth to ensure infiltration and storage of excess water for dry times.

The diverse soils of West Asia–North Africa are the outcome of parent material, climate, biological factors (mainly original vegetation), topography and centuries of man's influence. The wide variation in soils has been indicated previously (Clawson et al. 1971; Dregne 1976) and described more comprehensively in the World Reference Base for Soil Resources (Deckers et al. 1998). As this latter study used the FAO system of soil classification, the equivalents in terms of Soil Taxonomy (Soil Survey Staff 1975) are presented by Ryan et al. (2006). Middle Eastern soils are dominated by those containing calcium carbonate, often with gypsum; acid soils are almost completely absent (0.3%). Many of the soils (20%) are shallow. There are small percentages of saline or saline-sodic soils (which are significant only in irrigated areas), dark clay and sandy soils, and some with poor internal drainage.

Soils are classified according to various levels of generalisation in a hierarchical structure, with soil orders being the highest or broadest category. Thus, soils of arid regions (Kassam 1981) at the order level include Entisols (poorly developed, alluvial or sandy), Inceptisols (relatively developed as to soil features, horizons, depth, etc), Alfisols (high base status, weathered with more clay in subsoil), Mollisols (rich soils with relatively high organic matter), and Vertisols (shrinking-swelling clays), and in the extremely dry areas, Aridisols (arid or desert type). Cropland in North Africa is dominated by Inceptisols (20%), lithic or shallow subgroups of various soil orders (15.5%), Alfisols (11%), Fluvents or soils in river valleys (6.0%), and Aridisols (16.2%). In West Asia, the landscape is dominated by Calcids (with high concentrations of calcium carbonate in the subsoil), lithic sub-groups, moderately deep Inceptisols, Alfisols,(many typical 'Red Mediterranean' Alfisols), with some Gypsids in localised areas such as river valleys. By definition, cropping is normally not feasible without irrigation in Aridisols. Mollisols, with relatively high levels of organic matter, are not widespread, but are important locally in some countries such as Morocco, Syria, and Lebanon. Many soils with distinct features are often described by farmers in local terms, e.g. in Morocco, red soils are called 'hamri' and deep clay soils are referred to as 'tirs'.

Temperature and moisture are major variables in defining soils at the sub-order level, and therefore of major significance with respect to soils of the Mediterranean region. While many soil features are related to the current climatic conditions, the dominant influences on the type of soil are the climatic and geological conditions that prevailed during the ages in which the soil developed. Although broad soil variation can be expected under the wide climatic variation, soils can vary considerably under somewhat similar climates, particularly due to the influence of parent materials and topography. While farmers are not familiar with scientific classification terms, they appreciate the significance of colour (nutrient reserve), texture (cultivation), and depth (moisture holding capacity) with respect to cropping systems.

Because of the low rainfall in the region, the parent rock or transported material is not intensely weathered, resulting in a slow rate of soil formation. The temperature-moisture regime dictates that soil organic matter (SOM) is low – generally less than 1% in most arable soils. Little biomass accumulates and this is rapidly mineralised (Ryan 1998). The range of soil physical and chemical properties indicated by Deckers et al. (1998) strongly influence which crops can be grown, how they are managed and how efficiently they use water (Harris 1994). Some examples of the differences between soil types in terms of crop production and constraints follow.

Sandy light-textured soils have a low water retention capacity and are prone to drought. At the other end of the texture spectrum, heavy clay soils may have poor internal drainage and are difficult to cultivate when wet, thus limiting tillage practices and their timing. Soil depth is of particular importance in rainfed agriculture in the region where the capacity to store excess moisture from the winter rainfall for spring crop growth (along with some late spring rain) is crucial for high yields (Cooper and Gregory 1987). On three soil types in the Settat area with the same rainfall (471 mm, above-average and well distributed), average wheat grain yields were 1.2 t/ha in the shallow depth (30 cm) Rendoll soil, 1.7 t/ha in the medium depth (60 cm) Calcixeroll, and 3.9 t/ha in the deep (>1 m) Vertisol (Abdel Monem et al. 1990).

Crops that are productive on saline soils are limited to those which are salt-tolerant and are dependent on irrigation (e.g. sugar beet) and thus not applicable to rainfed farming. In saline rangeland areas, *Atriplex* thrives as a forage shrub.

Stable soil structure is critical for good seed germination, healthy water relations, and aeration. Excessive tillage can destroy soil aggregates mechanically and by promoting breakdown of the soil organic matter. Conversely, soil structure can be improved by crop rotations that include legumes, especially forages such as vetch and medics, and by good soil management (including application of chemical fertilisers) which increases yields and therefore the contribution of root biomass to soil organic matter (Masri and Ryan 2006; Ryan et al. 2008b). Organic matter can also be increased by shallow and reduced tillage, which minimise soil disturbance. Application of compost (Ryan et al. 2009; Sommer et al. 2011) can enhance the effect of vetch on SOM in a compost-amended cereal–vetch rotation over a long

(10 years) period (Pala et al. 2008). Although neither organic matter nor its effects on soil structure were considerations when various long-term trials were started, the conclusions that have emerged are that legume-based cropping systems can increase SOM and consequently soil aggregate stability. The increases in SOM that have been observed with shallow tillage, compared with conventional mouldboard ploughing (Ryan et al. 2009; Sommer et al. 2011), are likely to promote improved soil structure.

Soil organic matter acts as a reserve of nutrients, particularly nitrogen (N). During favourable temperature and moisture conditions in February–April, fractions of organic matter are mineralised, releasing N for crop uptake (Ryan 1998). However, levels of available N are generally lower than crop requirements and N deficiency is ubiquitous (Harmsen 1984; Ryan and Matar 1992: Ryan 2004). Deficiencies of phosphorus (P) are equally common (Matar et al. 1992). Potassium (K) is generally adequate for the growth of most crops except for some, such as potatoes and sugar beet that require high K levels (Ryan 2002). Similarly, the calcareous parent material contributes to adequate levels of calcium, magnesium, and sulfur.

Deficiencies of some micronutrients, particularly zinc and iron, are common and induced by the high soil pH (Rashid and Ryan 2008). Extensive field studies in the central Anatolian plateau of Turkey have shown widespread Zn deficiency for cereals (Cakmak 1998). While nutrient deficiencies are the more common occurrence, boron (B) toxicity can reduce crop growth in some areas (Yau and Ryan 2008). Boron deficiency is also common in the Indian sub-continent, especially Pakistan (Rashid et al. 1997).

Thus, one could conclude that the soils of the WANA region exhibit considerable variability, as expected from such a broad geographical landmass. For rainfed agriculture, both soil depth and texture are crucial factors in controlling water storage and water use efficiency. As in most agricultural lands of the world, both N and P are deficient; but K is generally adequate. Zinc deficiency and boron toxicity have been shown to be of local importance.

15.4 Farming Systems in WANA

The farming systems of the Mediterranean area of West Asia and North Africa have many features in common with other areas of the world with a Mediterranean-type climate. These common elements include temperate cereals, pulses, small livestock (sheep and goats), olives, vines, fruit trees and vegetables. While the prevailing rainfed farming systems that evolved in the region are largely dictated by climate and soil resources, the character of the systems (e.g. crop distribution, yields, sustainability) has been influenced by socio-economic factors such as population growth, urbanisation and urban demand, restrictive land tenure, the role of farmers in the political and social structure, and the degree of their commercialisation and production specialisation (Gibbon 1981).

Many techniques for the rainfed cultivation of cereals and legume crops evolved in the region (White 1970). During the Roman period and the later period of Arab Islamic expansion, agriculture in the Mediterranean region was the most organised and productive in the known world (Gibbon 1981). This was followed by stagnation in productivity during the era of colonial rule in the nineteenth and early twentieth centuries, which favoured the wealthy, large landowning class who focused on high-value irrigated export crops to the detriment of peasants in semi-arid lands. In the latter half of the twentieth century, agriculture in many countries of the region underwent various programs of agrarian reform resulting in land distribution (Amin 1976). With these developments came new laws regarding land ownership and inheritance in accordance with religious norms, all within the context of government control of markets and limited private enterprise. Thus, present day farming systems in the Mediterranean region are a product of the events of both long past and recent histories.

One of the earliest classifications (Gibbon 1981) identified rainfed systems of the Mediterranean region from the driest to the wettest environments.

1. *Steppe-based nomadic or semi-nomadic pastoral systems*: mainly involving sheep and goats. The livestock are kept in the drier areas in winter–spring, when some pasture is available; increasingly, the flocks or herds are supplied with supplementary feed and water. In summer, the animals are moved to arable areas and fed on cereal stubble and residues of other crops based on a fee charged by the landowners. This time-honoured pastoral system is linked to Bedouin tribes. In recent times, trucking has increased flock mobility and thus substantially altered the character of the region's transhumance. Grazing of crop residues, whether by migrating or sedentary flocks of sheep, contributes little to soil quality (by droppings), but subjects the soil to wind erosion by pulverising it with their hooves, and promotes subsequent water erosion by leaving the grazed surface bare.
2. *Rainfed cereal production systems,* based on: (i) wheat (bread wheat and durum wheat) in higher rainfall areas (<300–500 mm annually) in a cereal–fallow rotation, and (ii) barley in the lower rainfall zones and on shallower soils in the wetter areas. Increasing land-use pressure has contributed to a decrease in fallow and an increase in cereal monoculture.[2] On deeper soils (>100 cm) and where rainfall is favourable, crops grown in rotation with wheat include food legumes (chickpea, lentil, and faba bean[3]) and forage legumes such as vetch. Summer crops such as watermelon can be grown after winter fallow where stored moisture is adequate (Harris 1995). Normally, cereals are grown in rotations of two cycles, i.e. a cereal crop followed by an alternate crop, or land left uncropped in the case of fallow; or more rarely four cycles. Crop yields are related to the amount and distribution of rainfall received in the growing season (Keatinge et al. 1985, 1986).

[2] See Glossary.

[3] See Glossary for botanical names.

3. *Rainfed mixed tree and arable crop systems*: occurring in areas of high (>600 mm) annual rainfall and include goats or dairy cattle. The tree crops include olives, figs, stone and pome fruits (apricots, peaches, plums, pears, apples) and vines. There has been recent expansion in fruit and nut trees, which are more profitable than cereals.
4. *Irrigated farming*: a distinct and complex system in itself. Originally, irrigation was practiced in very low rainfall areas when rainfed cropping was impossible and where river water was available. Increasingly supplementary irrigation using ground water has encroached into normally rainfed areas (Oweis et al. 1998). The sustainability of such practices is questioned as water levels are declining. Larger schemes based on harnessing river water through dams have also been a feature of the irrigated sector in the past few decades. Slowly the traditional flood system has been partly replaced by sprinklers and, to a lesser extent, drip systems.

A schematic representation of the various agricultural production systems, developed by ICARDA (Fig. 15.3) illustrates the relationships of the various cropping systems. It broadly encompasses the overview of Gibbon (1981) described previously and is useful to show current cropping conditions. The main image that emerges is the dominance of cereals (wheat or barley) throughout the arable rainfall range and the involvement of small ruminants across the entire spectrum. In the mixed-farm zone, livestock are often nomadic and hence only temporarily part of any system.

In the very low rainfall or arid zone (<150 mm), the land is either under irrigated cropping or desert. As the mean annual rainfall increases, rainfall is sufficient to support native pastures in steppe land and in higher elevation mountainous areas. Barley integrated with livestock (sheep and goats) dominates the 200–300 mm rainfall zone; if rainfall is sufficient for a crop, the animals graze the stubble and if there is crop failure due to drought, the barley is grazed in the tillering or early growth stage. With increasing rainfall in the 300–500 mm range, wheat (durum wheat and bread wheat) is dominant, with forage legumes and pulses also common. In this more favourable rainfall zone, a greater range of crops can be grown given the lower risk of drought at the higher levels of rainfall, merging into the 500–600 mm range where a variety of tree and fruit crops are also grown. The variety of crops is broader in the higher rainfall areas. While considerable overlapping occurs between the agro-ecological zones, the trends are for increasing irrigation in arid areas, more supplemental irrigation in traditionally rainfed areas, and greater crop diversity in more favourable areas, especially with high-value tree and specialty crops.

Fallowing in alternate years has been traditional practice in the Mediterranean region, to increase the likelihood of obtaining an economic yield at least once in every 2 years (Cooper et al. 1987a; Harris 1995). Where clean fallow is practiced, i.e. the land is cultivated to control weeds, as in Turkey, the increased water storage carried over from the fallow year to the cropped year generally results in substantial increases of cereal yields. However, the water efficiency of fallow is relatively low, i.e. generally less than 15% (Pala et al. 1999). Another drawback of clean fallow or of grazed fallow is the susceptibility to erosion of the bare soil. Although this could be mitigated by allowing the stubble to remain on the soil, all residues and fallow weeds are presently grazed by animals. In countries of North Africa, where 'weedy' fallowing is practiced (to provide feed for animals during the rainfall season), the water efficiency of fallow is even lower. The practice of fallowing has been decreasing gradually in recent years due to increased land-use pressure from population growth; it is being replaced by either continuous cereal cropping, which is not sustainable, or by introducing a legume or other non-cereal crop in the rotation (Jones and Singh 2000; Harris 1995).

As in all cropping systems, tillage was intended to control weeds and prepare the seedbed. Most tillage in the WANA region is now mechanised, although animal traction is still common in the poorer areas, with small holdings and in mountainous areas; animal traction is still relatively common in countries such as Morocco, but rare in the West Asia region. The traditional tillage involves mouldboard ploughing (inherited from Europe) followed by cultivation with light implements such as disc harrows. This is normally done either after harvest or in the fall after the first rains of the season. In other countries, such as Morocco, primary and secondary cultivation is done with the offset disc harrow (Pala et al. 1999).

Conservation tillage and no-till (with stubble retention) have not yet caught on in the Mediterranean region despite considerable research (Mrabet 2008, Chapter 40). In some cases, no yield advantage was shown with conservation tillage, but the costs were lower and procedures more economical than with conventional tillage (Pala et al. 2000). Expansion of conservation tillage/no-till in the region is hindered by the cost of herbicides to financially-poor farmers and by traditional practices that require crop residues to be used for grazing by sheep and goats after harvest. Similarly, any reduction in energy costs of reduced tillage will be influenced by the extent to which governments of the region subsidise farm fuel costs. These considerations add a socio-political dimension that may not exist in rainfed areas of the developed world.

The possibility of increasing crop output is illustrated in Fig. 15.4. As the lands of the WANA region have been farmed for millennia, any increase in output has to come from land already in production (72%), with limited possibilities for expansion of new arable lands (7%). A significant portion (23%) of the potential increase in output can come from cropping intensification by reduction of fallow. Given the constraints imposed by moisture deficits, increasing output under rainfed conditions is a major challenge; it must come from increased and more efficient use of chemical inputs and the application of adapted technologies. With competition for land for other uses such as urban sprawl (in the absence of effective zoning regulations) and highways, the pool of arable land may actually diminish.

The following Sections will emphasise the effect of rotations, nutrient application, water-use efficiency and related agronomic, management and economic factors on the performance of Mediterranean rainfed cropping systems. The developments in these areas are to be seen in the context of improvements in other areas of agricultural research, particularly plant breeding. Germplasm improvement has focused on breeding for adaptation to drought and moisture-stressed conditions,

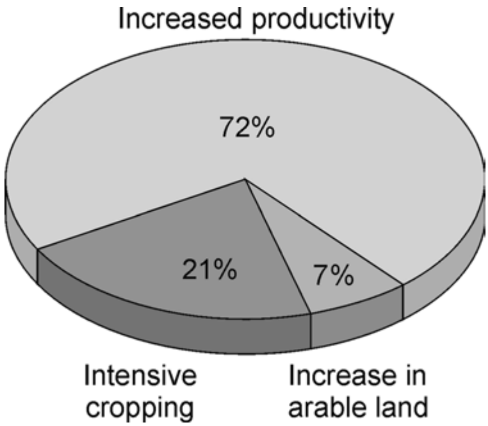

Fig. 15.4 Potential options for increasing crop production in the WANA region

high and low temperatures, and disease resistance. Considerable emphasis has been placed on use of biotechnology, in addition to conventional approaches, mainly for wheat and barley improvement.

15.5 Improving Soil Fertility and Plant Nutrition

The productivity and profitability of agricultural systems are dependent on the fertility of the soil, and its capacity to provide essential nutrients. Yields can only be maintained if the nutrients that are removed from the soil–crop system are replaced. Before the main era of chemical fertiliser use, since the mid-twentieth century, crop yields were related to the inherent fertility of the soil; what little nutrients that were added were in the form of animal manures, with some contributions of nitrogen from legumes. Records from Biblical times suggest that, in rainfed Middle Eastern agriculture, yields of cereal in good rainfall years and in fertile soils may have approximated today's yields without fertilisers. This indicates that the inherent potential of the system may not have substantially altered over the millennia (Amir and Sinclair 1994). Such yields may have been satisfactory to support the relatively low populations in the known world at that time.

Scientists and policymakers are becoming increasingly aware of the role of mineral fertilisers and adequate plant nutrition in contributing to global food security (Roy et al. 2006). Lonergan (1997) stressed the importance of diagnosing nutrient constraints in developing countries and their correction with fertilisers, as well as the development of crop cultivars that use nutrients efficiently.

15.5.1 Fertiliser Use

The use of chemical fertilisers in the Mediterranean region has to be seen in the context of global trends for both developing and developed countries (IFADATA 2006).

From the 1960s, fertiliser use (N, P, K) expanded rapidly to reach a peak in the 1980s. Since then, there has been a decline in developed economies and those in transition; only developing countries have increased their share of the global fertiliser market (particularly N and P). Growth in total fertiliser use is estimated at 2.2% per year in developing countries, but only 0.2% in developed countries.

The patterns of nutrient use in countries of the Mediterranean region were similar to global trends, but differed in magnitude. For example, three mainly rainfed cropping countries (Syria, Turkey, Morocco) show peaks in nitrogen (N) and phosphorus (P) consumption in the 1990s, with nil or minimal amounts of potassium (K) used in these countries. The low use of K reflects the generally adequate K-supplying power of Mediterranean soils, at least under rainfed conditions. The differences in ratios of nutrient use for the three major elements have implications for balanced fertilisation, a concept currently in vogue (Ryan et al. 2008d) and one that is amplified in Chap. 5.

15.5.2 Recent Research in Crop Nutrition

Crop nutrient status encountered in northern Syria's rainfed zone has mirrored that in the WANA region as a whole (Ryan 2004). Nitrogen is deficient in all crops except N-fixing legumes and, to a lesser extent, cereals that follow productive legumes in a rotation (Harmsen 1984). Field trials have confirmed significant yield responses to N, which increased as the seasonal rainfall increased in the range of 200–500 mm/year (Anderson 1985; Jones and Wahbi 1992). Earlier, Harmsen (1984) showed how critical effective N fertilizer use was for economical rainfed crop production, and this was echoed in numerous national program reports from the region, with a strong focus on N use efficiency (Ryan and Matar 1992). A subsequent meeting of scientists from countries of WANA reflected an evolution of N research, with a broader systems approach to such issues as nutrient cycling and N use efficiency (Ryan 1997). The workshop provided a benchmark for soil fertility in the WANA region, providing a synthesis of what had been achieved by previous research in the region, while calling for a more holistic view of: (1) N use, especially in relation to cropping systems; (2) the role of other nutrients such as P and micronutrients; (3) nutrients in relation to water use efficiency; and (4) implications for soil quality.

The most comprehensive consideration of N fertiliser use was in the 'Cropping Systems Productivity' trial described initially by Harris (1995) and later reported for the full 14 years by Ryan et al. (2008d). Nitrogen applications were assessed within seven rotations, i.e. wheat followed by: fallow, watermelon as a summer crop, wheat, forage legumes (vetch and medic) and food legumes (the pulses chickpea and lentil), under three cereal stubble grazing regimes (heavy, medium, zero). P was provided as a base fertiliser, while K and micronutrients were adequate in the soil. Responses in cereal grain yields to N fertiliser at application rates of 0, 30, 60 and 90 kg N/ha/annum were influenced by the rotation, and its influence on soil

Table 15.1 Overall effects of N on grain yields of durum wheat within each rotation

	Grain yield (t/ha)			
Rotation: wheat with Nitrogen kg/ha/year	0	30	60	90
Fallow	1.85	2.27	2.69	2.92
Wheat	0.74	1.11	1.24	1.25
Lentil	1.67	2.00	2.23	2.31
Chickpea	1.23	1.58	1.69	1.88
Melon	1.78	2.13	2.51	2.74
Vetch	1.84	2.18	2.29	2.35
Medic	1.76	1.84	1.92	1.99
Comparison of rotations within any N level SEM ± (0.057–0.078)				
Mean	1.55	1.87	2.08	2.21
Mean yield of straw (t/ha)	2.61	3.31	3.78	4.12

Overall mean of rotations within N level SEM ± 0.02

moisture and biologically-fixed N (Table 15.1). With a mean annual rainfall of 340 mm, rainfall during the 14 years of the trial ranged from 214 to 504 mm, most years being in the 300–400 mm range.

The mean responses of grain and straw to applied N, over all rotations consistently increased with N application rate. Percentage responses were highest for the fallow and melon rotations (although melons were grown in only 5 of the 14 years) and least for the medic rotation. As soil N was enhanced under medic through biological N fixation, the low response to applied N was attributed to limited available soil moisture, due to its relatively greater depletion by the medic treatment of the rotation series. Even with fallow, soil moisture availability was seen as the limiting factor restricting N responses.

Phosphorus is the second most important nutrient limiting plant growth in the predominantly calcareous Mediterranean soils. Through soil testing and subsequent calibration of crop responses in the field (Matar et al. 1992), critical test values of P availability were determined (Olsen P, 5–7 mg/kg) as well as fertiliser P application rates for different crops, including those in rotation (Ryan and Matar 1992).

Most of ICARDA's field studies of P responses were for single years, except for the long-term P trial ('P Dynamics') established in 1986, to examine the importance of residual P in a cropping systems context. This trial, reported by Ryan et al. (2008a), used a split plot design. The main plot treatments were five initial applications of P (0, 22, 44, 66, and 88 kg P/ha) – and split plots were annual applications of 0, 7, 14, 21, and 28 kg P/ha. The 9-year cereal/legume (mainly lentil) rotation was conducted at three stations of varying mean annual rainfall and initial levels of Olsen's available P: (Jindiress, 470 mm, 4.4 mg/kg, wheat/lentil; Tel Hadya, 340 mm, 6.2 mg/kg, wheat/lentil; and Breda, 270 mm, 2.7 mg/kg, barley/vetch).

This trial contributed to the efficient use of P in soils by identifying the minimum levels of P required for adequate yields without causing a negative P balance in the soil, i.e. a decrease in Olsen P with time, indicating that the amount of P added was not sufficient to compensate for the loss of P by crop uptake.

Overall yields from the trial were closely related to seasonal rainfall at the three sites. There was a significant yield response to P in cereals and legumes at Jindiress and Breda and in lentil at the Tel Hadya site, thus indicating a higher P requirement for lentil. Residual P (from the initial application) did not produce a significant yield response at any site. However, both residual and annually applied P increased available Olsen P levels as well as seasonal and total P uptake by the crops. Where no P or the lowest P level (7 kg/ha) was applied, there was a negative Olsen soil P balance, which was counterbalanced by applying an annual application of at least 14–21 kg P/ha. The relative changes in soil available P and crop responses provide guidelines for P fertilisation strategies. Whether one should apply a dressing of P fertiliser once every 3–4 years or each year in any particular cereal/legume rotation depends on the relative costs involved, and also the build up of soil P over time.

With the initial understandable concerns about N and P as production constraints, micronutrients or minor elements were considered of little consequence. However, research on micronutrients, notably in Turkey, Pakistan, and Syria (Rashid and Ryan 2008) identified widespread Zn deficiency, especially in cereals, on the Anatolian plateau of Turkey (Cakmak 1998). Zinc is now incorporated in compound fertilisers, with a significant impact on the Turkish economy through improved crop yields. Not all nutrient constraints can be rectified by soil application. In the case of boron toxicity, which occurs in some parts of the Mediterranean region in areas formerly influenced by maritime conditions (Yau and Ryan 2008), the only solution is a long-term one, of breeding for toxicity tolerance using genes from tolerant, locally adapted landraces.

15.5.3 Implications for Improved Management

The research chronology has progressed from identification of nutrient deficiencies, to demonstration of field responses to nutrients in individual crops and cultivars, to nutrient behaviour in long-term crop sequences. Thus, there has been an evolution from considering single-year crop yields of grain and straw, to the complex time-frame of crop sequences, where yield, crop quality, soil quality and environmental factors were all assessed.

Within the past few decades, rainfed agriculture in the Mediterranean region has made a rapid transition from a traditional system where little or no external chemical inputs (especially nutrients) were used, and where crop yields were correspondingly low, to a situation where fertiliser use is now standard practice for most farmers except those in poorer and remote areas with harsh climatic conditions. Better weed and pest control and improved varieties paralleled this development.

Along with the above trends in the WANA region, both research and practice have focused increasingly on the biological and economic efficiency of fertiliser use and the balanced use of nutrients. While farmers are generally aware of the importance of applying adequate P as well as N, the lack of adoption of soil testing in the region is still an obstacle to more efficient fertiliser use (Ryan and Matar 1992; Ryan 2004).

15.6 Enhancing Water Use Efficiency in Rainfed Cropping Systems

As soil moisture is invariably the most important constraint to rainfed cropping in the Mediterranean region (Smith and Harris 1981), the goal of applied research has been to devise strategies to increase the amount of product per unit of available water. Research by ICARDA has both helped to define the principles outlined in Chap. 1 on Water Use Efficiency (WUE), and to apply them.

Good agronomic management can influence the proportion of the available water that is useful to the crop, relative to that which is lost (Harris 1994, Chapter 4). Under a given set of rainfall conditions during the cool season, when the saturation deficit is small, any factor that contributes to maximising growth and increasing yield automatically improves WUE (Tanner and Sinclair 1983). By implication, any changes in crop management that promote early growth and vigour will provide crop canopy shading to reduce evaporation from the soil surface, and lead to more efficient water storage, transpiration and production (Cooper 1983; Cooper et al. 1987a).

Other factors such as weed control, soil surface mulching and reduced tillage reduce soil evaporation, thereby increasing the amount of water transpired by the crop and thus its yield (Cooper 1983). Any correction of limiting factors such as N and P deficiencies have major influences in improving WUE (Cooper et al. 1987b). Genetic improvements have also had direct and indirect effects on improving WUE.

The practical ways in which soil and crop management can be improved have been outlined by Cooper et al. (1987a). However, few notable studies have examined WUE of a whole rotation over a number of years. In a 6-year rotation trial conducted at Breda sub-station in the driest of the rainfall zones (annual mean 270 mm/year), WUE was compared between barley–vetch and continuous barley rotations. Harris (1994) noted that vetch rotations fertilised with N and P in the barley phase produced 0.6–0.9 t/ha more biomass than continuous barley (also fertilised), giving a 20–30% increase in WUE; the rainfall use efficiency (barley biomass yield per mm of rainfall minus soil evaporation) was higher after vetch than in continuous barley, i.e., 36.7 vs. 23.7 kg/ha mm. Based on such increased WUE and responses of barley to fertilisation, Harris (1994) concluded that it was biologically feasible to introduce forage legumes in such relatively dry conditions where previously only barley was grown.

Despite the high costs involved in monitoring soil water down the profile in long-term rotations, such measurements are important for understanding soil water dynamics. Thus, in the afore-mentioned 14-year ‘Cropping Systems Productivity’ trial (Harris 1995; Ryan et al. 2008d), profile moisture measurements were taken in selected rotations involving wheat in separate two course rotations with fallow, chickpea, and medic (Harris 1995; Pala et al. 2007).

The main limitation to growth was the supply of water from seasonal rainfall and not the soil moisture storage capacity; this is because the soil profile (varying in depth from 1 to 2 m, clay texture) was fully saturated only in the highest rainfall season (1987/1988, Dec-Jan only). Wheat grain yield was dictated both by the extent to which the alternative crops in the rotation depleted profile soil moisture, and also by the amount of seasonal rain and its distribution. When considered as a whole system (cereal and alternative crops in the rotation), the wheat–lentil or wheat–vetch rotations were most efficient in terms of WUE, producing 27% more wheat grain than the traditional fallow–wheat (though N supplied by legumes could also be a factor). Clearly, in terms of efficiency of crop water use within a system, these rotations offered a viable alternative to either the traditional fallow–wheat system, which is now disappearing in all but the driest areas, and continuous cereal, which is not sustainable, mainly because of disease build-up (see also discussion in Chap. 6).

There is considerable potential to increase crop yields by improved soil and crop management in association with improved germplasm. As fertiliser application, particularly for N and P, is now common in most countries of the WANA, and chemical weed control is practiced in many areas, these practices have contributed to both increased crop yields and increased WUE, outcomes which are inseparable in dry climates.

15.6.1 Other Rainfed Management Factors

While weeds compete for nutrients and light, their principal impact in Mediterranean rainfed systems is reducing water availability for the crop. In the WANA region, weeds were controlled mainly by cultivation, and by stubble and fallow grazing; however, in areas such as North Africa, weeds were considered a resource and pulled by hand for animal forage. At a WANA regional workshop in 1989 (Harris et al. 1991), it was concluded that weed control could be achieved by improving crop competition, grazing, appropriate rotation, use of weed-free seed, reducing weeds and weed seed set in fallow, hand pulling and chemical control. Chemical weed control was limited at that time but two decades later, it is common.

In the current drive to intensification of agriculture in the Mediterranean region, various developments include the use of disease-resistant and stress resistant (drought, heat, cold) germplasm and early sowing (late sowing, after early November reduces yield potential by 4% per week). A significant change in agriculture of traditional rainfed cropping areas has been the encroachment of supplemental or deficit irrigation in order to stabilise cereal yields (Pala et al. 2004). Deficit irrigation is highly beneficial to crop yields, but the effect of falling water tables on its sustainability cannot be ignored.

15.7 Sustainability of Rainfed Mediterranean Farming Systems

The concept of sustainability of rainfed cropping systems is relatively recent, especially in the context of Mediterranean systems that have persisted for millennia. However, given the current societal concerns about man's impact on the planet, sustainability enshrines the concepts of (1) profitable production without reducing the productive capacity of the resource base and (2) conservation of the environment, habitats and bio-diversity, as opposed to exploitation, degradation, and pollution (Jones 1993). Sustainability embraces issues ranging from food security to human equity. Agriculture in today's world is characterised by change – both in external inputs and technology and in the economic and social environment. An important question is how the impact of such changes on cropping systems can be measured. Long-term agro-ecosystem experiments have been seen as the logical approach to monitoring cropping systems. These are invaluable for assessing biological and environmental dimensions of sustainability as well as helping to predict future changes and trends (Rasmussen et al. 1998).

The value of long-term trials is that they: (1) measure the effect on crop yields of cropping practices or interventions, over time; (2) allow for measuring impact of treatments on soil properties; (3) generate data of value to farmers; (4) produce datasets for modelling; and (5) identify new or emerging research issues (Johnston and Powlson 1994). Most of the world's long-term trials still existing are in developed countries (UK, USA, Canada, Australia) with few that can be considered long-term ones in developing countries. Despite the relative small number of long-term trials in the Mediterranean region, it is useful to examine their contribution to sustainability of Mediterranean rainfed farming systems.

15.7.1 Conclusions on Sustainability from Long-Term Rotation Trials

The few cropping systems trials in the Mediterranean region, mainly comprise rotations of cereals (barley or wheat) with alternatives to fallow (food/forage legumes), or continuous cereal, often combined with variations in tillage. They have been conducted in Cyprus, Turkey, Morocco, and Syria, and to a lesser extent in Jordan, Egypt, and Iran (Jones 1998; Ryan et al. 2008d). Most of the rainfed system trials were conducted in northern Syria by ICARDA, mainly with a crop management focus, while the trials in Morocco were focused on tillage systems and soil quality.

The rationale for establishing the long-term trials, mainly in the 1980s, was based on the question of whether intensification of rainfed cropping systems was sustainable and how it impacts on the soil resource. For various reasons, mainly funding, few if any of these trials exist today. Nevertheless, the main findings and the conclusions regarding cropping system sustainability are presented below. Many of these are derived from the main cropping systems trials (Harris 1995), with respect to crop yields (Ryan et al. 2008d), crop quality (Ryan et al. 2008c), and water-use efficiency (Pala et al. 2007).

- *Continuous cropping of either wheat or barley is not an attractive option* in terms of economic crop yields. In all cereal-based trials in which rotations were compared, yields from continuous cereal cropping were always lowest, e.g. the

'Cropping Systems' trial with wheat (Ryan et al. 2008d) and long-term trials with barley (Jones and Singh 2000; Ryan et al. 2002)

- While cereals always yielded highest after fallow, a crop is harvested only once every 2 years. On an annual rotation basis (the cereal yield every 2 years divided by 2), yields from fallow–crop were only slightly above those from continuous cropping. In addition, *fallow is disappearing due to land use intensification, in all but the low rainfall zones* (less than 300 mm/year). Thus the fallow–cereal system is unsustainable. Farmers, particularly smallholders, are increasingly reluctant to have their land lying idle and producing no crop or economic output for the alternate year. Where 'clean' or cultivated fallow is practiced, the only benefit is some moisture conservation, but with the risk of wind and water erosion. Where 'weedy' fallow is practiced, some forage is provided for animals but the potential to conserve moisture is decreased.
- Most trials showed that *reasonable cereal yields could be obtained following N-fixing legumes in the rotation*. For example, in the 'Cropping Systems' trial, overall mean wheat grain yields were 1.59, 2.05, and 2.16 t/ha following chickpea, lentil, and vetch, respectively. While being lower than after fallow (2.43 t/ha), these yields were higher than with continuous wheat (1.08 t/ha).
- *Vetch as a forage crop for annual grazing, or for hay for animals, emerged as the most attractive option to replace fallow;* a similar conclusion had previously been drawn in Jordan (Tow and McArthur 1988). The inclusion of vetch in rotation with barley increased not only the biomass off-take (for animal food), but also cereal grain quality in terms of increased protein (Ryan et al. 2008c). Total soil N, as well as labile and biomass forms of N, were higher in forage-legume based rotations than with fallow or continuous cereals (Ryan et al. 2008d). Differences between vetch types existed in relation to adaptability. Despite all the studies in Syria and the Middle East region regarding the potential value of vetch as a forage crop, *adoption by farmers has been less than expected.*
- *While medic had beneficial effects on soil quality parameters, the evidence suggests that it is unlikely to be adopted in the rainfed farming systems of WANA.* This is mainly due to the difficulties of establishing a soil seed bank, because of overgrazing, and of harvesting seed (mechanical suction harvesting did not go beyond the prototype testing stage) (Harris 1995). Given these considerations and economic pressures, efforts so far to promote medic, or ley farming, have been unsuccessful (Christiansen et al. 2000)
- Given favourable product prices in the market place, *the food legumes (pulses) lentil and chickpea are attractive options as they yield a crop for sale in the alternate year and an acceptable cereal yield in the other year*. The short-season lentil gives higher cereal yields as it leaves some moisture (as well as N) for the succeeding cereal crop.
- *The rotations had different effects on the grain (and straw) quality of the associated cereal crop*. Over the 14-year long-term cropping systems trial (Harris 1995; Ryan et al. 2008c), wheat grain had an N content of 2.57% after medic, 2.20% after vetch, and 1.80% (the lowest) after fallow.
- *The increase in SOM in cereal-legume rotations is enhanced by conservation tillage* (Ryan et al. 2009)

15.7.2 Economic Assessment of Rotations

Economic assessment of rotations within Mediterranean rainfed systems is relatively rare, compared with agronomic assessment. For instance, among the 28 presentations at a regional workshop on fertiliser-use efficiency in rainfed Mediterranean agriculture, only two papers dealt with economics related to field crops, i.e. an analysis of fertiliser allocation strategies in Syria, and revenue associated with N use on barley in Morocco (Ryan and Matar 1992). In one of the most comprehensive studies of the economics of barley production in farmers' fields in northern Syria, based on optimisation analysis (Mazid and Bailey 1992), economically optimum fertiliser rates for barley were shown to vary with rainfall and relative prices of inputs and grain. With the expected rainfall in such dry areas, limited fertiliser use was not deemed as being as risky as was previously thought (Mazid and Bailey 1992). Indeed, the study was the basis for the Syrian government approving the allocation of fertiliser in the driest zones in Syria.

Despite the production limits of such dry areas, much hope was placed in technology to improve crop production, particularly wheat (Pala et al. 2004). Observations from the various long-term trials at ICARDA (Harris 1995; White et al. 1994; Ryan et al. 2002) permit some generalisation related to economics to be made, as follows.

In the wheat-based 'Cropping Systems' trial, preliminary analysis indicated that gross margins varied widely with the rotations (cereal and alternate phase), being highest for the full 2-year cycle of the rotation for wheat–vetch and wheat–lentil and least for continuous wheat. Wheat–fallow was only slightly better than continuous wheat (Rodriguez et al. 1999). Responses to N application were significant in all except the medic rotation, which added N to the soil through symbiotic fixation (a mixture of sown medic ecotypes became dominated by local ecotypes of *M. polymorpha*, *M. noeana*, and *M. rigidula*). Gross margins were higher in high rainfall years as was the economic response to N fertiliser. Using economic models derived from data of the early, wheat-based grazing trial, Nordblom et al. (1994) showed that, despite its soil quality benefits, the medic rotation was relatively unprofitable. Peterson et al. (2002) showed that farm income was mainly dependent on improvement in wheat grain yields. Given the complexity of long-term crop rotations, more rigorous analysis is needed to consider the value of animal production and forages.

15.7.3 Soil Quality in Rainfed Farming Systems

Soil quality refers to the favourable combination of soil chemical, physical, and biological properties that enable the soil to function as a medium of crop growth. While the concept has been in vogue for decades, it is relatively new in the context of cropping systems in the Mediterranean area (Mrabet 2008). The parameter of vital importance for achieving high soil quality is soil organic matter (SOM) (see Chaps. 6 and 14). Soils of the Mediterranean region are generally low in SOM, largely due to the low crop yields, the removal of residues by grazing and harvesting, and limited biomass input to the soil in the form of roots. When most long-term trials were started, soil quality was not an issue (Ryan and Abdel Monem 1998), but measurement of SOM later became routine in cropping system trials (Ryan and Pala 2007).

A few studies have demonstrated how the type of cropping system can positively influence SOM. For example, in the long-term cropping systems trial of Harris (Harris 1995; Ryan et al. 2008b), overall mean SOM levels after 14 years of cropping were highest for rotations containing the forage legumes (medic 1.32%; vetch 1.21%), intermediate for food legumes (chickpea, 1.17%; lentil, 1.13%) and continuous wheat (1.12%) and lowest for fallow (1.07%). In addition, mean SOM values increased with N fertilisation rate, being 1.12%, 1.13%, 1.19%, and 1.20%, respectively, for the 0, 30, 60, and 90 kg/ha N application rates. In contrast, increasing stubble grazing intensity tended to reduce SOM values, being 1.20, 1.15, and 1.14, respectively, for the no grazing, medium grazing, and heavy grazing treatments (Despite the relatively small numbers, these treatments were all significantly different as they are means over all rotations and N treatments).

The only study that showed a connection between SOM and soil structure or aggregate stability was that of Masri and Ryan (2006) in the long term trial of Harris (1995). Based on dispersion studies with wet-sieving, this study demonstrated a positive relationship between SOM and the degree of stability of the soil aggregates. Soil physical attributes such as water infiltration in the field, were measured on plots representing the various rotations, using a double-ring infiltrometer. Hydraulic conductivity was measured using soil columns in the laboratory. Rotations with the highest SOM (medic, vetch) had the highest infiltration and conductivity while fallow had the lowest.

Other earlier trials had shown the positive effect of legumes in the cereal–legume rotation on SOM, as well as the negative effect of fallow (White et al. 1994). Addition of N and P fertiliser improved SOM (Ryan 1998). Measurements in the barley grazing management trial were based on soil sampling within the growing season, after three cropping seasons, in plots where the barley phase of the rotation was fertilized with N. SOM values were consistently higher in the vetch (1.26%) and medic (1.25%) plots than with fallow (1.18%) or continuous barley (1.01) (Ryan et al. 2002). The values without fertiliser N were respectively 1.23%, 1.25%, 1.02%, and 0.86% for these rotations.

The values for soil total N and labile N essentially followed the same trends as SOM with respect to the rotations (Ryan et al. 2009). Total soil N values were (in descending order): medic (752 mg/kg), vetch (741 mg/kg), fallow (624 mg/kg), and continuous wheat (561 mg/kg); values for labile N were in the same order for the four rotations, i.e. 140, 135, 125, and 120 mg/kg. These studies indicate that organic N can be built up in the soil, given appropriate management (rotation, fertilisation, residue retention, tillage method) and can serve as a source of mineral N for crop uptake. Nitrogen was also shown to be variable in space and time, showing major fluctuations especially during the cropping season as rainfall and temperature changed. The microbial biomass fraction was most sensitive to such environmental changes.

As soil quality emerged as a major issue at the global level, for the environment and for cropping sustainability (Lal 2000), there was a dawning in the agriculture of the WANA region of the importance of SOM (Ryan 1998). The last decade has shown that SOM is linked to cropping systems, in being a sink or source for both nutrients and carbon dioxide and for enhancing soil physical properties. There are also implications, however modest, for combating global climate change.

15.7.4 Implications for Cropping Systems

The increase in fertiliser use and interest in nutrient use efficiency represents a paradigm shift in traditional Mediterranean agriculture towards intensive, more productive systems based on best management practices (Ryan 2008). Related research has established a rational basis for efficient use of fertiliser nutrients, not only to improve crop yields in a single season, but also for cropping over several years in repeated crop sequences (Ryan et al. 2008d). From the biological standpoint, alternative rotations involving food and forage legumes were shown to be sustainable as a replacement for fallow–cereal and continuous cereal in the medium-rainfall zone, (mean average rainfall of at least 340 mm), but not in the drier rainfall zone (less than 300 mm), when the low and precarious rainfall rarely allows another crop in the alternate year.

The rotation trials demonstrated an inter-relationship between fertiliser use, cereal grain yields, cereal straw yields for annual fodder or off-farm sales, as well as crop quality. Though no direct monetary value is assigned to the improvement in soil quality due to legume rotations, N fertilisation, and residue management, such actions contribute positively to sustainable plant growth through improved nutrient reserves and soil physical conditions. Thus, such integrated crop rotations have both yield (economic) and environmental implications.

15.8 Concluding Remarks

This chapter has sought to identify the interrelationships between soil and water resources in crop production under a moisture–stressed environment. It identifies some of the principles of a systems approach (Chap. 1) with respect to the rainfed farming systems of the Mediterranean/WANA region. Other publications have also directly or indirectly dealt with various aspects of rainfed farming in this region (Rao and Ryan 2004; Ryan 2002: Ryan et al. 2006).

Under a Mediterranean climate, dry conditions are an ever-present constraint to agriculture (Cooper et al. 1987a: Smith and Harris 1981) and *risk of crop failure* is an ever-present threat. Evolving over the millennia, the system of growing crops in the cool winter period when rain falls and evaporation is low is an *efficient system* for using the limited moisture. The use of fallow in alternate years contributed to *water-use efficiency* from the system perspective, by lowering the risk of crop failure and increasing the likelihood of a harvestable crop at least once every 2 years.

Animals are integrated with crops in Mediterranean rainfed agriculture; livestock depend on forages produced during the cropping season (including weeds, volunteer legumes and range pasture) and on crop residues after the cereal harvest. This animal–crop system is in turn *dependent on the human factor* – unfenced fields require constant shepherding as does the movement of animals from summer to winter forages. The system of agriculture that evolved over the ages had an element of s*ustainability* in that it depended on resources produced and *recycled* from within the system. For instance, soil fertility replenishment relied on addition of nutrients from animal manures or from N input from biological N fixation from native legumes (mainly annual species).

In some areas, the production system that sustained society collapsed centuries ago following deforestation and maybe overgrazing. This resulted in the abandonment of ancient cities, some now buried under wind and water-borne sediments. The current system evolved over the centuries and reached an apparent equilibrium between population, land and water resources, seemed to be sustainable, however is now definitely under stress from population growth and the inevitable *intensification of land use.* Factors such as the availability of mechanisation, artificial fertilisers and pesticides, and the drive towards supplementary irrigation, allied to the opening up of markets, the mobility of labour, and the need for food security, have brought change in the traditional Mediterranean rainfed farming system.

Apart from supplementary irrigation, fertilisers have had the greatest impact in rainfed agriculture. Significant crop yield increases have been invariably shown for applied fertiliser N in virtually all rainfall and soil situations, except where the previous crop was a well-managed legume that contributed substantial N to the soil. Where no P was previously applied, crop growth responses to applied P were significant, but these diminished as the level of available soil P increased under regular P fertilisation. All yield increases evoked by the use of major or minor nutrients also contributed to greater WUE. Similarly, weed control practices, whether mechanical or chemical, lead to higher WUE through increased yields.

A recent external factor that affects agriculture in general, and society as a whole, is the escalating cost of energy, exacerbated by the gradual policy of many governments in the region to phase out or reduce subsidies that favoured the agriculture sector. In response to internal and global economic forces, relatively new crops have appeared on the scene such as cumin,[4] coriander, rapeseed/canola, sesame, sunflower, safflower, and camelina or false flax, while older crops such as olives, and pomegranate have been given renewed prominence. These new forces also called for a re-assessment of the *sustainability* of traditional rainfed agriculture. Furthermore, the new demands on land use will test the *resilience* of the system. Conservation agriculture, with minimum tillage or direct drilling/no-till is likely to be more widely adopted in the future, thus contributing to reduced soil degradation

[4] See Glossary for botanical names.

and reduced energy costs (see Chap. 40). While developments in agronomic research and practice will influence rainfed cropping sustainability, the role of economics is much less clear as governments' control of market prices gives way to a more free market economy.

Mediterranean agriculture cannot remain static and immune to change, which is inevitable. The extent to which Mediterranean rainfed cropping systems respond to outside and internal influences will depend to a large degree on how the agriculture sector embraces the fruits of applied research. It is hardly coincidental that the pace of change in technology adoption in rainfed farming in the WANA region has accelerated in the past 30 years, a period that spans the existence of ICARDA. This Centre works in collaboration with national agricultural research systems in its mandate region of West Asia and North Africa, thus enabling its applied research in rainfed cropping and associated farming systems to be applied in the region. Much of the progress that has already been made in the broad area of agronomy, including adaptation of new varieties, fertiliser practices, water and nutrient use efficiency, and rotational systems, has influenced farmers throughout much of the region. Current efforts are being focused on the adoption of conservation tillage or no till, while even bigger and more daunting challenges will need to be overcome to mitigate and adapt to climate change, which is likely to cause increasing aridity in the Mediterranean region.

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Chapter 16
Rainfed Farming Systems in South Africa

Mark Hardy, Luthando Dziba, Willem Kilian, and John Tolmay

Abstract Rainfed farming systems form an important part of South Africa's agricultural sector, despite being constrained by the country's socio-political history, local and international economic forces, physical environmental factors such as inherently poor quality of soils, low and variable rainfall as well as limited amounts of arable land. About 85% of the potentially arable land is under freehold tenure. This supports a dynamic, commercial agricultural industry of mainly summer and winter grains that accounts for 95% of the marketed output. The remainder of the arable land is in the former homelands. These communal lands contribute to the food requirements of the 2.3 million households, with some small-scale commercial farming. Maize is the most important crop; it is produced mainly in the Interior Plateau, often in rotation with other summer crops such as sunflower, sorghum and soybean. Wheat is also grown in the rotation during the cool dry winter months of the summer rainfall areas but only on soils with a shallow water-table and using bare fallow. Rainfed sugar cane is grown in the humid and sub-humid coastal areas in the east of the country. Winter cereals, predominantly wheat, are produced in the winter and all-year rainfall regions, in rotation with annual or perennial legume pastures and, on a smaller scale, in rotation with canola and lupins. Livestock, mainly cattle in the summer rainfall areas and sheep in the winter and all-year rainfall areas, form an important component of many rainfed farming enterprises and contribute to the sustainability of the commercial farming systems. Livestock are also important in communal farming systems, contributing significantly to food security and sustainability.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_16,

Keywords Commercial and subsistence agriculture • Summer and winter rainfall • Semi-arid cropping • Maize • Wheat • Legume pastures • Livestock production

16.1 Introduction

South Africa is a dry country with more than 80% (98 million ha) of its land surface classified as arid to semi-arid (Schultz 2006). Approximately 16.5 million hectares are arable (Anonymous 2006), but of this only 22% is classified as having high potential for field crops and less than 10% is irrigated (Schultz 2006). About 14 million ha have been cultivated at some time in the country's past; however, low and erratic rainfall, rugged topography and variable soil characteristics as well as national and international marketing variables restrict the area allocated to crop production to about six million ha in any one year (Anonymous 2006). In addition some 2.5 million ha of the arable land are planted to rainfed pastures; the remaining 5.5 million ha lie fallow or have been abandoned. Non-arable areas covered by natural vegetation are allocated to extensive livestock production systems that usually include cultivated pastures and/or crop residues, and may form an integral part of the farming system practised in a region. Seasonal rainfall patterns with low and erratic falls, variable topography and soil physical characteristics all influence the development of rainfed farming systems practised in South Africa.

16.1.1 Topographic, Climatic and Soil Factors Influencing Rain-Fed Farming Systems in South Africa

16.1.1.1 Topography

The land surface of South Africa comprises two main physiographic regions divided by the Great Escarpment (Divide) – the Marginal Zone and the Interior Plateau (Fig. 16.1).

The Marginal Zone comprises a coastal strip and coastal hinterland. The low-altitude (less than 300 m) narrow coastal strip widens on the northern parts of the east coast and the south-western and western coastal regions, and extends into the north-eastern borders of the country (Fig. 16.1). The adjacent coastal hinterland has extreme altitudinal variability (300–1,500 m) and, in the east of the country (between about 27°E and 31°E), has an undulating topography dissected by deep valley systems.

The Interior Plateau is relatively flat with altitude falling gradually from 1,500 m in the east to 900 m in the west. The eastern and central parts of the Interior Plateau are the most important rainfed crop production regions. The Great Escarpment reaches altitudes in excess of 3,200 m in the east (Fig. 16.1).

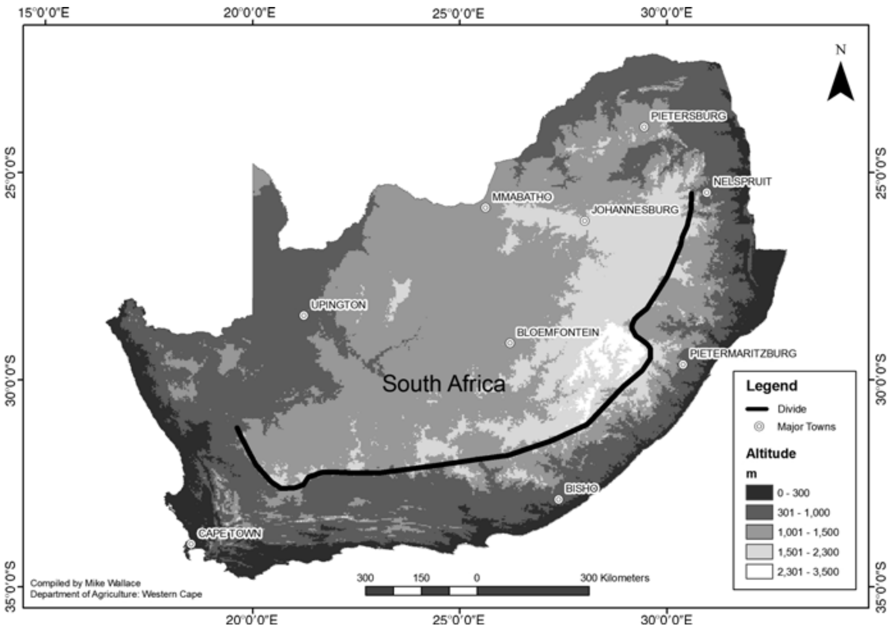

Fig. 16.1 South Africa – physical

16.1.1.2 Climate

Lying between latitudes 22°S and 35°S, South Africa has a climate influenced by the subtropical belt of high pressure cells in summer and winter, by the cold sea surface temperatures of the Atlantic Ocean and the warm sea surface temperatures of the Indian Ocean. These influences are modified by the topography.

During summer, warm moist winds from the Indian Ocean flow into the eastern and central parts of the country to generate summer rainfall through orographic influences. Equatorial air occasionally moves south during the summer months providing widespread rains to the interior plateau and the eastern parts of the country.

During winter, the high-pressure belt is located further north resulting in dry weather for the interior and eastern parts of the country, while the frontal systems move across the western and south western coastal and coastal hinterland regions. The resultant mixing of cold and warm air masses causes winter rainfall for the south western regions of the country (de Jager 1993).

The frontal systems that move from west to east across the country in winter also introduce polar air bringing occasional snow to high areas and severe cold spells to the interior of the country.

With low sea surface temperatures from the Benguela current, the west coast experiences a temperate climate and mean annual rainfall declines dramatically towards the north. This is in contrast to the east coast. At the latitude of about 30°S,

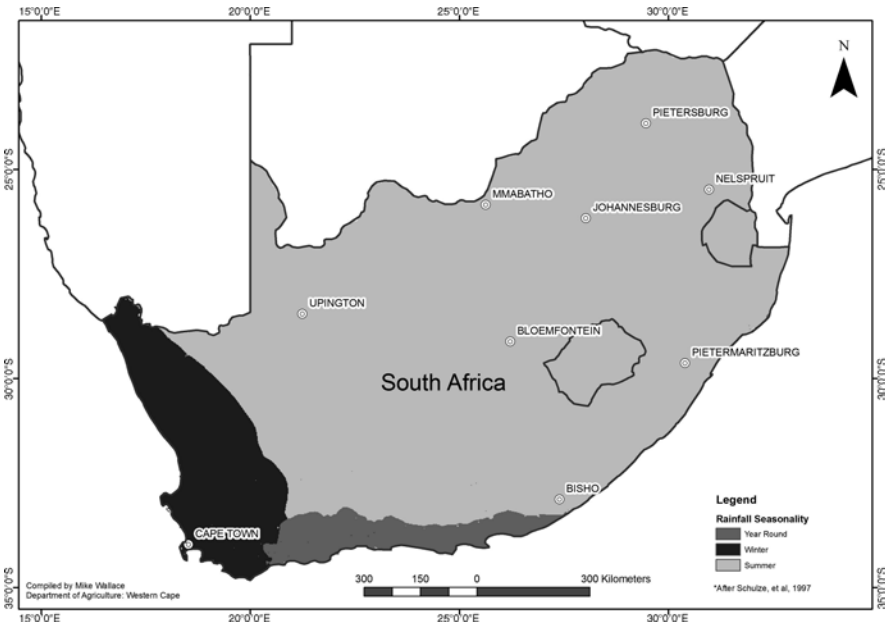

Fig. 16.2 Seasonality of rainfall in South Africa

for example, the mean annual temperature and rainfall on the east coast are 21°C and 1,000 mm respectively, compared to 14°C and 65 mm respectively on the west coast (Smith 2006).

Winter rainfall dominance (>80% of the mean annual rainfall falling between April and September) occurs adjacent to the west coast of South Africa in a region west of 21° 30′ E. All-year rainfall occurs in a narrow coastal strip between 21° 30′ and 26° E. The rest of the country experiences summer rainfall (Fig. 16.2). Within the summer rainfall region, there is a general trend for rain to fall later in the summer months as one moves from east to west. Mean annual rainfall in the rainfed farming systems of the winter and all-year rainfall regions varies from about 200 to 450 mm. In the rainfed farming areas of the summer rainfall regions, it varies from about 900 mm to about 400 mm with a gradual decline from east to west (Fig. 16.3).

16.1.1.3 Soils

Soils in South Africa are highly variable. They include deep sands associated with low rainfall and poor fertility, and poorly developed soils on rock that are also associated with low rainfall in the western, south western and central parts of the country. Well-drained, highly weathered acid soils occur in the high-rainfall eastern regions of the country. (For greater detail on the soils of South Africa the reader is referred to the Land Type Series (SIRI 1987)).

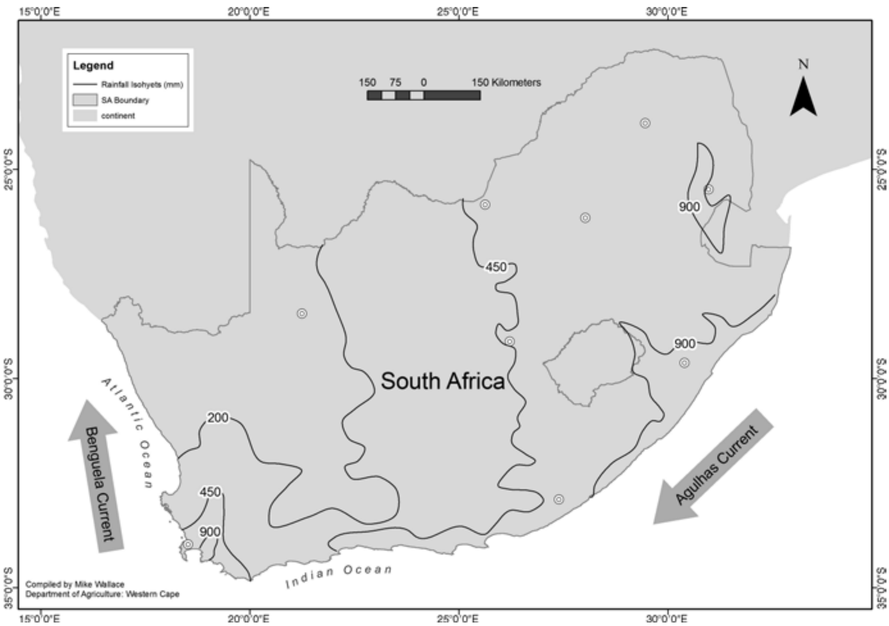

Fig. 16.3 South Africa – mean annual rainfall isohyets (mm)

Most top soils in South Africa, especially in the eastern regions, extend to a depth of 25–30 cm with slightly thinner top soils at 20–25 cm in the semi-arid and central west regions, and small tracts of land where the topsoil horizon is less than 20 cm deep (Schultze and Horan 2006).

Sub-soils display a greater range of thickness than the topsoil, from a thickness of less than 10 cm in parts of the west and south to more than 60 cm, particularly in the moister eastern regions of the country (Schultze and Horan 2006). While most soils in the country contain sufficient plant available K for crop production, there are widespread deficiencies in P (Miles and Manson 2000). Natural and agronomically induced soil acidity and aluminium toxicity also occur in the higher rainfall, summer cropping regions (Miles and Manson 2000). Liming is therefore widely recommended to reduce the negative effects of soil acidity and aluminium toxicity on crop production. Top- and sub-soil thickness together with soil physical and chemical characteristics obviously influence factors such as water holding capacity, plant available nutrients and physical limitations to plant growth.

16.1.2 External Factors Affecting Rainfed Crop Production Systems in South Africa

Rainfed agricultural systems in South Africa range from large and small-scale commercial enterprises to subsistence farming (Andrew et al. 2003). Commercial agriculture accounts for more than 95% of the marketed agricultural output while subsistence agriculture provides a basic (but usually insufficient) livelihood for the vast majority of the rural population living in communal areas (Schultze 2006). Most of the following discussion refers to established commercial agricultural operations while rainfed subsistence-based agricultural systems practised in the communal areas will be discussed in Sect. 16.4 of this chapter.

Government policies, local and international agricultural commodity markets and capital input requirements for commercial agriculture have all influenced the profitability of farming enterprises and therefore the rainfed farming systems practised in South Africa today.

16.1.2.1 Legislative Influences

Local agricultural commodity markets were strictly controlled by some form of government legislation until the 1990s. The winter cereal and summer grain production systems, for example, were included in single channel marketing legislation whereby the Wheat and Maize Boards were the only buyer and distributor of these cereals in the country (Anonymous 1976). The producer price for these crops was determined as a function of average production costs for a particular season plus a margin. Product prices were therefore not subject to normal market forces and were often abnormally high. Board control extended to the quality requirements of the grain and grain products, and costs of producing meal and flour, as well as the price to the consumer (van Eeden 2000).

This price control encouraged practices that were essentially non-sustainable, both economically and environmentally. Areas with marginal production potential were brought into production, mono-cropping was widely practiced and, as farms were relatively small, there was a tendency to over-capitalise on farm machinery and equipment. The policies resulted in about two million ha of wheat and more than 4.5 million ha of maize being planted during the early 1970s (Anonymous 2006).

Dramatic changes in areas planted to grain crops occurred as a result of changes in marketing and government policies from the 1990s. Under deregulation, import control was replaced with an import tariff which had little impact on the price of imported grain, thus exposing growers to the world market.

16.1.2.2 Local and International Market Influences

From the 1990s, producers were fully exposed to the international commodity market. A weak local currency from the mid-1990s to 2001 provided some respite on grain prices but producers were then exposed to increased costs of imported oil and capital items such as farm machinery and implements. Local market forces also instituted a ‘transport differential’ on the grain price to take into account the transport costs from the coastal harbours to the most important inland markets.

The inherently low crop production potential of the country has restricted the development of primary and secondary industries that would normally develop in support of the agricultural production systems. Most agricultural inputs – and fuel – are imported, inflating fixed and variable costs.

The reduced margins and the need to implement sustainable farming systems have taken annual cropping out of low-potential lands. This resulted in a substantial reduction in areas planted to crops such as maize and wheat by the early 2000s. By then, the average areas planted to these two crops were 3.2 million ha and 0.8 million ha respectively (Anonymous 2006).

Improvement of production potential is also restricted by limited investment in research and development within the agricultural sector, and the lack of research and technical personnel. With few new technological developments, the ability to adapt agricultural systems to cope with factors such as climate change, increased food demand and bio-fuels remains limited; however, many new technologies are imported and adapted for the local conditions. The harsh environment within which most farmers have had to operate since farming started in the country has ensured that those who continue to farm use their limited resources efficiently.

16.2 Rainfed Farming Systems in the Summer Rainfall Region

Most of the grain and oil seed production in the summer rainfall region of the country occurs within the Interior Plateau (Fig. 16.1). There is also a relatively small area of summer grain production in the higher elevation coastal hinterland areas of the eastern seaboard. Sugar cane is produced only in the humid coastal and coastal hinterland parts of the Marginal Zone in the east of the country (Fig. 16.1).

16.2.1 Interior Plateau – General

The climate and soils of the Interior Plateau are well suited to producing maize. With an increasing southern African population who use maize products as their staple diet and the need for locally produced energy sources for the animal feed industry, it is not surprising that maize production, at 2.6 million ha (in 2007), is the most important farming enterprise in the Interior Plateau. Farming systems have therefore developed to support sustainable production of maize. The areas planted to the other main crops (sunflower, wheat, soybean, sorghum and groundnuts) are far smaller, and react to market potential and climatic conditions (Anonymous 2006). Low annual rainfall and, in the eastern high-lying parts of the Interior Plateau, low heat unit levels preclude double cropping – that is, only one crop can be planted and harvested per year.

Wheat is planted in the winter months into soils where stored water is available to carry the wheat plants through the dry winter months. This moisture is needed until spring and early summer rains allow the crop to mature. Rotations of winter and summer crops require long periods of bare fallow (e.g. 12 months between harvesting the summer crop and planting the next winter crop), to allow sufficient time for soil water storage. This implies a system where two crops are produced in 3 years. In the bare fallow system, maize stubble is initially retained on the soil surface for grazing purposes, but the residue is then incorporated in late summer to prepare a seedbed before planting the winter crop. This period of bare fallow is best suited to soils that have (1) a clay layer at 60–150 cm below the soil surface that prevents water from percolating to deeper levels, and (2) an inherently high water holding capacity. Wind and water erosion will occur under fallow conditions and therefore, ploughing of grazed stubble is postponed until late summer. Actual soil losses vary according to conditions and are difficult to quantify.

As the area planted to maize is more than four times greater than the area planted to all the other summer crops combined, there are few opportunities for incorporating alternative crops to break the maize monoculture. However, more than half the country's wheat is produced in the summer rainfall region and wheat is increasingly being used as a staple food due to urbanisation with associated changes in diet. Wheat is, therefore, an important crop in the rotation systems applied. The main reason for rotating summer crops with wheat is economically driven and usually not to control weeds or diseases. The latter would be an additional advantage that also promotes the storage of water required for rainfed wheat production. The establishment and early season growth of wheat (until spring) relies on rainfall conserved during the previous summer's rainy season. Planting time, therefore, is not dependant on rain occurring directly before or during planting, as is the case in the winter rainfall region. Producers deliberately plant over a 2-month period in order to spread risks such as cold damage during flowering, Russian wheat aphid[1] infestation and the variable distribution of spring rains.

There are three main production regions identified within the Interior Plateau: eastern, central and western (Fig. 16.4). These are based on soil type, on rainfall potential, and on available heat units (degree days between 10°C and 30°C for the summer growing season – October to March).

16.2.2 Interior Plateau – Eastern Region

16.2.2.1 Background

The mean annual rainfall of 550–700 mm provides the highest production potential of the three regions, and allows both summer and winter crops to be grown.

[1] See Glossary for scientific name.

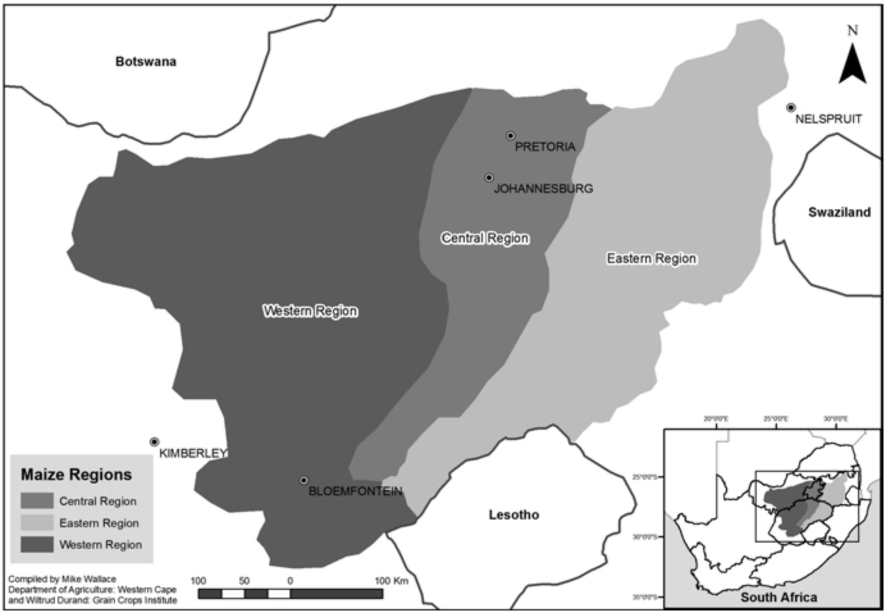

Fig. 16.4 Maize-growing regions of South Africa

Although little rain falls in the cooler months (May to September), accumulated soil water from summer rainfall allows winter crops to grow in the cooler months until spring rain falls.

16.2.2.2 Cropping Systems

The main summer crop is maize. Small grain, especially wheat, is widely planted but double cropping is not possible, due to both the low levels of heat units (1,400–1,800) that prolong the maize growing period to maturity and also the need for a bare fallow period of up to 11 months. However, in good rainfall seasons, winter crops can be grown in succession using a shorter fallow period of 6 months. Since summer crops do not rely completely on stored soil water, summer crops can be rotated without including a winter crop if spring rains are sufficient. Diseases and insect pests can build up under continuous cropping.

The growing periods for the main crops in the region are summarised in Table 16.1 and the major constraints in Table 16.2.

Several other minor crops and pastures are grown in cropping systems in the eastern region, resulting in numerous possible combinations. However, similar principles are used to decide on the crop rotation. The rotations depend mainly on market forces and rainfall, and are flexible in the medium term. The most limiting factor is soil moisture availability through the growing season. For summer crops,

Table 16.1 Main crops used in the cropping systems of the eastern region of the interior plateau

Crop	Planting	Harvesting
Maize	October	June
Sunflower	September	March
Beans	October	April
Wheat	June	December

Table 16.2 Constraints for cropping systems of the eastern region of the interior plateau

Crop	Insects[a]	Diseases[a]	Other
Maize	Maize stalk borer Cutworm Black maize beetle	Grey leaf spot Common rust Northern corn leaf blight *Diplodia* ear rot *Fusarium* ear rot	Weed infestation, especially broadleaf Soil temperatures – early-frost
Wheat	Russian wheat aphid Oat aphid (wet years) English grain aphid (wet years) Rose grain aphid (wet years) False wire worm (dry years) Bollworm Brown wheat mite (sporadic in dry years)	Stripe rust Root rot Crown rot	Hail Late-frost Preharvest sprouting Bird damage
Sunflower	Bollworm Dusty surface beetle	*Sclerotinia*	Birds Boron deficiency

[a]See Glossary for scientific names

Table 16.3 Typical crop sequences used in the cropping systems of the eastern region of the interior plateau

Production system	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months
Summer and winter crops	Maize	4	Maize	12	Wheat	6	Wheat	10
Summer crops only	Maize	4	Maize	4	Sunflower/ beans	6	Maize	4

amount and distribution of rainfall are the important factors while, in the case of winter cropping (wheat), soil water conservation in the fallow period is a key to successful production. In some instances, legumes are used in the crop rotation system to enhance the physical and nutrient status of soils. Fluctuations in input costs such as the recent large increases in the costs of agricultural chemicals and fertiliser also influence the choice of crop rotation in the medium term. Typical crop sequences are listed in Table 16.3.

16.2.3 Interior Plateau – Central Region

16.2.3.1 Background

Although the central region (Fig. 16.4) experiences more heat units (1,800–2,000) than the eastern region, the lower annual rainfall (450–550 mm) results in a lower crop production potential. Livestock, mainly cattle, are an important part of some farming systems. In these systems, crop residues are used as supplementary fodder during the winter months. Fodder crops, such as sorghum in the summer and oats in the winter, may also be planted to support livestock production. The shallower soils with lower clay fraction and lower rainfall have a reduced capacity for storing soil water, except in areas with deeper, duplex soils. Winter cropping may occur if sufficient summer rain falls, and fallow in summer and early autumn is combined with retention of crop residues from the previous season and weed control. Sandy soils in this region are vulnerable to wind erosion, and reduced tillage practices help to lower soil losses. Crop residues are inadequate for good quality no-till practices, but stubble retention does contribute towards soil conservation.

16.2.3.2 Cropping Systems

Maize is also the main crop in the Central Region, and also provides crop residues for grazing in the winter months. The other main summer crops are sunflower and grain sorghum. Wheat is the only winter crop that can be produced on an economically sustainable basis.

The growing periods for the main crops in the region are summarised in Table 16.4 and the major constraints in Table 16.5. Planting time for summer crops is limited mainly by the timing of spring and early summer rainfall and by heat units whereas the time for planting wheat is constrained by the potential threat of frost damage during flowering.

Production systems have developed around maize as the most important crop due to its superior economic returns. Maize is grown mostly in monoculture but may be rotated with sunflower in the west and sorghum in the north-east. The short fallow period of 4 months requires adequate spring rainfall to sustain maize monoculture, but spring rains are often inadequate. Where soil moisture becomes a limiting factor, sunflower is often included because of the extended fallow period

Table 16.4 Main crops used in the cropping systems of the central region of the interior plateau

Crop	Planting time	Harvesting time
Maize	November	July
Sunflower	September	March
Sorghum	November	March
Wheat	May	November

Table 16.5 Constraints for cropping systems of the central region of the Interior Plateau

Crop	Insects[a]	Diseases[a]	Other
Maize	Maize stalk borer	*Diplodia* ear rot	Weeds, especially grasses
	Cutworm		Drought stress
	Black maize beetle	*Fusarium* ear rot	Planting date dependant on rain (soil moisture)
		Maize streak virus	Plant damage on sandy soils due to wind
			Soil erosion under heavy rainfall
		Gibberella ear rot	Compaction – sandy soils
			Leaching of fertilisers – sandy soils
		Stalk rots	Early frost and hail storms
Sunflower	Bolworm	White rust	Birds
	Dusty surface beetle	(*Albugo*)	High soil temp during emergence
Sorghum	Maize stalk borer	Head moulds	Weeds, especially grasses
	Chilo	Ergot damping off of seedlings	Drought stress
			Planting date dependant on rain (soil moisture)
			Plant damage on sandy soils due to wind
			Soil erosion under heavy rainfall
			Compaction – sandy soils
			Leaching of fertilisers – sandy soils
			Early frost and hail storms
			Birds
Wheat	Russian wheat aphid	Stripe rust	Hail
	Brown wheat mite	Root rot	Late-frost
	False wire worm	Crown rot	Preharvest sprouting
	Bollworm		Bird damage
	Oat aphid (wet years)		
	English grain aphid (wet years)		
	Rose grain aphid (wet years)		

[a]See Glossary for scientific names

following its harvest, until the next summer crop is planted (see Table 16.4). Wheat may be grown in rotation with maize on deeper soils where sufficient soil moisture can be stored from summer rains on lands managed as bare fallows. Typical crop sequences are listed in Table 16.6.

Crop rotation systems that include wheat in the winter months are applied to promote economic sustainability of production. This system (refer to Table 16.6) essentially leads to the production of three crops in 4 years. Production decisions are, however, largely influenced by the short and medium term marketability of wheat.

Table 16.6 Typical crop sequences used in the cropping systems of the central region of the interior plateau

Production system	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months
Maize monoculture	Maize	4	Maize	4	Maize	4	Maize	4
Summer cropping systems	Maize	4	Maize	4	Sunflower/ Sorghum	8	Maize	4
Summer and winter crops	Maize	4	Maize	12	Wheat	6	Wheat	10

16.2.4 Interior Plateau – Western Region

16.2.4.1 Background

Mean annual rainfall over the region (Fig. 16.4) is low (400–550 mm) although more heat units (2,000–2,400) are available for summer crops than in the central and eastern regions. Much of the soil is deep but often sandy and thus is vulnerable to wind and water erosion. Shallow water tables are found in some areas of the region.

Soils without shallow water tables are more suitable for summer crop production whereas those with water tables can grow winter crops, mainly wheat, during the dry winter months.

16.2.4.2 Cropping Systems

The dominant crop is maize, rotated with other summer crops such as sunflower, soybeans, groundnuts and sorghum. Wheat is grown in the winter months on soils with shallow water tables, which can vary in depth from 50 to 90 cm. Livestock production is an important aspect of farming operations in this area but occurs mainly on natural pasture. Annual (e.g. *Eragrostis teff*) and perennial (e.g. *Anthephora pubescens* and *Digitaria eriantha*) subtropical pastures are also used in the livestock production system. The perennial pastures may be permanent, in which case they do not form part of the cropping system or they may be used in a long-rotation of 5 years pasture followed by 5 years of crops in various crop sequences. The annual pastures may be planted once in 5 or 6 years on the same field to break the cash-crop sequence.

The growing periods for the main crops in the region are summarised in Table 16.7 and the major constraints in Table 16.8.

The western region of the Interior Plateau is the largest maize production area in South Africa with stable yields; these are a function mainly of uniformly deep soils as well as areas with shallow water tables, sufficient heat units and flat topography. Fields are large and homogenous – which simplifies the management of the production systems.

Table 16.7 Main crops of the cropping systems of the western region of the interior plateau

Crop	Planting	Harvesting
Maize	November	July
Sunflower	September	March
Sorghum	November	March
Groundnuts	November	June
Wheat	May	November

Table 16.8 Constraints for cropping systems of the western region of the interior plateau

Crop	Insects[a]	Diseases[a]	Other
Maize	Maize stalk borer	Northern corn leaf blight	Weeds, especially grasses
			Drought stress
	Cutworm	*Gibberella* ear rot	Planting date dependant on rain (soil moisture)
		Diplodia ear rot	Plant damage on sandy soils due to wind
			Soil erosion under heavy rainfall
			Compaction – sandy soils
			Leaching of fertilisers – sandy soils
			Early frost
Sunflower	Bolworm	White rust	Birds
	Dusty surface beetle		High soil temp during emergence
Sorghum	Maize stalk borer	Head moulds	Weeds, especially grasses
	Chilo	Ergot	Drought stress
		Damping off of seedlings	Planting date dependant on rain (soil moisture)
			Plant damage on sandy soils due to wind
			Soil erosion under heavy rainfall
			Compaction – sandy soils
			Leaching of fertilisers – sandy soils
			Early frost
			Birds
Wheat	Russian wheat aphid	Stripe rust	Hail
	Brown wheat mite	Root rot	Late frost
	False wire worm	Crown rot	Pre-harvest sprouting
	Bollworm		Bird damage
	Black maize beetle		
	Leafhoppers (maize streak disease)		
	Oat aphid (wet years)		
	English grain aphid (wet years)		
	Rose grain aphid (wet years)		

[a] See Glossary for scientific names

Table 16.9 Typical crop sequences used in the cropping systems of the western region of the interior plateau

Production system	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months	Crop	Fallow months
Maize monoculture	Maize	4	Maize	4	Maize	4	Maize	4
Summer cropping systems	Maize	4	Maize	4	Sunflower/ Sorghum	8	Maize	4
Summer and winter crops	Maize	4	Maize	12	Wheat	6	Wheat	10

As indicated for other regions, there are numerous crop sequences that could be followed within the farming system. Typical crop sequences are listed in Table 16.9.

Maize production is more profitable than other summer and winter (wheat) crops in the region, and is well adapted to the local soil/climate environment. Soil moisture availability, as in the central region, is an important factor when deciding on an appropriate rotation. Sunflower is used in rotation, but to a lesser extent than in the central region. Wheat is well adapted to soils with shallow water tables, and developments in the world grain markets could lead to increased areas being planted to wheat in the medium term. While maize production is economically favourable, livestock production is an integral part of farming operations in the region and maize stubble is used for grazing purposes.

16.2.5 Marginal Zone (Summer Rainfall)

16.2.5.1 Sugar Cane

The sugar industry in South Africa lies between latitudes 25°21′ and 31°S in the low-lying coastal and coastal hinterland areas of the eastern seaboard (Fig. 16.1). It is one of the driest rainfed cane-producing areas in the world with average yields of about 50 tonnes of cane/ha/annum (Meyer 2007) and an estimated annual production of 2.5 million tonnes of sugar (Meyer 2007). About one third of the farmers are large-scale producers and these account for 80% of total production. Most of the crop is still harvested by hand, although there are calls for reduced burning and for mechanical harvesting. Rainfed sugarcane production on about 350,000 ha in this area accounts for 80% of the total area planted to sugarcane in South Africa.

Cane is produced in monoculture for 9–12 years (depending on climatic conditions and heat units) before the rootstock is removed and the land re-planted after a fallow period of 3–12 months. The sustainability of sugarcane production using current agronomic practices is "currently under the spotlight as in many parts of the industry monocropping has resulted in nutrient mining, declining levels of soil organic matter and an increase in soil acidity" (Meyer 2007). While productivity has not declined, a ‘yield plateau’ seems to have been reached leading to renewed investment in research on the maintenance and improvement of soil health/quality within cane production systems. This research has provided recommendations, for example, that a green manure crop should be planted on the lands during the fallow period. The positive effects of green manuring should persist for at least the first and second ratoons after re-establishing the cane-land, and include conservation of soil organic matter, the control of nematodes and increased soil organic nitrogen availability (Meyer 2007). Green manures include oats (*Avena sativa*) and legumes such as lupins (*Lupinus angustifolius*) or sun hemp (*Crotalaria juncea*).

16.2.5.2 Summer Grains

Approximately 100,000 ha of commercial plantings are allocated to summer grains under rainfed conditions, between about 29° and 31°E and 27° and 31°S, in the coastal hinterland regions of the Marginal zone (Fig. 16.1). Traditionally, maize has been planted in monoculture but, in recent years, some producers have included soybeans in a 2-year maize 1-year soybean rotation. Practical limitations – such as most producers having limited capacity to harvest soybeans efficiently – have prevented high proportions of the cultivated areas being planted to soybeans. Furthermore, while the benefits of rotations are recognised, economic considerations currently favour maize monocultures. The inclusion of soybean in the rotation provides approximately 45 kg N/ha to the following maize crop and assists with controlling major pests such as maize stalkborer (*Busseola fusca*) by removal of the pests’ host plants for a season. Most plant diseases are controlled through the use of appropriate fungicides but rotation with soybeans has been shown to reduce the onset of major diseases such as grey leaf spot (*Cercospora zeae-maydis*) in the subsequent maize crop (Thibaud personal communication). Knowledge of the benefits of including soybean in the cropping system provides producers with opportunities to implement crop sequences that are less vulnerable to increasing input costs and widely fluctuating international maize prices.

16.2.6 Summary of the Summer Rainfall Region

Most of the country experiences summer rainfall (Fig. 16.2) that varies from about 900 mm in the east to less then 400 mm in the central and western regions. The central and eastern regions of the Interior Plateau are the most important rainfed cropping areas of the country with about 2.6 million hectares of maize under cultivation in 2007. Maize is produced in monoculture and in rotation with other summer crops such as sunflower, soybeans and sorghum. Wheat is the only rainfed winter crop that can be grown economically in the Interior Plateau. Rainfed wheat that is planted in early winter (June) can be produced in this summer rainfall region only on soils that have shallow water tables and where a period of bare-fallow has been allowed during the summer for sufficient soil water storage to maintain the wheat plant during the dry winter months. In these circumstances wheat forms an important part of crop rotation systems applied in the region. In many areas crop residues provide an important source of winter feed for cattle. Livestock, mainly cattle, also graze on perennial subtropical pastures that may form part of a long-rotation crop–pasture rotation system (5 years of cropping followed by 5 years of pasture).

Sugar is the main rainfed crop grown in the eastern coastal and coastal hinterland on about 350,000 ha. This region is among the driest cane producing regions of the world.

Most of the summer rainfall region has developed a productive system. However the dominance of maize brings into question the long-term sustainability for many of the farms. The decision on crop sequencing is based mainly on the financial sustainability of the farming enterprise in the short- to medium-term (1–5 years). During the period 2000–2008, maize production has proven to be the most profitable choice and therefore it became the preferred crop. The challenge in future will be to convince producers to redefine sustainability in terms of the effect that production systems have on soil health. This can only be achieved if research can illustrate the beneficial effects of good conservation tillage practices on the long-term sustainability of crop production. Since crop rotation is an integral part of conservation agriculture, it will probably lead to the inclusion of other crops in the system.

16.3 Rainfed Farming Systems in the Winter- and All-Year Rainfall Regions

Winter cereals and oil and protein seeds are the main crops produced in rainfed farming systems in the winter and all-year rainfall regions of the Western Cape Province. These crops may be grown in continuous cropping systems or in rotation with legume pastures. Most farms would therefore have a portion of the available arable land planted to crops – with the remainder under pure legume pastures.

The areas planted to spring wheat, barley, canola and lupins in these winter and all-year rainfed crop production regions (in 2007) were 320,000, 80,000, 34,000 and 14,000 ha respectively. About one third of the remaining 0.9 million hectares of arable land is planted to perennial (lucerne) and annual (medics, clovers and subclovers[2]) legume pastures (approximately 250,000 ha) and forage crops such as oats for grazing, hay and silage (approximately 100,000 ha). The other two thirds are either left fallow with weedy volunteers used for additional grazing (approximately 200,000 ha) or are abandoned lands with extremely poor production potential (approximately 350,000 ha) (Anonymous 2003).

[2] e.g. *Medicago truncatula* , *Trifolium hirtum, T. michelianum* and *T. subterraneum.*

There is insufficient plant-available soil moisture in the all-year rainfall region for rainfed crop production in the summer months. This is due to the low and infrequent rainfall between November and April as well as the low moisture-holding capacity of the shallow, stony soils, and high summer temperatures and evaporation rates.

16.3.1 Climate

The winter- and all-year rainfall regions located in the south-western coastal areas of the country (Fig. 16.2) are characterised by cool, wet winters and hot, dry summers. The two main production regions are the Swartland (on the west Coast) and the Southern Cape (coastal hinterland of the south coast) – Fig. 16.5.

The Swartland has a typically Mediterranean climate with more than 80% of annual rainfall occurring from mid-autumn to early-spring (April to September). Legume pastures that are used in crop–pasture rotations in the Swartland are restricted to annual species.

Rainfall distribution in the southern Cape varies from 75% between mid-autumn and early-spring (April to September) in the western parts to 55% in the eastern extremities (Fig. 16.5). Lucerne pastures can be established and persist because a

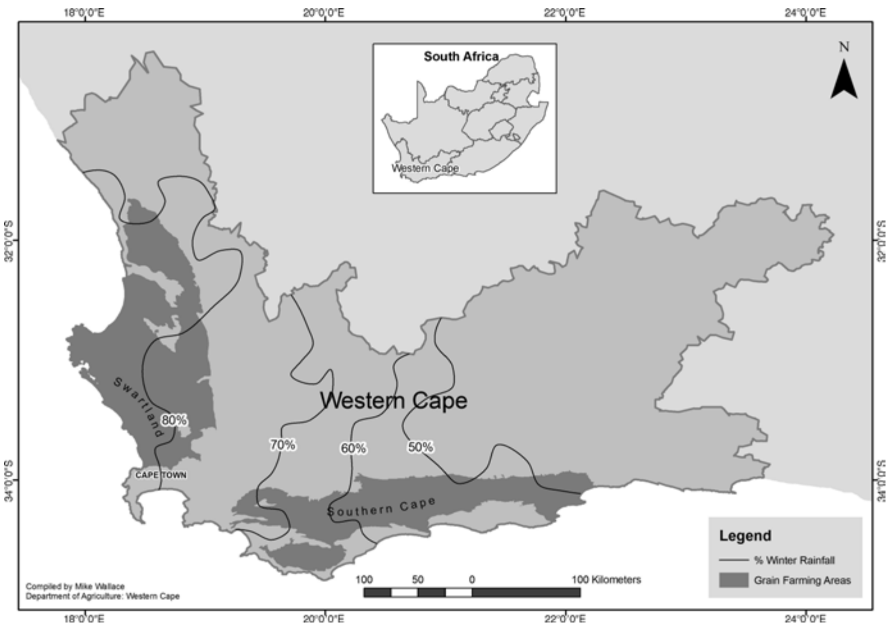

Fig. 16.5 Western Cape grain farming areas showing percentage of rain falling in winter

higher proportion of rain falls during the summer months and climate is milder and more temperate than in the Swartland.

Both regions where cereal grains are produced have rainfall of between 250 and 450 mm, but most of the area allocated to rainfed farming systems in the region receives less than 400 mm (Fig. 16.3). With its Mediterranean climate, the region is characterised by unpredictable fluctuations in the temporal and spatial distribution and amount of rainfall (van Heerden 1991). In such conditions, the success of rainfed wheat and other cereal production is uncertain (Lòpez-Bellido et al. 1996), particularly in a deregulated, free-market economy (Troskie et al. 1998).

16.3.2 Soils

Soils of these two grain-producing regions range from shallow clay-loams (10–20% clay) derived from shale, to well-drained sands (SIRI 1987). The average depth (topsoil plus sub-soil) of the relatively fertile shale-derived soils varies from 200 to 400 mm, but many of these soils have a stone fraction of more than 30%. Low soil volume limits crop production on these shale-derived soils but, in some areas, the shale layers tend to be off-horizontal, allowing roots to penetrate between layers of unconsolidated rock.

Aeolian calcareous, sandy soils are found in the western and southern coastal areas. These soils are deeper than the shale-derived soils (>750 mm) but have low clay content (less than 5% clay), resulting in low water-holding capacity and thus low crop production potential.

The lower proportion of winter rainfall in the southern Cape results in inherently higher risks with winter crop production. However, summer rainfall and milder climatic conditions result in a more rapid breakdown of crop residues that are then more readily incorporated into the soils of the southern Cape than is the case in the Swartland. Typically, soil organic carbon in the southern Cape tends to be above 1.5% compared to 1.0% and lower in the Swartland.

16.3.3 Crop and Crop–Pasture Systems in the Winter and All-Year Rainfall Areas

Farming systems practised in both the winter and the all-year rainfall regions are based on winter cereal production under various continuous cropping and crop–pasture rotations. While soil and climatic constraints govern the range of crop and livestock products in this region, the farming systems are still strongly influenced by external factors that include the historical single-channel marketing legislation, the recent 'scrapping' of those laws, changes in government policies on agricultural subsidies, exchange rates and exposure to international grain markets.

16.3.3.1 Crops and Pastures in the Winter and All-Year Region

Wheat, barley and oats have been produced in the winter and all-year rainfall regions of the country for centuries and, for most of that time, to the exclusion of other crops. The most promising crops for rotation with the cereals are canola and lupins. Other crops such as faba beans,[3] field peas, chickpeas, linseed and flax, that are suited to winter rainfall regions have been evaluated in the Western Cape. However the lack of stable local markets and handling facilities, together with the high risk of poor yields, has prevented their general use in crop rotations. Hard-seeded, self-regenerating annual (medics[1] and clovers) and perennial (lucerne) legumes are the most important pastures used in short- and long-rotation systems with cereal, oil and protein crops.

Canola, introduced into local cropping systems in the 1990s, has moderate yield potential but is limited by soil moisture availability. Despite research and on-farm management practice demonstrating the production potential and advantages of growing canola in the rotation, many producers find the crop difficult to manage and do not achieve its production potential. This results in the areas planted to the crop (in 2007) remaining relatively small (approximately 35,000 ha per annum). Lupins have been used extensively, mainly as grazing for sheep and for grain production. Lucerne was introduced in the early to mid-1900s, but only started gaining favour in rainfed farming systems together with annual medics and clovers in the 1970s (van Heerden 1998).

16.3.3.2 Crop Rotation

Price controls and the availability of selective herbicides encouraged monocultures, mainly with wheat, until the early 1990s. In the winter rainfall region of the Swartland, wheat monoculture is still practiced on some smaller production units, but crop rotation, either continuous cropping or crop–pasture, or both, is more typical. Continuous cropping is used in areas with high production potential and low risk of crop failure while a wheat-annual legume pasture rotation is applied throughout the region. Crop rotations show clear benefits in local field research. For example, in a high potential production area of the Swartland, wheat production increases by 35% following annual legume pasture and by 20% in wheat following canola, compared to wheat monoculture where no-till farming practices (crop residues and stubble retained) are applied (Hardy 2007). Long-term (20 years) economic modelling of a 'typical' Swartland farm indicates that wheat–annual legume and wheat–canola–wheat–lupin rotations provide a higher return on capital investment and greater economic stability, than wheat monocultures or rotations where wheat is produced for two or more consecutive seasons (Hoffmann and Laubscher 2002). Despite this the greatest proportion of

[3] See Glossary for botanical names.

land on many farms in the Swartland is planted to wheat each year, implying that, in most instances, it is planted for at least two consecutive years. In such cases conventional tillage practices are followed, crop residues are baled and stubble is burned.

In the Southern Cape, which receives some rain in the summer (Fig. 16.5), crop–pasture rotations are more common than in the Swartland. This is because of the higher risk of crop failure due to a lower and less reliable rainfall during the growing season than is experienced in the Swartland. Long rotations, where lucerne pastures are kept for 5–7 years followed by a 5–7 year cropping phase, are most common. Forage availability from lucerne is highest in late winter, spring and autumn, while the low and irregular summer rainfall is sufficient only for its survival. Sheep therefore graze crop residues during the summer, mainly residues of cereal grains but also of protein- and oil-seed crops, and are moved to lucerne pastures in autumn before lambing. Forage production from lucerne is generally low, varying between 2 and 5 t/ha/year depending on the timing and amount of rain. Therefore stocking rates tend to be conservative – equivalent to about 3 ewes and their followers per hectare of lucerne pasture. The cropping phase is dominated by wheat and barley, with crops such as oats and bitter lupins playing a minor role. Canola has been a valuable option in these rotations since the 1990s by providing opportunities for controlling grass weeds and reducing the incidence of soil-borne cereal diseases. Narrow-leaf lupins (*Lupinus angustifolius*) are also used in the rotations – but on a small scale.

Annual ryegrass (*Lolium rigidum*) is the main problem grass weed, while ripgut brome (*Bromus diandrus*) and wild oats (*Avena fatua*) are also problem weeds in most areas. Broadleaved weeds are easily controlled in a cereal phase but cause problems in broadleaf crops (canola and lupins) and pastures (medics and annual clovers). Broadleaf weeds include ramenas (wild radish, *Raphanus raphanistrum*), spiny emex (*Emex australis*), cape weed (*Arctotheca calendula*) and musk heron's bill (*Erodium moschatum*). Herbicide resistance (mainly in *Lolium* species) is becoming a serious problem in the cropping systems of the winter and all-year rainfall regions of the Western Cape, with crop rotation being advocated as one of the main options for managing the problem.

The main soil-borne diseases in cereal crops are take-all (*Gaeumannomyces graminis* var. *graminis*) and crown rot (*Fusarium pseudograminearum*). Research has shown crop rotation to be an effective method of managing soil-borne diseases in the local environment (Lamprecht et al. 2006).

Blackleg (*Leptosphaeria maculans*) has caused major crop losses in canola. Various options advocated for managing the problem include: (1) not planting canola on the same land more than 1 year in four; (2) using certified seed of cultivars with high blackleg resistance rating; and (3) varying cultivars used on a farm from one season to the next. Production of broadleaf lupins (*Lupinus albus*) production was halted in the Western Cape by widespread outbreaks of anthracnose (*Colletotrichum gloeosporioides*) in the late 1990s. Various cultivars of narrow leaf lupins (*Lupinus angustifolius*), less susceptible to anthracnose than *L. albus,* are now used despite their lower yield and market value.

The above mentioned weeds and diseases all have major effects on the crop production system and are taken into consideration by producers when applying different crop rotations on their farms.

16.3.3.3 Tillage Practices

In Southern Cape, conventional tillage has been reduced since the 1980s so that, by 2007, no till was used on 60% of arable lands and minimum till on 30%. Minimum and no-till practices have reduced input costs through savings on energy and maintenance of equipment. Machinery costs have been reduced on a per unit area basis, provided producers have increased the areas of their farming units. In addition, they have provided for improved soil moisture management through retention of crop residues. This improves control of time of planting, soil condition and seedling establishment – all of which potentially improve crop yields. A consequence of the application of reduced tillage practices has been an increase in use of herbicides and wider acceptance of the benefits of crop rotation. These practices have resulted in increased margins and provided greater economic stability to the farming systems (van Eeden 2000).

16.3.3.4 Farm Size

Where a greater proportion of the total farm area is arable, farm size tends to be smaller. In the 1970s and 1980s, under single channel marketing and price controls, a farm with an area under cultivation of about 500 ha was considered a sustainable economic unit. Many such units became uneconomic following deregulation of the grain markets, removal of government subsidies, free-market importation of grain and a weakening currency. This was particularly so for those farms where a large proportion of their arable land had low production potential (low and variable rainfall and poor soils) and where the livestock component was small or non-existent (Hoffmann personal communication).

The average size of a sample of farms in a region of the Swartland with an average production potential in 2007 was about 1,200 ha, with 90% of the total area being operated by the owner and 10% leased. About 80% of the area of the farm would be cultivated. In areas with low production potential, farm units are larger (1,600 ha) with 30–60% of the total area of the farm cultivated and the remainder of the area being natural vegetation.

16.3.3.5 Division of Farm Land

The gross division of the farm into areas allocated to cash cropping and areas allocated to pasture and fodder production each year depends on production potential and risk of crop failure. In areas of high production potential and low risk of crop failure in the Swartland (most rainfall in winter), up to 60% of the arable land on a farming unit would be planted to cash crops – mostly wheat. The rest is under annual fodder cereals and annual legume pastures, or fallow. These proportions change dramatically in areas of the Swartland with lower production potential where only 40% or less of the arable land is planted to cash crops and the remainder planted to annual fodder cereals and annual legume pastures, or left fallow (Hoffmann personal communication).

The lower proportion of annual rainfall that occurs in winter in much of the Southern Cape results in a higher risk of poor production from winter cereals. Less than 50% of arable land on farms here would be planted to cash crops in any year. The rest of the arable land is planted mainly to lucerne pastures. Fodder cereals and annual legume pastures are also planted, while some lands may be fallowed. Non-arable land is mainly covered by native vegetation and is used for extensive livestock production (Hoffmann personal communication).

16.3.3.6 Livestock Production

Livestock play an extremely important role in maintaining the stability of the farming operation in regions with low and variable crop production resulting from low and variable rainfall or shallow, infertile soils. Wool and mutton (based mainly on the Merino, Dohne Merino and SA Mutton breeds) are the main livestock products produced in rainfed agricultural systems in the winter and all-year rainfall regions of the country. Some wool farmers increase mutton output by mating a portion of their Merino ewe flock to rams of mutton breeds such as the Dormer in a terminal cross production system. Sheep graze mainly on legume pastures that are grown in rotation with winter cereal and oil-seed (canola) and protein-seed (lupin) crops, and on the crop residues during the dry summer months. Maximum stocking rates of 1.0–1.5 ewes plus their followers per hectare farm (i.e. pasture, cropping lands and non-cropped areas included) are generally recommended, to limit the risk of feed shortages and the need for purchased feeds.

The sheep production system, in its simplest form, provides ewes with the opportunity to gain weight and condition following weaning in early spring before being mated in early summer for lambing in late autumn. Ewes are therefore dry during the hot, dry summer months with a low nutrient requirement in the first 4 months of pregnancy. Crop residues (including straw, fallen grain and stubble) therefore provide roughage of adequate quality for ewes during summer, provided they start summer in good body condition. Small quantities of a supplement comprising high bypass protein and energy are fed to the ewes just prior to and following lambing when pastures also become available for the sheep. Stored roughages in the form of hay (e.g. lucerne) and grain (e.g. oats) may be fed in the event that pastures are not ready due to poor autumn rains. Lambs in the 'fat' lamb production systems are usually weaned and marketed at 130–150 days old.

In marginal areas of low and variable rainfall and thus high risk for the cropping systems, some producers have spread their risk by diversifying into dairy production. Dairy production is based on purchased concentrate feeds and farm-produced roughages (mainly silage and hay) made from cultivars of cereal crops such as oats, barley and triticale that have high dry matter yields. Input costs for silage and hay are low relative to cereal grain production, due mainly to lower fertiliser, herbicide and fungicide requirements.

The production of these roughages is associated with the occurrence of late season moisture deficits. In most seasons, there is sufficient moisture for the cereal crops to achieve maximum dry matter yields for production of hay and silage. These crops are often prevented from achieving their grain production potential by late season moisture deficits However, in seasons when sufficient moisture is available for the crop to achieve its grain production potential, a portion of the areas allocated to roughage production may well be opportunistically kept for grain production, Decisions on this will depend on grain prices relative to the costs of roughages and the amount of roughage required by the dairy enterprise. This system therefore allows for flexible use of crops for either grain or roughage for animal feed, depending on production potential and product price.

16.3.3.7 Sustainability of Farming Systems

Sustainability of the rainfed farming systems in the winter and all-year rainfall regions of South Africa (Fig. 16.5) has not only required increased areas for each farming unit but also changes in farming practices that reduce input costs and capital investment in equipment per unit area. Conservation farming practices such as reduced tillage and no-till, including retention of crop residues, not only achieve this but also promote the improvement of soil production potential.

New and better-adapted cultivars of the main crops are continually being evaluated and identified to ensure maintenance, improvement and regional stability of crop production. The adoption of both improved cultivars and improved agronomic practices over the past three decades has led to an increase in wheat production from approximately 1.35 t/ha in the 1970s to an average of about 2.1 t/ha over the last 10 years (1998–2007). Producers in the region who have increased the livestock component of their farming systems have been better able to cope with the widely fluctuating grain price and the risk of crop failure (Hoffmann personal communication).

16.3.4 Summary of Winter and Year-Round Rainfall Regions

The winter- and all-year rainfall regions located in the south-western coastal areas of the country are characterised by cool, wet winters and hot, dry summers. Rainfall in these farming areas varies between 250 and 400 mm per annum. In the western parts of the region, rain falls mainly in the winter months while in the southern parts rainfall pattern varies from mainly winter to all-year rainfall. The mostly shallow, shale-derived stony soils and the relatively deep, sandy soils found in the region have inherently low water-holding capacities. This, together with low and variable rainfall, makes rainfed crop production risky.

Spring wheat is by far the most important crop followed by malting barley. Canola and lupins are minor crops accounting for about 10% of the area allocated to cash crop production each year. Livestock, mainly sheep, are an integral part of most rainfed farming systems in the region. A few farmers still apply conventional tillage and monoculture (with wheat) in their farming systems but most farmers apply some form of continuous crop or crop–pasture rotation and conservation farming. In the area where rainfall occurs mainly in the winter, pastures are based on annual *Medicago* and *Trifolium* species while in the area that receives a portion of its annual rainfall in the summer months pastures are based on pure stands of lucerne.

The design of rainfed farming systems in the winter and all-year rainfall regions is based mainly on minimising the risks associated with low and variable rainfall. Agronomic practices such as conservation farming using minimum tillage or no-till and stubble retention promote moisture conservation. Crop and crop–pasture rotations assist with both diversifying financial risk associated with annual variation in grain prices and also with lowering input costs. Rotations also assist with managing problems with weeds and soil-borne diseases. Livestock production enterprises (mainly sheep) become more important on farms where risks of crop failure are high.

16.4 Communal Rainfed Farming Systems

16.4.1 Introduction

The communal areas in South Africa are largely associated with the former homelands (shaded areas in Fig. 16.6). They occur in arid, semi-arid and humid climate zones of summer rainfall regions, and their dynamics are largely influenced by climatic variability and by other factors such as the socio-economic and political history of the country. There is also great variation in soils, vegetation and rainfall in communal areas because they occur in pockets in almost all provinces throughout the country. The total area of the former homelands is about 17.1 million hectares translating to 16.2% of the area of the country (Anonymous 2006). Most of this land area is allocated to communal rainfed agriculture in support of about 2.3 million rural households (Shackleton et al. 2001). Communal agriculture is a mixed form of farming where communities, working together, engage in various agricultural activities such as crop production, vegetable gardening and livestock production in order to provide for the needs of a household. The household encompasses immediate and extended family members and other co-dependent

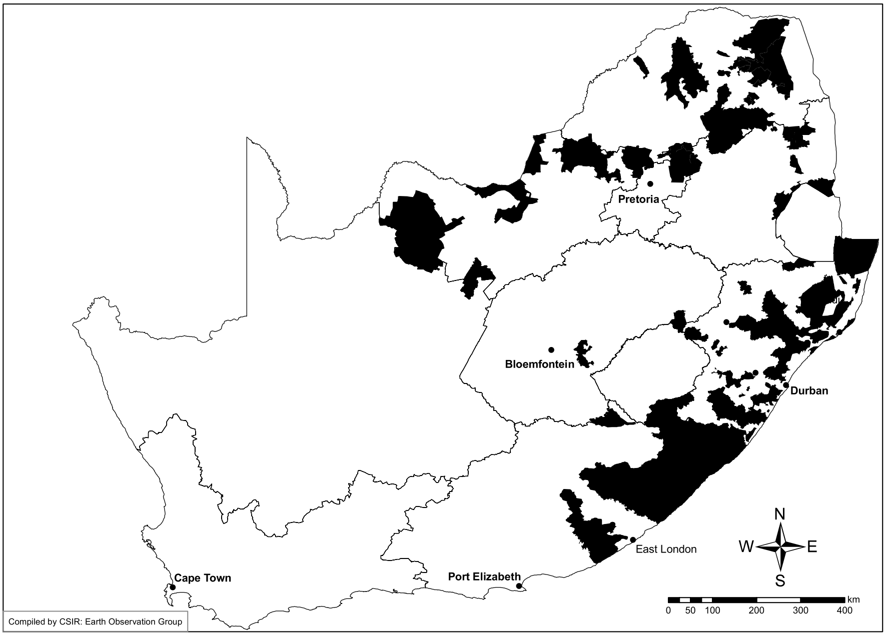

Fig. 16.6 The former homelands and independent states of pre-1994 South Africa

families who share close ties and resources such as labour and animal draft power. Communal agriculture is thus an extremely important activity that contributes significantly to the livelihoods of these poor rural communities.

Limitations to commercial agricultural production in communal areas include poor access to agricultural markets and services such as credit, technology and agricultural support. Other severe constraints include limitations to the area of lands available for individual farmers or farmer groups and insecurity of land tenure. While commercial farming is practised in certain communal areas, the majority of farming systems in South Africa's communal areas are restricted mainly to subsistence agricultural activities based on livestock and crop production for home consumption. A relatively small proportion of the total arable area is cultivated, the remainder being used for livestock.

Communal areas support about 40%, 12% and 70% respectively of the total number of cattle (beef and dairy), sheep and goat numbers in South Africa (Department of Agriculture 2004). The contribution of cropping systems is, however, difficult to quantify due, in part, to large variations in the amount of land under cultivation at any one time. Factors influencing the area of land under cultivation include availability of labour, money, equipment, rainfall and help from the community. Most of the non-arable areas are used for livestock production.

16.4.2 A Background to Communal Areas in SA

Communal farming is many centuries old and has had many different forms depending on the tribal groups and prevalent environmental conditions (Thompson 2000). Nomadic pastoralists who lived off the land in a “hunter-gatherer” existence occupied the more arid and mountainous parts of the country. In the wetter parts, farmers living in semi-permanent villages practiced mixed farming; they kept livestock and grew crops.

However, the recent form of communal farming is a product of a land tenure system that was introduced through the Native Land Act of 1913, which consigned Africans to ‘native reserves’ or ‘homelands’. More than 80% of the population was restricted to making a living from less than 7% of the total land mass, often in areas of marginal agricultural potential (Everson and Hatch 1999; Thompson 2000). By 1939, the amount of land in the homelands had increased to approximately 12%. The Act marked the decline in farming by Africans as many, especially men, were forced to seek employment in the cities. Many households were unable to produce enough food to meet their needs and generate extra income from the limited land subsequently allocated to them (Thompson 2000). The mobility of farmers with their livestock was also significantly limited, making it difficult for farmers to seek better grazing for their animals. A report by the Tomlinson Commission in the early 1950s stated that the homelands were over-populated and severely degraded (Union of South Africa 1955). This report led to the implementation of betterment planning for most of these areas.

‘Betterment planning’ introduced a form of ‘organisation’ into settlement of the homelands. Under the scheme, individual households were each assigned ‘free’ land for homestead development (the village), rangelands and croplands according to potential. The scattered homesteads, which were characteristic of the homelands before the ‘betterment planning’ era, were replaced by modern-day villages of several households with a relatively secure tenure system (Everson and Hatch 1999). The land was considered state land and was allocated to households by the local tribal authority (Mokgope 2000). The process of allocating land has become more open and equitable since the abandonment of the former tribal system after 1994. Traditional leaders still play a role but within a democratic process as opposed to the former more authoritarian one.

Cropland allocated to a household is available for growing various summer and winter crops. The main crops are staple food crops such as maize, sorghum, millet, and wheat. After the harvest, the crop residues from all fields are available for grazing by the combined herd of the whole community. A substantial portion of the land was allocated as rangeland and is used for livestock grazing and other purposes such as harvesting of timber, fuel wood, medicinal plants, and food gathering. Members of the community have common access to rangelands, with no limits imposed on the number of animals an individual or household can keep (Everson and Hatch 1999). Households normally grow crops and also own livestock, although the area cultivated and the numbers and kinds of livestock kept vary significantly among households.

Fences were erected to separate croplands from rangelands. Fencing was also used to divide rangelands into paddocks or camps, helping to control livestock movements and introduce a form of rotational grazing. How well the system worked depended on community leadership and extension service support. The rotational grazing system worked well under the authoritarian leadership style, before the 1994 democratic era, when the decision-making power resided solely with the headsmen and chiefs. Fences also helped to alleviate the need for herding cattle, especially before harvest of crops from the fields. However, fences have not been maintained for a variety of reasons, significantly increasing the risks of crop damage by free-ranging livestock.

16.4.3 Characteristics of Communal Systems

The key elements and operational features that characterise communal farming systems are described in Table 16.10. Although this list is not comprehensive, it gives a good idea of the strengths and weaknesses of communal farming systems in South Africa.

16.4.3.1 Livestock Production

Goods and services provided by livestock (mainly cattle, sheep and goats) have historically been the preferred livelihood options of rural households in the communal farming areas of the country, and this is still the case (Andrew et al. 2003). The preference for livestock farming is evident in that much of the land carries high numbers of animals and, in many cases, is overstocked. Considering their importance to rural livelihoods, there is a perception that livestock are owned by most households. In most communal areas, however, livestock ownership is limited to a minority of households, approximately (30%) but varies widely among communal areas by 10–70% (Shackleton et al. 2000). The benefits communal farmers derive from keeping livestock include draft power (animal traction), commercial sale, security (investment), milk production, meat, social exchange and prestige (Cousins 1998; Everson and Hatch 1999). These benefits, with regard to cattle in particular, do not accrue only to the livestock owners but also to members of the community who do not own cattle. This is achieved by bride-wealth payments, loaning of animals, co-operative ploughing, sharing meat and milk, and rentals of goods and services (Shackleton et al. 2000).

The current overstocking of communal rangelands can largely be attributed to the high human population density in these homelands under a communal land tenure system. Even mine workers and city dwellers who originate from the rural areas and who have families living in the homelands (reserves) buy and keep livestock in the rural areas. Their families in rural communal areas, wives and children, look after the animals. Grazing is 'free' in the sense that it costs nothing in the

Table 16.10 The key elements and operational features, strengths and limitations of communal farming systems in South Africa

Key elements	Operational features	Strengths	Limitations
Mixed farming systems, but largely livestock-based	Communal grazing rights are free. Crop fields are private, but winter grazing on stover communal.	No fixed costs (no payment for land or grazing rights)	No formal management system in place.
Democratic process recently replacing authoritarian leadership	Community participation through meetings and elected representatives	A democratic process and participatory approach to managing resources	No control by individuals or households over use of communal resources
Animals kraaled[a]	Animals usually kept in an animal enclosure overnight.	Safety of animals from theft or predation	Kraaling requires labour
Crop production mainly for human consumption	Seasonal calendar (e.g. date of first rains) determines activities	Low input cost as little or no inputs are used	No control over production, fluctuations
Marginal crop production and reliance on rangelands for livestock production	Little or no inputs at all for crop production Crop residues used for livestock	Kraal manure sometimes used as fertiliser, reducing input costs	No fodder flow planning.
Little use of machinery and equipment	No significant capital investment Family owned and managed Animal traction, but hired tractors used	Family as labour reduces costs	Ageing population, and children going to school Limited efficiency

[a] Placed in a kraal or animal enclosure

immediate future to the individual livestock owner; but this has had longer term negative environmental and economic impacts (Hoffman et al. 1998).

Farmers keep a variety of mainly nondescript cattle breeds and a small variety of other breeds such as the Nguni and Brahman crossbred with nondescript cattle. Chickens, sheep and goats are largely a variety of indigenous breeds that are locally adapted but are from time to time crossbred with a variety of other breeds introduced to communal areas. A good example is that of indigenous goats that are smaller framed and hardy animals that are usually crossed with the purebred Boer goat to improve meat quality. Although there is no formal breeding program, the communal areas can be credited with conservation of genes of the Nguni cattle breed that has recently ascended in popularity among commercial farmers due to its local adaptation.

The reasons for the emphasis on livestock farming vary from household to household, but communal farmers are rational about why they keep livestock and why they sometimes do not sell, even though conventional wisdom (in commercial livestock production) would suggest they should. Recent studies suggest that communal farmers who have been trained on how livestock markets operate and who have access to markets are more than willing to sell, *but only at a good price* (Grwambi et al. 2006). They also understand that animals must be in good condition to fetch a good price, which implies that rangelands must also be in good condition, and that sufficient crop residues for dry season feeding should be available to support sustainable livestock production. However, this does not translate into reduction of livestock numbers on communal rangelands. Instead, farmers may lease land from private owners or government or buy the extra feed needed to maintain animals in good body condition when it pays to do so. They also buy more animals to maintain their livestock numbers or increase their investment.

Croplands play a major role in providing fodder in the form of crop residues during the dry winter months and early growing season. The entire system is rainfed and production is, therefore, highly variable depending on prevailing climatic conditions from year to year. Lactating females and young animals (calves, kids, and lambs) are let out to graze during the day and kraaled overnight.

16.4.3.2 Crop Production

There are approximately 2.5 million hectares of arable land in the communal areas (Anonymous 2006). The proportion of arable land that is under cultivation varies considerably from one communal area to the next. For example, about 10% of potentially arable land in the former homelands in the Eastern Cape is currently under (mainly subsistence) cultivation (Hobson personal communication). In contrast, over 66% of arable land was cultivated for commercial production in a former homeland area of the North West Province by the late 1980s, and there has been expansion of the cultivated area since then (Andrew et al. 2003). In the latter case, home gardens were also being cultivated for household food production.

There are two main categories of cropping land:

1. Land surrounding and close to the homestead that ranges in size from small gardens of a few square metres to about 0.25 ha. Most rural households have access to these small 'homestead' plots. Some also have access to homestead plots of 3–4 ha dedicated to staple food crops such as maize and sorghum as well as vegetables. These crops are mainly for household consumption but surpluses are usually marketed (or donated to needy individuals) in the local community (Shackleton et al. 2000). Intercropping with beans, pumpkins and wild spinach grown between rows of maize and sorghum is often an integral part of the cropping system.
2. Larger areas of arable land that may be located several kilometers away from the homesteads. These areas usually provide small grower schemes with a degree of commercialisation in the crop production system, with maize the most important crop. Relatively few households are involved in such small grower operations.

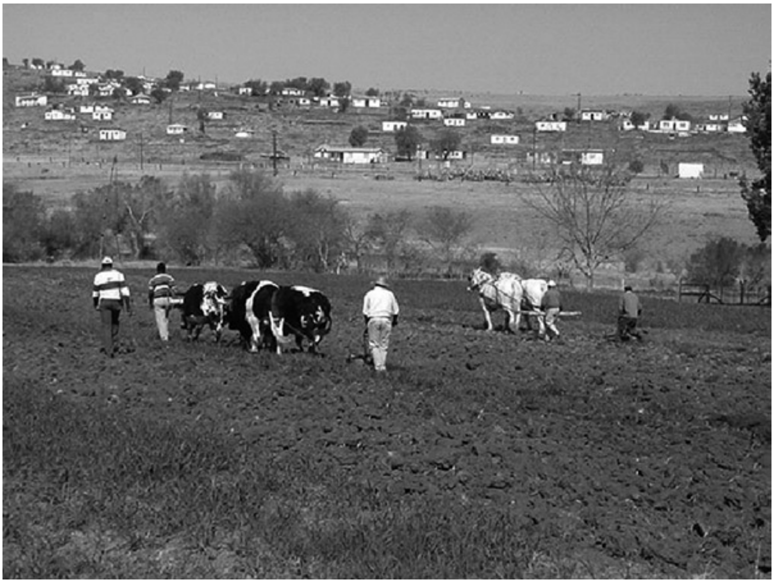

Fig. 16.7 Animal traction is commonly used for cultivating crop fields, planting, weeding, and transporting goods within short distances

As with the small plots in and around the homesteads, the crop residues are available to the whole community for winter-feeding of livestock.

Fields are cultivated after the first rains using draft animal power. Animal traction is the main means of cultivating, planting and weeding crop fields (Fig. 16.7). Although horses and donkeys are used, cattle are the main source of draft power as they are most readily available. Animal-drawn implements such as ploughs, planters and weed-cultivators are commonly used by families who own or have access to animals. However, other tools such as hand-held hoes are used for post-planting activities such as weeding, especially for small fields. Hired tractors are used where they are available but, with increasing fossil fuel prices, they may soon be too expensive for many households.

A typical cropping calendar for planting, harvesting and labour availability is presented in Table 16.11.

16.4.4 Inputs into Communal Systems

Communal rangeland-based livestock production is traditionally regarded as a low-input system but this perception is changing. Besides the initial investment in fencing during the implementation of 'betterment planning' and the maintenance of those fences, farmers or communities invest little in infrastructure development of rangelands. However, there is significant investment of time and labour in running a successful small-scale livestock enterprise. The degeneration of fences around

Table 16.11 An example of a typical cropping calendar for planting, harvesting and labour availability in Bergville, KwaZulu-Natal (Carr et al. 2004)

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Potatoes												
Maize												
Sorghum												
Beans												
Cowpeas												
Groundnut												
Labour												
Men												
Women												
Children												

Cropping cycle	
Fallow period	
Harvesting	
Labour availability	

crop lands has increased the need for herding but most boys, who traditionally were herders, are now going to school. Herding is now the new cost and pegged with the introduction of regulated minimum wages. This puts a financial strain on the women and men who own livestock or keep livestock for urban dwellers.

Supplements are rarely purchased to meet animal requirements (Nyamukanza et al. 2008) although farmers may buy in feed during droughts. Hay and some energy licks will be given preferentially to the weaker animals to keep them alive until the next growing season. Recently, however, farmers who have access to, and understand, markets are more willing to purchase supplements to improve the condition of their animals so they can fetch good prices when sold (Baldwin Nenghovela personal communication). Farmers now also sell animals to buy feed for periods of severe feed shortage in the late dry to early growing season.

The collapse of government-sponsored animal dipping systems in many communities leaves no veterinary inputs in the communal systems. Few farmers buy veterinary medicines and those who buy are either well-to-do or own larger herds. Traditional medicines derived from medicinal plants growing on rangelands play a key role in herd health management, but this traditional knowledge is being eroded.

In crop lands, the inputs are also low compared to commercial crop production enterprises. Farmers add kraal manure every couple of years to their fields to improve soil quality and yields. Livestock grazing of crop residues reduces the need to carry manure to the fields while trampling the crop residues incorporates organic material into the top soil.

In the small homestead plots, inorganic fertilisers and other agricultural chemicals may be applied sparingly because of their high cost and poor accessibility in remote rural areas; weeds are controlled by hand. Normal agronomic inputs to optimise economic returns may be applied on lands cropped for small- and larger-scale commercial production where financial and agricultural support services are available, as in parts of the former homeland of the North West Province. These farmers are supported through their close proximity to commercial farmers on privately owned farms. Their marketing networks provide access to information about markets and technology, as well as to skills, implements, machinery and agronomic inputs (Andrew et al. 2003). This is mainly done through semi-structured and voluntary mentorship programs facilitated by farmers' unions.

Family labour comes mainly from women and children, who reside in the village throughout the year (Table 16.11). Men, who usually work in urban areas, are normally available during the summer vacation from the mining, manufacturing and construction industries. Seeds are usually retained for planting in the following growing season but, if all the seed is eaten, new seed would have to be purchased from agricultural cooperatives. Where implements and labour are limited, the community is invited to assist with crop farming activities such as hoeing and harvesting. The household then often 'pays' for these inputs through provision of traditional beer and food including meat from the slaughter of a sheep or a goat. This becomes a big social event that mobilises a community for a day or two to help a particular household. Attendees are usually unemployed men and women who dwell in the village.

16.4.5 Outputs from Communal Systems

Livestock products, such as milk, meat and hides, are used for subsistence at household level. Only 9% of livestock is sold for profit (National Livestock Strategy 2005; Shackleton et al. 2005) because of low prices offered by speculators, low production, high household demand and lack of access to markets. It is too simplistic to say that communal farmers do not sell their animals because they view their cattle as a symbol of wealth and status. Livestock have multiple uses in communal areas (Ainslie et al. 1998; Cousins 1998).

Rangelands also provide many goods and services in addition to forage for livestock. Many communities harvest medicinal plants, wild fruits and foods, game and bird, firewood, timber, fencing material from rangelands. Open rangelands also often have an important aesthetic value as relief from the overcrowding, noise and air pollution of urbanisation.

The direct value of livestock goods and services have been evaluated in several studies. Because inputs and overhead costs are low, net returns per hectare from communal rangelands may exceed those for typical privately owned commercial livestock production systems (Shackleton et al. 2000). A rangeland-based livestock production system contributes significantly to food security and sustainability, in addition to a number of social, economic and cultural roles (Cousins 1998; National Livestock Strategy 2005).

Values of all goods and services (including the hidden values of food resources used before the end-of-season harvest) suggest that cropping lands "provide as much as a quarter to a half of total food requirement" of rural communities. However, subsistence agriculture in the communal areas may contribute about 10–50% to household income (Shackleton et al. 2000). Additional household income is obtained from social grants and income is also gained from employment outside of the communal area.

Agricultural activities in rural areas are closely associated with socio-economic development, as a large proportion of the South African population, most of whom are the poor, are dependent on rural agricultural production (Eastwood et al. 2006).

16.4.6 Summary of Communal Systems

The challenges of South Africa's communal rainfed farming systems can be addressed by looking at the system in a holistic manner taking into account the socio-economic and political influences over and above the biophysical environment. Communal rangelands are tenured in such a way that communities have common access to the resources. They have been governed traditionally, however poorly, through a system that gives power and authority to community leaders to ensure sustainable management. However, since the early 1990s the power of the chiefs and headsmen has been diluted by the ascendance of a modern democratic society. Under the new dispensation, communities make common decisions about how resources are managed and utilised and government is expected to provide support through the extension services. There are many challenges as communities learn how to work together in a newfound democratic process. However, there is increasing recognition that the land belongs to the people and that any attempts to attain sustainable resource management must start by involving communities in stewardship. This has led to a number of initiatives on community based natural resource management.

Croplands and rangeland-based livestock production contribute significantly to food security and sustainability. In addition, livestock perform a number of social, economic and cultural roles and functions in communal areas (Cousins 1998; National Livestock Strategy 2005). Livestock food products are major contributors to a balanced diet whereas livestock fibre products are significant in the clothing, leather, housing and decorative industries. Food crops provide the staple foods for the communities. Community dwellers also grow vegetables, albeit on a small scale, which also contribute to a balanced diet. Communal areas, therefore, play an important role in human development in that they contribute to income generation, creation of jobs, food security, and human dignity.

Communal areas, however, do not meet the full needs of rural communities and external sources of income are required to maintain livelihoods. Thus service delivery and extension services in these rural communities must be improved in order to optimize crop production in homestead plots as well as in larger cropping lands in the vicinity of the homesteads. Communities should be supported with both technology and finance, to incorporate land that currently lies fallow and arable land that has never been cultivated into the crop production system. This must be done judiciously, taking into account the need to maintain biodiversity and enhance sustainable management of natural resources.

Rangeland issues are much more complex given that there has been no success in promoting reduction of livestock numbers. Attempts to educate communities about sustainable management of rangelands have better chance of success than encouraging farmers to reduce their livestock numbers.

16.5 Summary

Physical environmental factors such as poor quality of soils, low and variable rainfall, and limited amounts of arable land severely constrain rainfed agriculture in South Africa. Of the 16.5 million ha of potentially arable land (about 14% of the country's surface area) only 22% is classified as having high potential for field crop production. The country's socio-political history and local and international economic forces further limit the potential for increasing agricultural output from rainfed production systems. Despite these constraints these farming systems form an extremely important part of South Africa's agricultural sector.

Rainfed farming systems in South Africa range from large and small-scale commercial enterprises to subsistence farming. Commercial agriculture accounts for 95% of the marketed output while the majority (about 2.3 million households) of the rural population rely on subsistence agriculture for a considerable proportion of their livelihoods.

The central and eastern regions receive summer rainfall and are the most important rainfed cropping areas of the country with about 2.6 million hectares of maize under cultivation in 2007. Maize is produced in monoculture and in rotation with other summer crops such as sunflower, soybean and sorghum. Under certain circumstances, wheat is included in the crop rotation systems applied in the region. Rainfed wheat can only be produced in this summer rainfall region on soils with shallow water tables and where a period of bare-fallow has been allowed during the summer for sufficient soil water storage to maintain the wheat plant during the dry winter months. In many areas, crop residues provide an important source of winter feed for cattle. Sugar is the main rainfed crop grown in the eastern coastal and coastal hinterland areas on about 350,000 ha. This area is among the driest cane-producing areas of the world.

Farming systems of the winter and all-year rainfall regions of the country have developed in support of winter cereal production. Wheat and, to a lesser extent, barley are the most important crops. Ten percent of the area cropped each year is planted to canola and lupin combined. Continuous cropping and crop pasture rotations are commonly applied although some farmers still practice wheat monoculture in a conventional tillage system. Livestock production (wool and mutton/'fat' lamb) is an important component contributing to the sustainability of these systems. It becomes increasingly important in the all-year rainfall area where there is a higher risk associated with cereal grain production than in the winter rainfall area due to lower and less reliable growing-season rainfall. Livestock graze mainly on pure legume pastures based on annual species of *Medicago* and *Trifolium* in the winter rainfall area, and on the perennial *Medicago sativa* (lucerne) in the all-year rainfall area.

South Africa's communal areas are located within the summer rainfall regions of the country, and farming systems there are restricted mainly to subsistence agricultural activities based on livestock and crop production for home consumption. There are, however, a number of 'emerging' commercial farmers who operate within some communal areas. A relatively small proportion of the total arable area is cultivated with the remaining areas of potentially arable and non-arable land being used for livestock production.

The staple crop produced in communal areas is maize that provides a supply of fresh cobs for household consumption during the growing season as well as grain. Sorghum is also a significant crop. Vegetable crops such as beans, pumpkin and wild spinach[4] contribute greatly to home food production both during the growing season and for the winter, spring and early summer where the grain crops are either not growing or are still in early stages of growth. Crop residues are fed to animals during the dry season.

Livestock production in communal areas contributes significantly to food security and sustainability. In addition, livestock perform a number of social, economic and cultural roles in these areas. Livestock food products are major contributors to a balanced diet whereas livestock fibre products are significant in the clothing, leather, housing and decorative industries. Net returns from livestock goods and services, calculated in terms of return per hectare have been shown to exceed returns per hectare calculated for typical privately owned commercial livestock production systems.

Together crop and livestock production in communal areas play an important role in human development in that they contribute to income generation, creation of jobs, food security, and human dignity.

Acknowledgements The discussions with and contributions of colleagues throughout South Africa assisted with the development of this chapter and are gratefully acknowledged. In particular we thank Professor André Agenbag (HOD Agronomy, University of Stellenbosch), Guy Thibaud (Department of Agriculture, KwaZulu-Natal), Bradly Flett and Thinus Prinsloo (both of the ARC–Grain Crops Institute) and Pietman Botha (Grain South Africa) for their assistance in gathering information and valuable insights. Mike Wallace (Department of Agriculture, Western Cape) and Wiltrud Durand (ARC– Grain Crops Institute) kindly provided most of the maps. We thank Alan Short and Baldwin Nengovhela (ARC-Animal Production Institute) for comments on earlier drafts and sections of the chapter.

[4] Leafy greens of various nightshade, legume and cucurbit species.

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Chapter 17
Farming Systems, Emerging Farmers and Land Reform in the Limpopo Province of South Africa

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Abstract Limpopo Province, in the north of the Republic of South Africa, has traditionally had two agricultural sectors, commercial and subsistence, that evolved under the land and social policies of pre-democracy governments. Post-apartheid land reform has created opportunities for the previously disadvantaged population to own and farm land. These new farmers, together with subsistence farmers attempting to commercialise, now make up a middle group termed the 'emerging farmer' sector. However, these emerging farmers face significant barriers that include lack of secure tenure inadvertently created by government policies and inadequate delivery of government services. Other challenges result from poor knowledge about farming, lack of motivation and organisation, and previous unsustainable land management practices. Despite these barriers, new farming systems are developing which provide farmers with opportunities to share resources, and to co-operate in purchasing better quality inputs, in the development of specialised markets for livestock, and in bulking commodities and other farm produce to meet market specifications. Many of these opportunities will require outside assistance to develop new systems and build human capacity. Improving the livelihood of emerging farmers needs an integrated approach between the farmers, extension workers, research and development advisors and government policy makers. Intervention strategies must take into account the risk, resource constraints and the social and economic objectives of the individuals or groups concerned, with progress through small incremental changes.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_17,

This chapter provides background on the origins of the emerging farmer sector and focuses on practical opportunities for supporting these farmers.

Keywords Limpopo Province • South Africa • Emerging Farmers • Land reform • Agricultural development

17.1 Introduction

Limpopo Province, one of the nine provinces of the Republic of South Africa, shares international borders across the Limpopo River with Botswana, Zimbabwe, and Mozambique (Fig. 17.1). The Province is divided into five districts, Capricorn, Mopani, Sekhukhune, Vhembe, and Waterburg, and covers an area of 12.5 million (M) hectares (ha), constituting 10% of South Africa's total land area of 122 Mha (Statistics South Africa 2006). Of the total land area, 6.3 Mha (50%) is used for grazing; 1.7 Mha for nature conservation and 0.9 Mha is arable farmland. The remaining area supports forestry, urban and rural communities, mining and other activities.

Fig. 17.1 The Republic of South Africa' Provinces and Provincial boundaries, highlighting the location of Limpopo Province[1]

[1] Map drawn using GIS data from Municipal Demarcation Board, Republic of South Africa (2005) (http://www.demarcation.org.za/) and Environmental Systems Research Institute, Inc. (ESRI), (2008) (http://www.esri.com/).

Limpopo is situated in a dry savannah sub-region, characterised by open grasslands with scattered trees and shrubs. According to Adcocks (1988), there are 15 veld types represented in the province covering the three biomes of bushveld, grassland and forest. The climate and vegetation, which are modified by mountain ranges and elevation, vary widely from semi-arid and arid rangelands through to sub-humid forests. Rainfall is strongly summer-dominant, with high temperatures and high evaporation during the summer months (M'Marete 2003).

The Province has a rapidly growing population, and currently comprises 5.3 million people or 12% of the national population of 45 million (Statistics South Africa 2006). Provincial growth and development strategies are centred on further promoting agriculture, mining and tourism, with agriculture comprising 15% of Provincial GDP and 20% of the workforce. Socio-economic problems persist amongst the majority rural based black African population with high levels of poverty, unemployment, and problems of infrastructure and social breakdown. Unemployment levels range from 30% in the Waterburg to 70% in Sekhukune (Limpopo Growth and Development Strategy 2005). Other socio-economic indicators such as the dependency, human development and poverty indices and life expectancy (52 years in 2003) all indicate significant and urgent developmental requirements. A range of initiatives are aimed at addressing these issues, with broad-based black economic empowerment, land reform and small, micro and medium enterprise (SMMEs) development as key strategies.

17.2 Contrasting Agricultural Systems in South Africa

There is essentially a dual agricultural economy in South Africa – commercial and subsistence – whose evolution has its origins in the land and social policies of pre-democracy governments. For most of the twentieth century, and particularly during the apartheid era (1948–1994), the commercial agriculture sector largely followed a capital-intensive trajectory; it was supported by a system of production and input subsidies, taxation benefits, assistance from government sector and access to cheap labour. Within the Bantustan (homeland territories set aside to concentrate designated black ethnic groups into autonomous nation states) constraints such as land tenure, lack of arable land, information and finance contributed to the development of subsistence agricultural systems that still persist. The subsistence agriculture sector is highly resource-constrained with low levels of productivity compounded by the high climatic variability of the semi-arid environment. While climatic variability poses significant risks to farming, uncoordinated policies and the unintended effects of policies (lack of secure tenure) have also contributed to sub-optimal growth and investment in the subsistence sector (National Department of Agriculture 2001).

A change in national policy for agriculture, which commenced in the early 1990s, has increasingly emphasised the deregulation and liberalisation of agricultural production and marketing. This followed a world-wide trend to freer trade in agricultural commodities and was also in response to pressure from development financiers such as the World Bank (National Department of Agriculture 2001). This shift includes a reduction of barriers to trade in agricultural imports and exports, abolition of tax concessions and subsidies, reform of labour legislation and the implementation of land reform programs. The result is a more competitive and open agricultural economy with increased exposure to global market forces. This new context has placed an even greater barrier to the small-holder and subsistence farming sectors gaining effective access to mainstream commercial-based agriculture. The cycles of unemployment, poverty and land degradation therefore continue to be serious problems in the former homelands, and efforts to overcome them remain high in priority at both national and provincial levels.

17.3 The Dual Agricultural Sectors

Agriculture in Limpopo Province remains structured around the two distinct agricultural systems: commercial and subsistence agriculture which respectively occupy 14.7% and 14% of the province's land (Department of Environmental Affairs and Tourism (DEAT) 2007). While the two systems notionally produce similar crops and livestock, they differ markedly in the typical scale of operation, method of production and market orientation.

17.3.1 Commercial Farming

The commercial farming sector in Limpopo province is composed of some 5,000 enterprises contributing about 70% of the agricultural GDP (Statistics South Africa 2002). These enterprises are typically located on the better agricultural land, practise large-scale farming with advanced production technologies, employ large numbers of farm workers, are well organised politically and are connected within formal agricultural market chains. The commercial sector is dominated by horticulture which accounts for 62% of gross income followed by animal industries and field crops at 30% and 7%, respectively (Statistics South Africa 2006). There is a large range in farm size and capital intensification, but the most capital-intensive irrigated horticultural farming takes place in parts of Mopani district near Tzaneen and in the Vhembe district. One example of the success of horticulture in the Province is the 'ZZ2' tomato farms in Mooketsi, near Tzaneen which employ more than 6,000 people and distribute more than 130,000 tonnes of tomatoes to the fresh produce market annually. Commercial animal industries include intensive chicken and pig production centred on Polokwane and Bela Bela, several large feedlots finishing beef on grain for the domestic meat market, as well as extensively-grazed beef and game meat enterprises. While intensive livestock activities (poultry, pigs, dairying and feedlotting) are commonly integrated on grain-producing farms, extensive cattle production is more typically confined to specialist farms composed mostly of natural pastures with lesser areas of sown fodder crops. Often located in less favourably endowed areas of soils and rainfall, many of these farms have recently abandoned cattle in favour of game ranching for meat or hunting purposes.

Commercial field crop production, particularly with maize and beans, is largely concentrated on the rich soils of the Springbok flats near Bela Bela, some of which use centre-pivot irrigation systems. Land claims, facilitated by recent land reform and economic development policies, have been made over many commercial farms so a high level of uncertainty and pessimism about the future of farming pervades this sector.

17.3.2 Subsistence or Smallholder Farming

Subsistence agriculture, practised by about 273,000 smallholder farmers (Statistics South Africa 2002) is mainly located in the former homelands. Because cropping and livestock activities are usually managed separately, there are few examples of crop–livestock systems able to take advantage of the synergistic opportunities of mixing enterprises.

17.3.2.1 Cropping

Cropping, particularly with maize, bambara groundnut (*Vigna subterranea*) and peanuts (*Arachis hypogaea*), is typically undertaken on small plots of arable land ranging in size from 0.5 to 2 ha that are located close to villages or in backyards. Access to these arable lands by individual households has traditionally been determined by local chiefs under a 'permission to occupy' arrangement. Despite the lack of a formal title, households appear to have secure access to the same portion of land for as long as they maintain some agricultural activity upon it. Crop productivity is typically low; it results from poor agronomic practices, particularly in land preparation, crop establishment with low and uneven plant density, poor weed control, and low fertiliser inputs in inherently infertile soils. While drought and high rainfall variability are typical of the climate, poor agronomic practices usually result in low water-use efficiency. Crops are grown during the summer wet season (November to April), mainly for household consumption, with surpluses being sold locally in informal markets.

Once most of the crops have been harvested, herds of village cattle and other livestock such as goats and donkeys are usually allowed free access to crop residues and any unharvested crops. Techniques such as direct planting into a mulch of crop residues cannot be adopted without changes to the system. These grazing practices also result in poor ground cover and high erosion potential.

17.3.2.2 Livestock

In the former homelands, the main livestock are cattle and goats owned by individual households. Large herds of these animals generally graze community-owned natural grasslands (veld) throughout the year and graze arable lands after they have been harvested, usually in winter. Formal management of total grazing pressure, veld condition, animal nutrition and breeding is virtually non-existent in most smallholder communities. Livestock, and especially cattle, fulfil traditional roles as a source of status, a store of wealth in the form of a 'walking bank account', or are kept for slaughter at special functions – rather than for commercial production.

Some communities are fencing communal grazing land and imposing some form of management in an attempt to control resource degradation and increase animal survival and growth rate. Stocking rates, veld condition and animal health are monitored and some stock sold when they reach a saleable condition – or need to be culled. Several large community farms (crop and livestock) created under recent land reform initiatives, notably under the Settlement Land Acquisition Grant (SLAG) scheme (Lyne and Darroch 2003), are seeking to maintain a unified management regime on former commercial grazing land acquired on behalf of disadvantaged communities and presently held in trust by the Limpopo Department of Agriculture. These community-based management arrangements face many challenges. Their ongoing survival is often compromised by poor management skills, a lack of resources to install and maintain necessary infrastructure, and limited ability to exclude grazing by livestock that belong to non-participants in the collective schemes.

17.4 The Influence of Land Reform Policies on the Agricultural Sector

The current government policies of land reform in South Africa are an attempt to redress the skewed land ownership patterns created by a white majority owning large tracts of land, while confining the black majority to a small percentage of land (Ramutsindela 2007). This unfair distribution of agricultural land within South Africa has created a moral and political imperative to create land reform and land restitution programmes. From the mid-1990s, a number of government land reform initiatives have been initiated across South Africa including the SLAG scheme, and the Land Redistribution for Agricultural Development (LRAD) scheme (DHA 1997). The beneficiaries of SLAG and LRAD schemes have been identified as 'emerging' farmers (see following section), largely because the schemes were meant to be a catalyst for entry to the commercial farm sector.

The SLAG scheme largely aimed to assist members of poor communities to acquire tracts of agricultural land for settlement and establishment of small farming enterprises (Lyne and Darroch 2003). In practice, because the only land available for purchase was typically an existing commercial farm which few individuals could afford to purchase and maintain in their own right, SLAG scheme acquisitions commonly involved large numbers of beneficiaries (e.g. 200–300 individuals) pooling their small grants (~15,000 Rand) to acquire a single farm to be operated under a common deed of trust and management structure. The performance of such collective enterprises has often been exceptionally poor, in most cases resulting in the complete collapse of agricultural production (Du Toit 2004).

The present LRAD scheme, which has largely superseded SLAG, is more focussed on providing grant assistance (~20,000–100,000 Rand per applicant) to individuals from the black African, Coloured and Indian communities. This allows them to acquire existing agricultural enterprises, purchase plant and machinery or develop infrastructure, as a step towards becoming commercial farmers (Wegerif 2004). The grants provided under LRAD are intended to serve as a financial supplement to the individual applicant's own cash, in-kind and labour contributions.

In addition to the grant-based land redistribution schemes, there is also an ongoing land restitution process within South Africa (Restitution of Land Rights Act 22 of 1994). This is for land claims made by communities or individuals who claim to have been removed from their lands following the introduction of the Native land Act of 1913 or were further disadvantaged by subsequent legislation, such as the Native Trust and Land Act of 1936 (Bosman 2007). The 1936 legislation prevented black South Africans from legally acquiring land. This applied even within native reserves where control of land allocation reverted to tribal chiefs, whose authority often exceeded that previously held under customary law. Individuals, who escaped losing their land rights through the 1913 and 1936 laws, were largely dispossessed by a second wave of evictions primarily brought on by the Group Areas Act of 1950 that forced farmers either to relocate to the homelands or accept work as labourers on commercial farms. The legacy of this historic undermining of land ownership by black South Africans remains strongly reflected in the skewed ownership of the commercial agriculture sector.

The imperative for land reform was a central component of the ANC Freedom Charter and a high priority for constitutional reform process leading up to the 1996 Constitution (Bosman 2007). To date, the process of resolving the many and often conflicting land claims has been steeped in legal and practical difficulties (Lyne and Darroch 2003; Bosman 2007; Ramutsindela 2007). The original 1998 deadline for resolving outstanding restitution claims was extended initially to 2005 and then to 2008.

Notwithstanding the urgent moral imperative, land claims and the slow process of their resolution are having a negative impact on the profitability and sustainability of many commercial operations in Limpopo Province. DuToit (2004) disturbingly documents many examples across South Africa of highly productive commercial farming operations being rendered unproductive within a few years of a change in ownership following land reform. There is obviously a failure in the process and this exacerbates tensions within the community and actually increases rural poverty. Where the land reform process is unavoidable, the transition of ownership must be managed so that farming operations under the new arrangements and management continue with minimal disruption. There are examples of successful transitions occurring where a community acquiring land initially took a shareholding in the business and the enterprise continued as a viable operation; similar successful transitions have occurred where the transition of ownership has been delayed until the new owners have become proficient managers. Government will have to make large investments in training new farmers and providing on-going support for farmers, through public infrastructure development (e.g. roads, saleyards) and well-trained and resourced extension officers.

17.5 The Emerging Farmer Sector

As a consequence of the land reform program, a third ‘emerging farmer’ sector is joining the commercial and subsistence sectors making up Limpopo agriculture. These emerging enterprises are typically owned and managed by individuals who have acquired agricultural land through support from land reform programs such as the LRAD grants; many have no prior farming experience or were subsistence farmers attempting to make a transition to commercial-based agriculture. Most emerging farm operations in Limpopo Province that have originated from the land reform schemes are attempting to undertake extensive livestock production, primarily cattle and goats, in the lower rainfall rangeland (veld) areas. Existing examples of emerging farmer enterprises include the ‘Steilloop farms’ in the Waterberg Region and the ‘Nwanedi farms’ in the Vhembe Region. In these examples, commercial cattle farms were acquired and reconfigured into new farms, each 500–1,500 ha in area, with an individual title; these were released for purchase by emerging farmers with LRAD scheme support. The uncertainty over pending land claims also applies to the emerging sector. Thus one of the Steilloop emerging farms has already been subject to a successful claim and the majority of the Nwanedi farms are presently subject to unresolved claims.

The creation of crop-based emerging farm enterprises has been less common in Limpopo Province; most involve pre-existing smallholder farmers from the former homelands. Most of these have not obtained land through the land reform process, although some will have received support through the LRAD scheme to install infrastructure (e.g. irrigation) or purchase farming equipment. In most situations, mechanised tillage equipment is available for hire (but is often expensive and substandard), and no planting equipment is available, so these farmers will plant by hand. Harvest is also by hand as the layout of most fields is not suitable for machine harvesting. With an aging farm population and a scarcity of labour for hire, finding suitable labour is also difficult.

This ‘emerging farm’ sector does represent a significant opportunity for new farming systems to emerge in Limpopo Province, particularly for medium-scale enterprises. Opportunities exist through resource sharing and co-operative efforts for purchasing better quality inputs (e.g. seed and fertiliser) and for bulking commodities for sale (e.g. groundnuts and other cash crops). Attempts to develop specialised markets for livestock (e.g. for indigenous cattle breeds), crops and other farm produce provide incentives to change animal husbandry and cropping practices to produce to market specifications (Winter 2007). Farmer organisations such as the National Emerging Red Meat Producers Organisation (NERPO) have also identified the need for producing and marketing better quality products through acquiring additional management skills and practices.

Table 17.1 Some of the major issues facing the emerging farmer sector in Limpopo Province

Livestock farmers	Cropping farmers
• Competitive nature of commercial agriculture – efficiency driven, capital-intensive, high information requirements.	• Low fertility of soils
• Lack of clear title and uncertain ownership	• Recurrent droughts and harsh weather conditions
• Insufficient farm size to be commercially viable	• Inadequate access to machinery for farm operations
• Poor condition of land and veld resources on most farms	• Inability to stop animals grazing cropping lands during the dry season
• Inadequate or damaged infrastructure (including theft and vandalism).	• Limited capital and access to credit
• Inability to control animal numbers and hence grazing management	• Ageing operators, limited access to labour
• Limited capital and access to credit compared with commercial, capital intensive systems	• Limited technical skills and farming background
• Absentee ownership/distance from homes	• Limited knowledge of market opportunities
• Limited technical skill and farming background	• Poor infrastructure for tillage, grain storage, transport, marketing
• Fragmented (often contradictory) sources of technical and financial advice	• Fragmented (or no) sources of technical and financial advice
• Poor access to extension officers, who are overcommitted and under-resourced	• Poor access to extension officers, who are overcommitted and under-resourced
Unclear farmer goals and confused leadership – is the aim to be commercial or just own land and cattle?	Unclear farmer goals and confused leadership – is the aim to be commercial or just own land and farm for household food?

Despite the opportunities for emerging farmers, there are major barriers. Some of the more challenging constraints identified by farmers are summarised in Table 17.1. Some have been inadvertently created by government policies (lack of secure tenure for some livestock farmers) and by inadequate delivery of government services (technical advice). Other challenges have developed as a result of previous unsustainable land management practices and the large-scale movement of young people from rural to urban areas as they seek better lifestyle opportunities.

17.6 Approaches for Developing Opportunities for the Emerging Farmer Sector

Whilst aware of the many problems facing emerging farmers, the following discussion proposes some ways of assisting the emerging farmer sector to develop production systems that are both profitable and sustainable. These proposals are drawn from authors' observations, project[2] findings and discussion with African colleagues and farmers.

Three strategies are seen as critical to enable emerging farmers to become part of mainstream agriculture – possibly assisted by intervention[3] programs supported by government or development agencies[4]:

1. An integrated systems approach where intervention strategies consider the whole system, including social, technological, economic and environmental aspects, together with infrastructure and services.
2. A participatory approach where farmers or communities are involved in the planning and development of any project from the outset.
3. On-going support to build local capacity to continue the development process when external support ceases.

The following sections deal with practical solutions based on these strategies.

17.6.1 Motivation and Skills

Most emerging farmers, both communal and individual, have no farming background and lack the knowledge and skills that are necessary to operate commercial enterprises. Moreover, some individuals who have acquired land with public support do not have the development of a commercial farm operation as a priority, but may be motivated by status or the opportunity to obtain a subsidised capital asset (e.g. land, livestock, and motor vehicles). Hence, management interventions aimed at improving animal or veld condition may not be seen by the farmers as being directly related to their priorities such as income generation, and so may be of limited interest.

Current research and development agendas[5] relevant to emerging farmers are heavily influenced by government and agency agendas. For example, a primary emphasis of agencies has been to get as many people registered for support as possible with little attention given to the skills and resources available to them as prospective new entrants to farming. Successful applicants for support are generally treated as if they were already participants in the commercial farm sector or remain attached to the subsistence sector. In many instances, high-level research and development (R&D) priorities, such as herd and crop genetic improvement or advanced marketing processes are less appropriate to the emerging farmers' needs than resolving some fairly basic husbandry and agronomic issues. Determining needs as

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[2] Australian Centre for International Agricultural Research (ACIAR) project. See Acknowledgements.

[3] A project or set of activities, designed to correct a problem. It may include provision of information or advice or an action plan.

[4] Non government organisations and overseas organisations such as ACIAR and GTZ.

[5] A list of aims or possible future achievements, which may have an organisational bias.

perceived by the rural communities is a priority if constraints to growth and success of the emerging farmer sector are to be overcome. Agencies need to embark on a dedicated program to determine the most critical constraints. Moreover, this needs to be undertaken with a realistic view of where the emerging enterprises presently lie on the path towards real commercial status.

17.6.2 Policies That Support Appropriate Interventions

Supporting effective change in the emerging farm sector will undoubtedly require a change in government policies and better mechanisms for appropriate delivery of information and enforcement of regulations and local rules. For example, emerging livestock farmers who genuinely aspire to become commercial operators, turning off finished animals each season might begin to grow forage crops and conserve feed for the dry season. Such a practice could both maintain animal condition and reduce the grazing pressure and reliance on their pastures. However, policy and interventions would need to change to accomplish this basic management strategy. Emerging farmers need information on farm and business management, and need a better understanding of the various constraints to their achieving commercial success. In regions such as Limpopo Province, these interventions will inevitably need to originate from within the resources of the Provincial Government.

Delivery of relevant information is also a key factor for the success of farmers establishing new enterprises. At this stage, they may be more interested in making better use of the existing resources than in introducing new strategies or making substantial investments. In communal areas, for example, where several emerging livestock enterprises might be starting with relatively few animals, with the intention of building numbers by breeding, there are advantages in initially combining several small herds for management as a single herd. This strategy would enable better grazing management of the pastures which often need rehabilitation and, by reducing the need for labour for herding, release some of this scarce resource for undertaking other tasks on the farms or for off-farm employment to fund future improvements.

17.6.3 Being Realistic About Farm Size and Economic Success

Despite the best intentions of some emerging farmers to make the transition to a commercial farmer status, many of the new farms are too small to be economically viable. For example, livestock farms with carrying capacities below 400 livestock units (LSU – animal with a weight of 450 kg) struggle to survive (ABSA 2003). Many new farms have an effective carrying capacity of less than 150 LSU, largely due to their small initial area. They are constrained further by poor land condition (mostly bush encroachment). Such a farm cannot support the needs of the household, and the farmers typically have to seek employment in other regions. This further compromises their ability to implement sound farm management. Policy makers must therefore be able to recognise what is an economically viable farm size, based on current farm resource condition.

17.6.4 Rural Infrastructure Enabling Other Opportunities

Emerging livestock farmers who are determined to become commercial operators will need alternative strategies that will immediately alleviate the pressure on their veld resources, and open the way for livestock and veld improvement. The strategy of taking off-farm employment could allow farmers to reduce the number of livestock required to maintain an acceptable standard of living. Emerging farmers in this situation might also benefit from integrated approaches that include the whole community. For example rural communities might benefit greatly from better roads and communication infrastructure that could also create improved access to markets or alternative sources of paid employment. Achieving such improvements would require appropriate alliances between rural communities, the Department of Agriculture and other policy agencies. This could allow rapid and effective growth in the emerging farmer sector.

17.7 Improving Research, Development and Policy

Agricultural research and development projects in Limpopo Province over the last 15 years have had a high failure rate (Connolly et al. 2006). Those that have succeeded in achieving their aims should be evaluated as guides to framing successful projects in the future. The essential attributes of the more successful projects have been a high level of community involvement and a strong sense of ownership of the R&D activities by the members of the targeted communities, the project staff and the agency senior managers. Frequent communication between researchers, extension staff and the community as well as targeted extension activities have also been important ingredients for success. Extension material is usually best developed by combining the research outputs and recommendations with information that places those recommendations in a local context. For example, in the case of improving livestock enterprises, appropriate extension material may span a range of topics including animal and veld management, bush control, use of fire, animal health, and financial management and record keeping. It should encourage a step-wise application of the information.

To ensure long-term benefit from R&D investments in Limpopo Province, government policy makers need to ensure that the project outcomes are well-coordinated with other national, provincial and local initiatives. For both the subsistence and emerging farm sectors, personal and community capacity building[6] and technical skills development are important for lasting improvement in farming systems design and practice. These communities are strongly dependent on guidance from Provincial and Municipal extension personnel. As many of these also lack strong skills on technical and community empowerment,[7] provision of adequate training and resources is an additional imperative for government. Provincial and regional policy makers are influenced by analyses of economic, environmental and social costs and benefits of new management options to the subsistence and emerging farming systems. Increasing the investment in social and physical infrastructure and motivating the sustainable development of communal land remain the most important policy opportunities.

The co-ordination of research and development, extension and policy definition for rural communities is a complex challenge. It will require a high level of co-operation between various government agencies and personnel from provincial, national and international projects. Co-ordination is necessary both between and within agencies and projects. This could greatly improve the scope for projects to improve farming systems and to provide lasting benefits. Agencies and specialist groups such as the ARC (Agricultural Research Council) and the Range and Forage Working Group (a network of livestock and pasture specialists coordinated by the national Department of Agriculture) could become more active in this pivotal coordination role.

17.7.1 The Role of Government

The level of governmental support for assisting subsistence and emerging farmers varies between regions. In general, the effectiveness of both provincial and municipal support is limited by a lack of appropriately trained and equipped extension staff, agricultural specialists and technical knowledge. Some of these limitations are being addressed as the provincial government services seek to attract and employ better skilled staff, and also through initiatives by donor organisations such as the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), BASED program and the Australian Centre for International Agricultural Research (ACIAR) travelling fellowships and post-graduate training schemes. However, more effort is needed to develop broad-based extension training opportunities that cover topics and issues relevant to their farmer and community clients. Providing training in basic crop and pasture agronomy and livestock fertility management may be more beneficial in the immediate term to the majority of farmers than the development of advanced cattle genetics or alternative crops, including those associated with biofuel industries. An understanding of the whole system (social, economic and technical) is therefore needed to set sensible priorities.

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[6] Activities which strengthen the knowledge, abilities, skills and behaviour of individuals and improve institutional structures and processes such that the organization can efficiently meet its mission and goals in a sustainable way.

[7] Skills that enable individuals to play an active role in the decisions that affect their community.

17.7.2 The Role of the Private Sector

Consistent with the technical and capital-intensive nature of modern farming systems, there has been a longstanding and mutually beneficial association between the commercial agricultural sector and private agribusiness operations. Running in parallel with the growing emphasis on the emerging farm sector has been the growth in private agribusiness linkages to that sector. For example, the private sector views emerging farm enterprises as potentially significant producers of maize and livestock. They are now therefore developing programs to capture the growing market for seed, fertilisers and other farm inputs, and to purchase commodities from these enterprises. Importantly, some emerging farmers are actively participating in farmer groups and associations in an attempt to develop better production and marketing systems that may lead to improved returns (Clark et al. 2005; Winter 2007).

The formation of a community development program by Progress Milling, a long-established private company, is one example. The company obtains maize, sorghum, sugar beans (*Phaseolus lunatus*), cowpea (*Vigna unguiculata*), bambara groundnut (*Vigna subterranea*) and peanuts (*Arachis hypogaea*) from 65 delivery depots distributed throughout the province. A community development program was initiated in the late 1990s, primarily to promote the commercialisation of smallholder agriculture. It aimed to alleviate poverty and food insecurity in rural communities and to procure local products for milling in order to reduce transport costs. Through partnerships with the PANNAR seed company and the Omnia fertiliser company, Progress Milling is supplying inputs to smallholder farmers through its depots, while buying some 6,000 tonnes of maize grain per year from them.

17.7.3 Commercialisation of Smallholders – The Bohlobela Model

The dominance of the commercial and emerging farm sectors need not preclude the commercialisation of smallholder or subsistence farm households. These can successfully commercialise some parts of their farming enterprises as demonstrated in the Bohlobela district. In this district, which is a nationally identified area of poverty, two large farming communities (Kulani and Sismukuni) are pursuing this option.

This region has a large, rural-based population with a strong local demand for produce such as groundnuts and cowpea. A simple and practical approach to commercialisation has been developed by a core group of local farmers, and is termed the 'Bohlobela Model'. A strategic pathway for developing capacity to produce and market agricultural products includes:

1. Identifying the potential market opportunities.
2. Undertaking strategic research to identify appropriate varieties, agronomic practices and productivity potential of the proposed crops.

3. Building the farmers' agronomic knowledge and skills in crop production, through formal and informal training
4. Supplying or subsidising appropriate inputs such as new varieties and fertiliser.
5. Identifying and addressing other constraints such as storage, packaging and marketing of produce.
6. Providing on-going technical and logistical support.

Under the Bohlobela model, a group of South African and Australian researchers gathered information about the current farming system, agronomy and soils from ten subsistence farmers. Production of the various crop options and the effect of fertiliser and planting dates for the previous 25 growing seasons were simulated using a crop model incorporating local long-term weather records. The results were used to determine the best bet planting times and input levels, and this information was communicated to farmers through extension material. Over the first three seasons, the number of farmers actively involved in the project increased to 50. While logistical problems and drought in the initial years resulted in production being too low for a surplus to the household requirements, productivity and enthusiasm of the farmers was increased. In the wet season of 2007/2008, several of the farmers produced enough surplus produce for the packaging and sale of groundnuts to occur.

A key ingredient to the success of the Bohlobela model has been the engagement of a well-respected and reliable extension officer. This highlights an important issue – every development project needs a local 'champion' (see also Chap. 37). This champion is someone – either local extension worker or respected local farmer – who believes in the aims of the project and who is prepared to put extensive effort into promoting the project and making it succeed (Cramb 2000).

17.8 Summary and Conclusions

High levels of poverty and unemployment, as well as problems of infrastructure and social breakdown persist amongst the majority rural black African population of Limpopo Province. In contrast to this, a relatively small population of mostly white farmers manage the larger part of the agricultural lands and grow the bulk of livestock and crops using generally well-organised and modern farming practices. The dual agricultural sectors, namely subsistence-smallholder agriculture and commercial agriculture, and the geographical arrangement of these systems have developed largely as a result of past government policies that actively discriminated against the majority of the population. These policies ensured that access was denied to the best land resources, technical support for farming and marketing practices and to education.

Despite the end of the apartheid era in the mid-1990s and deregulation of the agricultural sector, the subsistence-smallholder farming sector has largely failed to become part of mainstream commercial agriculture. In the reality of a much more competitive and open trading economy for agricultural products and industrial inputs, and with limited infrastructure and technical support, this failure is not surprising. Much policy hope is presently being vested in the emerging farm sector, for a more equitable representation of previously disadvantaged people within the commercial agricultural sector. This sector is broadly made up of (1) new entrants to agriculture, assisted by the land reform programs or (2) those drawn from the ranks of existing subsistence farmers who are attempting to make a transition to commercially based agriculture. The growth in a third, ‘middle’ sector is seen to be an obvious avenue for allowing the mainstream and disadvantaged black African population to both contribute positively to the formal agricultural economy and also share in any financial, social and environment benefits from this change.

However, there are significant barriers to this successful transition and to date, few success stories. Despite these barriers, the emerging farmer sector does represent a significant opportunity for new farming systems to emerge, particularly for medium-scale enterprises. Opportunities do exist to share resources (e.g. tillage equipment, milling equipment) and co-operative efforts for purchasing better quality inputs (e.g. seed and fertiliser) or timely operations (ploughing contractors). Attempting to develop specialised markets for livestock (e.g. indigenous cattle breeds), and bulking commodities (e.g. groundnuts) and other farm produce provide incentives to change animal husbandry and cropping practices, in order to produce to market specifications. Most of these plans will require outside assistance to demonstrate and build capacity, at least initially.

Importantly, attempts to improve the livelihood of emerging farmers need to involve an integrated approach between the farmers, extension workers, research and development advisors and government policy makers. Intervention strategies must take into account the resource constraints, risk management, and the social and economic objectives of the individuals or groups concerned. Progress will best be made through small incremental changes in all these factors. Emphasis should not just be on improving elements of the prevailing farming systems, such as resource condition or increasing the volume of livestock or crops produced, but must also include system-wide improvements to ensure the development of sustainable livelihoods. Setting sensible research and development objectives and creating sensible policy therefore requires an understanding of the whole system.

The commercial sector could play a key role in the training and mentoring of emerging farmers, especially during any transitional arrangements in land ownership. This, however, would require a new level of trust and communication between the commercial sector, the government services responsible for land reform and farmer support and the emerging farmer sector.

Acknowledgements The Australian Centre of International Agricultural Research (ACIAR) funds project LPS/2002/081 in Limpopo Province on the Development of Emerging Farmer Crop and Livestock Systems. Our African colleagues and farmers on the project – especially Mr Frits van Oudtshoorn, (Bushveld Environmental Consultants, Modimolle), Mr Terries Ndove (Department of Agriculture) and Mr Madambi Wilson Muvhulawa, chairperson of the National Emergent Red Meat Producers Organisation (NERPO) – are acknowledged for their insightful thoughts and discussions, many of which are reflected in this chapter.

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Chapter 18
Modernisation of Eritrean Rainfed Farming Systems Through a Conservation Farming Systems Approach

Jay Cummins and David Coventry

Abstract Agricultural productivity improvements, particularly in grains for human consumption, are essential in Eritrea if this developing country in eastern Africa is to achieve food security. The central highlands of Eritrea, where much of the grain is produced, is characterised by low (though high-intensity) rainfall that limits the growing season to a length of 4–5 months, highly erodible soils and intense land use competition from pastoral activities. The cultural practices of Eritrean farmers, which appear to have changed little over hundreds of years, include cultivation by oxen, broadcasting of seed by hand and hand harvesting. Animal threshing of grain is still common in many of the agricultural areas. The crop and pasture residues are normally grazed, or used for fuel, thus leaving the soil exposed to wind and water erosion. Eritrean farming systems are complicated by social pressures from practices such as communal grazing and, for many farmers, a revolving 5–7-year land tenure system. With a need to achieve food security, the key to sustainable farming in Eritrea may be to develop agricultural systems based on conservation farming practices, within a farmer participatory framework, where indigenous knowledge systems are recognised and respected. This will need to be done by gradual incremental improvements that address both the socio-economic and technological barriers to systems improvement.

Keywords Rainfed farming systems • Conservation agriculture • No-till • Communal grazing • Agricultural extension • Modernisation of agriculture

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_18,

18.1 Introduction

Eritrea (Fig. 18.1) is a country characterised by frequent droughts, low crop production and the constant challenge to satisfy basic food security. In 2008, world cereal stock reserves were expected to decline further, reaching their lowest level since 1982. Further, market signals are distorted by increased competition for agricultural commodities from the bio-fuels sector and increasingly frequent, weather-related production shortfalls (FAO 2008a). In the 12 months to December 2007, the FAO Food Price Index for grains rose 43%, compared with 7% the previous year (FAO 2008a). Such increases in world prices for basic food grains are already challenging the populations in many developing countries, and highlight the need to develop farming systems that can achieve basic food security. Food security is of paramount importance for the future of Eritrea, which is one of the ten poorest countries in

Fig. 18.1 Eritrea, located in eastern Africa

the world. In 2007, the cereal import requirement for Eritrea was 207,000 tonnes, and was predicted to increase to 326,000 tonnes in 2008 (FAO 2008b).

The Government of Eritrea has set a priority to reduce its dependency upon food aid programs. In 2005, it revised its food aid policy towards a 'work for food' program, whereby those in need of food have to be involved in employment programs. Improving productivity in the agricultural sector is seen as a key to the future of the country, where 70% of the population derive their living from subsistence-based agriculture.

In this chapter we explore the options for improving productivity in rainfed farming systems across Eritrea, based on the experiences of the authors through their involvement[1] there in agricultural development projects and on local information gained from project partners. Throughout our discussion, we refer to experiences from Australia as one basis for developing options for improving Eritrean agriculture. This is done because the two countries have common needs to optimise water use efficiency (WUE) in a low and variable rainfall environment, control soil erosion caused through wind and water, improve soil fertility and intensify agricultural production.

The recent development of rainfed conservation farming systems in Australia has resulted in significant improvements in WUE. Productivity improvements have been achieved through the adoption of no-till conservation farming systems, with improved crop varieties and agronomic management. Crop productivity in Australia in the period 1977/1978–2001/2002 has increased at a mean rate of 4.8% per annum (Productivity Commission 2005).[2] In contrast, it appears that there has been little improvement in rainfed farming system operation or productivity in Eritrea since European colonisation in the 1800s.

18.2 Eritrean Farming Systems and Prospects for Conservation Farming

18.2.1 Current Cropping Practice

More than 70% of the population of Eritrea relies on agriculture for their livelihood (NEPAD 2005), practicing a subsistence form of farming. However in a good season, surplus grain is traded in order to provide some form of cash flow for families,

[1] The authors have worked as consultants to the Hamelmalo Agricultural College, Ministry of Education Eritrea, over a period of 4 years, supported by the Australian Department of Agriculture, Fisheries and Forestry, Rural Solutions SA and The University of Adelaide.

[2] Based upon a multifactor productivity MFP index, defined as growth in output relative to the combined contribution of key inputs, usually labour and capital, or the increase in output that cannot be accounted for by an increase in inputs. Evidence of productivity growth usually means that ways have been found to create more output from given inputs, or alternatively, to produce the same output with fewer inputs (Productivity Commission (2005) Trends in Australian Agriculture Research Paper, p. 117).

Table 18.1 Mean monthly rainfall (mm) and monthly minimum and maximum temperatures for the highlands (Asmara) and lowlands (Massawa), Eritrea

Month	J	F	M	A	M	J	J	A	S	O	N	D
Asmara												
Rainfall	4	2	15	33	41	39	175	156	16	15	20	3
Min. °C	4	5	8	9	10	11	11	11	9	8	7	5
Max. °C	22	24	25	25	25	25	22	22	23	22	22	22
Massawa												
Rainfall	35	22	10	4	8	0	8	8	3	22	24	40
Min. °C	19	19	20	22	24	26	28	28	26	23	21	20
Max. °C.	29	29	32	34	37	40	41	40	39	36	33	31

Source: World Climate (2009); climate-charts.com. Data rounded to nearest whole number

and much needed grain for the domestic market place. Eritrean farmers grow a wide variety of crops that include wheat,[3] barley, maize, taff (*Eragrostis tef*) and sorghum, in addition to oil seeds and horticultural crops. Frequently these are grown as mixtures of several landraces of the various crops (Woldeamlak et al. 2008). Temperate crops are grown in the central highland regions of Eritrea, 1,500–2,500 m above sea level, with corresponding temperature changes. The range of temperatures from coast to highlands is shown in Table 18.1. In favourable rainfall seasons, chickpeas are also produced, and assist in building soil nitrogen levels (FAO 2006). Many of the current field crop varieties have been hand selected by farmers over generations. An example of a traditional mixed cropping system known as *hanfets*, in which barley is the primary crop, is described by Woldeamlak et al. (2008).

Annual rainfall ranges from less than 400 to 700 mm across much of the area devoted to crop production in the central highland region, with the growing season between the warmer months of June and October. Rainfall is considerably less in the lowlands. Mean monthly rainfall figures for Asmara (capital city of Eritrea, located in the central highlands) and for Massawa (a coastal settlement bordering the Red Sea in the low lands) are presented in Table 18.1.

Rainfall is characterised by intense downpours, resulting in low rates of infiltration and high rates of run-off. The associated loss of soil on freshly sown fields carries with it seed and fertiliser.

Rainfed agriculture still relies on traditional methods of production. The average yield of most field crops is less than 1 t/ha, with many less than 0.5 t/ha in poor years. Contributing to this low productivity are minimal soil cover by crop residues (leading to soil erosion, often the result of intense rainfall events), local low yielding varieties, crop pests and diseases, lack of adequate farm technology (machinery and chemicals) and low inputs (particularly of plant nutrients). Widespread tree felling during the war years of 1960–1991 and the continuing demand for wood as a fuel have contributed to soil loss and poor rainfall infiltration rates. It has been estimated that the average annual soil loss from Eritrean cropping lands is 12 t/ha (Department of Environment 2001).

[3] See Glossary for botanical names of crops.

Current farming systems in the central highlands of Eritrea involve intensive cultivation. Traditional crop establishment methods rely mainly on oxen-drawn cultivators (single furrow, steel-tipped wooden ploughs) (Fig. 18.3), with only limited use of mechanical traction. After the field has been tilled, seed is hand-broadcast and then incorporated with a follow-up cultivation. These cultivation and sowing methods result in variable sowing depth, poor seed–soil contact and loss of valuable soil moisture, leading to poor crop establishment and growth.

The exposure of the soil surface by cultivation further reduces crop yields through soil erosion and poor water infiltration (Kidane 2004). Protection of the soil by crop residues is reduced after harvest when crop residues are eaten by livestock as part of communal grazing practices (de Araújo 2003), (Fig. 18.2). Any conservation-based farming system is impeded by the use of crop residues as feed for livestock, as fuel or for constructing housing. (see Chap. 11 for recent research on pasture species for Eritrea). Conservation of fodder is discussed below.

Most crops are hand weeded, outside of the pre-sowing cultivation time. A few farmers use 2,4-D for broadleaf weed control. The semi-parasitic witchweed (*Striga hermonthica*) is widespread, especially on low fertility cropping land. This weed receives little competition, is rarely controlled, and rapidly builds up its seed reserves.

The level of food self-sufficiency in Eritrea averages 60%, but ranges from 50% to 90% between regions. About one million hectares of land are currently cultivated for crop production, mainly in the highlands. Of the 180,000 ha suited to irrigated production, less than 10% is being used in this manner (Ogbazghi et al. 2007). If the area under crop production is to be expanded or used more productively, economically and

Fig. 18.2 A field prepared for sowing near the village of Hamelmalo, Anseba region, shows the lack of soil cover and potential for erosion (Photo J Cummins)

Fig. 18.3 Land being cultivated with oxen, Keren Eritrea (Photo D. Coventry)

sustainably, farming practices must be appropriately modernised. Such modernisation needs to be based upon a conservation farming systems approach aimed also at improving the natural resource base. Key elements of such a system aim to integrate best practice agronomy and soil management, and to use available soil moisture fully and efficiently. This would involve use of no-till and stubble retention practices, and improved crop varieties.

However, as seen from the above analysis, the introduction of conservation farming would be a complex process, involving many changes to traditional farming methods. Further, the question arises as to the level of influence that local social and environmental characteristics may exert, and how far they may act as either barriers or encouragement to the adoption of conservation farming systems. While some agronomic improvements could be addressed with comparative ease, developing appropriate extension strategies that take into consideration the local socio-economic characteristics will be more complex.

18.2.2 Socio-Economic Barriers to Conservation Farming

There are a wide range of both socio-economic and technologically based factors that are likely to influence the adoption of conservation farming practices in Eritrea. These are summarised as follows:

Land tenure: A 7-year revolving land tenure system operates over much of Eritrea, with village elders responsible for allocation of land to local farmers. Thus there is little 'personal, emotional attachment' to the land, resulting in less incentive to invest in improvements in soil quality and land management.

Communal-based grazing of livestock: This is the common means of livestock management. Village elders assist in grazing management to reduce the potential for overgrazing. Nomadic pastoralism is also an important characteristic of Eritrean livestock production systems, and 'post-harvest conflict' often occurs between farmers and pastoralists in competition for the valuable crop residue reserves (Dinucci and Fre 2003). Crop residues are also frequently conserved, simply by storing the straw in overhead tree branches where animals cannot readily reach them, or in small hay stacks on the ground, fenced off with thorny tree branches.

Resource poverty of farmers: The low availability and affordability of agricultural inputs are major constraints to the adoption of improved farming systems. Such inputs include seed of improved crop varieties, plant protection pesticides, herbicides and fertiliser (organic or manufactured). Lack of affordable mechanised equipment and other technologies contribute to a low level of adoption. Much of the animal manure that could be returned to the land is used as fuel for cooking and heating. Poor returns from farming often force farmers to search for off-farm income from seasonal labour in services and manufacturing, to sustain the family livelihood (NFIS 2005). This reduces the labour available for operations in crop production. Whilst some project funding from the Government or NGOs may help provide hand tools and equipment for new conservation farming techniques, farmers are generally resource poor, with limited financial capacity.

18.2.3 Research and Extension Capacity

The intended outcomes of Eritrean research and extension services are improved food production and enhanced food security through a partnership between farmers and extension providers (Steele 2002). However, the adoption of technology and agronomic practices and sustainable use of natural resources are generally limited by availability of trained personnel and operating funds.

Training opportunities for professionals are limited by government budget constraints. Responsibility for the delivery of extension services is at the local government or sub-zoba (district) level, where extension officers work closely with influential village elders and other farmers who are considered to command respect in local communities. Where project funds are available, local influential farmers may receive some small remuneration to assist in the dissemination of key extension messages.

18.2.4 Availability and Adaptability of New Equipment for Proven Practices

The development of conservation farming systems requires new or adapted mechanised seeders capable of sowing seed through crop residues and without prior tillage.

Some project development work has been undertaken by the National Agricultural Research Institute, but the techniques and no-till seeding equipment are not widely accessible to farming communities. This is due to: (1) limited financial resources available for the demonstration and extension of such farming practices; (2) the high cost of the equipment relative to the income earning capacity of farm households; and (3) the remoteness of many village communities. Furthermore, the adoption of conservation farming methods requires a participatory approach in which farmers are involved in the adaptation and development of techniques suited to local farming environments. There is strong evidence from past and current agricultural extension initiatives that farmers value the opportunity to contribute towards the development of new farming practices and cultivars (Ceccarelli personal communication 2008). This indicates the potential benefit of such a participatory approach for the development of no-till conservation farming systems. Development needs to take place on-farm, in rural communities and away from agricultural research centers. It is important, however, to identify opportunities for accessing other sources of funding to support the purchase of specialized equipment, for which farm households lack resources.

Both tractor-mounted and animal-drawn zero-till seeding equipment has been imported to the Hamelmalo Agricultural College, where it has been assessed and modified to suit local farming conditions. Similar initiatives have been undertaken by the National Agricultural Research Institute (NARI) at their Halhale Research Station south of the capital Asmara. These processes of adaptation have been slow, because of a lack of suitable expertise and financial resources to conduct trials and demonstrations. Further work will be conducted with both tractor-mounted and animal-drawn equipment. In the interim, animal-drawn seeding equipment probably offers the best chance of adoption by resource-poor farmers, provided such equipment can be made cheaply by local artisans, as has been done in other African countries such as Zambia, Kenya and Tanzania.

Fig. 18.4 Wind-blown soil erosion during cyclonic winds in the semi-arid region of Kerkebet (Source: Kahsay 2002)

18.3 Development of Conservation Farming Systems Using the Australian Experience

The concept of farming systems development was formally recognised during the 1970s. It was partly driven by instances of new technology not being adopted when the complexities of the whole farming system were not appreciated and taken into account. Traditional extension models had focused upon ‘transfer of technology’, often characterised by the one-way flow of information from the research/extension professionals to the targeted farmer. Dependency on simple solutions increased the reliance on single inputs such as herbicides and fertilisers – aided by a highly competitive agribusiness retail sector. This method did little to develop the problem-solving skills of farmers in an integrated systems approach to managing their farms.

Over much of southern Australia in the 1980s the failure to adopt conservation farming practices such as no-till planting was the result of farmers’ inexperience in chemical use, inadequate sowing and harvesting machinery capable of handling high levels of plant residue and an increase in cereal root diseases such as *Rhizoctonia,* the incidence of which initially became more evident under reduced tillage situations. In effect, there was failure to consider all of the relevant interacting factors within the farming system (Cummins 2007).

Fortunately extension systems in Australian agriculture have evolved to take these shortcomings into account in recent years. They have moved from providing basic technical information, to encouraging the formation of partnerships for developing new technologies, through to empowerment of farmer-driven groups (Bimer et al. 2006).

In the face of complex technology, advisers and consultants can provide general awareness and information but farmers also look towards practical solutions and experience, particularly from other farmers who have, through trial and error, adapted the systems to suit local farming conditions. The adoption of no-till practices occurs in a step-by-step process (Cummins 2007) (as summarised in Fig. 18.5), in which the farmer progressively:

1. becomes aware of the technology
2. seeks more information
3. looks to the experiences of other farmers
4. makes a conscious decision to try the new technology
5. modifies specific planting techniques to suit local farming conditions and needs – often through ‘trial and error’.

To achieve the change to no-till, a farming systems approach needs to be adopted, with inclusion of advisers, consultants and farmers, to take into consideration a wide range of complex and interacting factors. All this is needed for successful development and adoption of improved management techniques. It requires farmers to be active participants in the process, as an appreciation of a variety of socio-economic influences will assist in developing practical extension approaches.

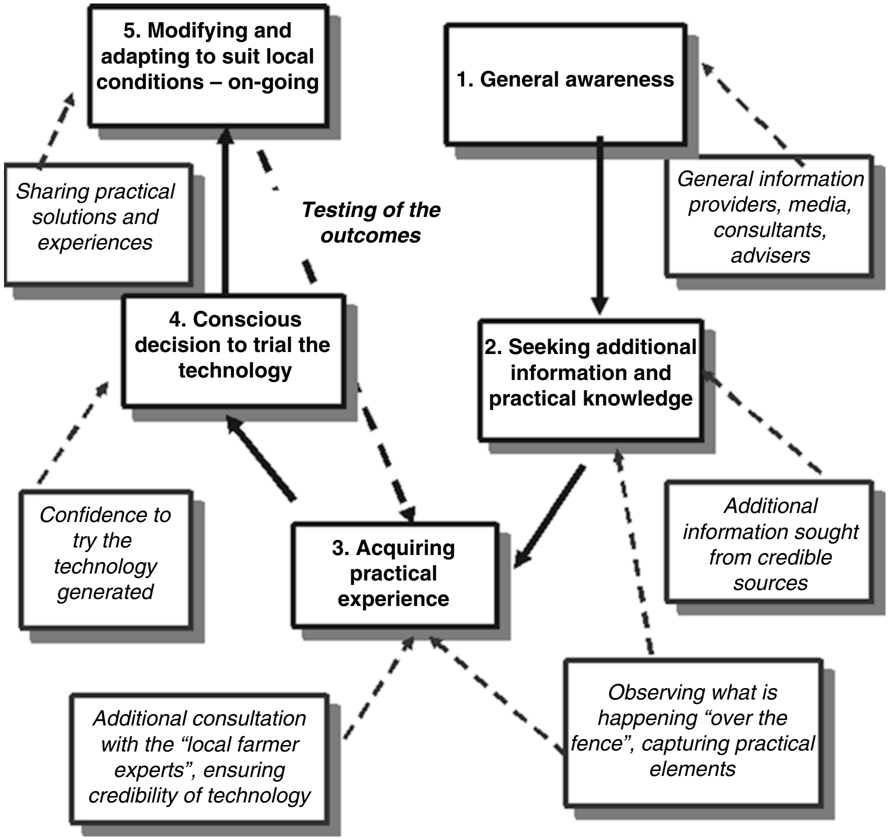

Fig. 18.5 The influence of the agricultural knowledge system in relation to adoption of no-till planting systems in Australia (Source: Cummins 2007) Solid arrows indicate cyclical path of the stages of adoption; dotted arrows indicate intervening relationships that influence the adoption process

18.4 Developing Improved Systems for Eritrea

There are opportunities to enhance the reliability and productivity of crop production in Eritrea, provided there is an appreciation of the processes involved in the adoption of relevant technology, and the recognition of the need to undertake a five step, approach, as presented in Fig. 18.5, involving farmers from the outset. Severe land degradation must be addressed, and efforts made to produce more reliable crop yields, particularly during years with low rainfall.

Through addressing the barriers to adoption of conservation farming practices, it should be possible to introduce change to Eritrean food production systems. The major barriers are socio-economic and structural in nature, and need to be thoroughly understood and addressed in order to gain small incremental improvements in the overall farming systems; Adapting to local environmental characteristics is important in the development of opportunities. Such an approach has been extremely successful in other African countries where stakeholders have united in the adoption of simple improvement in systems associated with conservation agriculture (Baudron et al. 2007).

Aiming for small incremental improvements is an important approach to take, given the lack of resources available to many subsistence-based farmers. For many of these farmers, it is an achievement just to grow enough grain to feed their own families for a whole year, let alone be able to produce surplus grain for sale in the market place.

Such a first step may assist in providing a suitable platform, albeit small, for the next incremental improvement in the system. This process needs to be carefully guided as it is unlikely to self-start. It has to begin with the simplest of technologies (e.g. better crop and pasture cultivars, weed and pest control), with a strong element of participatory farmer-led research, development and extension. It is however critical to consider and keep in mind all relevant components of the farming system in order to develop integrated solutions for problems and sustainable productivity. The following examples indicate potential means of achieving incremental improvements in the farming system through addressing combined socio-economic and technological barriers. Farmers themselves need to identify the first step in their systems improvement, but this decision may need to be guided to achieve the first step.

1. Recognition of local indigenous knowledge systems:
   The development of conservation agriculture systems for Eritrea will be heavily dependant on developing local solutions to problems. Any development model must recognise both indigenous knowledge and the existing decision-making processes for community-based land tenure and grazing management. This is illustrated by the following passage from a study on Eritrean agro-pastoralism;

   > Over time, the pastoralists in Eritrea have developed indigenous skills that help them mitigate the effects of unpredictable environmental conditions. They practice range management techniques as a way of saving forage for critical periods. Enforced by the local power of leadership, the pastoral communities have also set rules for regulating herd movements and for conflict resolutions (Kahsaye 2002, p. 181).

   In the same way, the successful development and adoption of conservation agriculture systems in Australia relied on the recognition of local agricultural knowledge, supported by a participatory-based farming systems approach.

   In Eritrea, practical field demonstrations of a range of agronomic practices can help achieve change at the local farmer level but the farmers themselves must be involved in the identification and development of effective practices, and have the opportunity for comparing them against traditional practices. The management of risk is crucial to the successful adoption of new approaches associated with conservation agriculture. There will still be significant constraints to improving the overall farming system, such as restricted availability of chemical fertilisers and pesticides.

Addressing communal grazing systems: issues relating to communal grazing systems present significant challenges, including the need to understand the reasons for traditional practices through working with village communities. Experience suggests that the grazing of communal village lands requires much skill and expertise in itself, with village elders playing a key role in maintaining livestock condition (Kamphurst personal communication 2007). In many parts of Eritrea with nomadic pastoralism, livestock are herded across large tracks of land with distinct grazing strategies according to rainfall patterns and maturity of different plant species (Kahsaye 2002).

Conservation farming relies on retaining plant residues (be they pasture or crop stubbles) on the soil surface. Any development of different grazing management systems must involve the decision-makers (such as the village elders) and individual farmers who undertake the farming practices. Any change would require the full cooperation of village elders – and demonstration of the advantages. There are examples where such approaches have been successfully introduced in the area of livestock and grazing management; for example, (1) the selection of indigenous fodder species and specific plant types for grain production, and communal management of animal grazing systems at the village level in the central highlands of Eritrea.

2. Improved forage legumes and grazing systems:
Improved dual purpose forage/crop species can cover the ground early in the season, produce more feed for livestock and also provide food for human consumption under adverse seasonal conditions. Legume species with potential for the temperate highland regions include vetch, field peas and lupins; grasses include ryegrass and triticale (Calegari 2004).

The introduction of improved species needs to be developed in association with grazing management that excludes stock both during plant establishment and after seed set (to maintain seed carry-over and reserves for future growing seasons). Livestock systems of Africa are also discussed in Chaps. 11, 16 and 17.

3. Improved plant establishment through no-till:
The development of no-till systems presents a significant opportunity to achieve earlier and more timely planting, more even planting depth and better seed–soil contact. These benefits alone could increase crop yields by more than 20% and farmers might be able to harvest a crop in seasons where no harvest was possible under conventional practices.

Developing conservation agriculture requires simple and cheap oxen-drawn, single and multiple no-till planting methods (as illustrated in Fig. 18.6). Mechanised systems would introduce additional barriers to adoption, including the high costs of investment, availability and cost of fuel, and the need to use syndication ownership models (Pieri et al. 2002).

4. Management of risk:
Management of risk in rainfed environments is essential in order to survive the variability in rainfall and crop production. Eritrean farmers tend to manage risk by selecting a range of crop types and times of sowing; for example, late-maturing crops tend to be sown at the start of the cropping season, followed by quick-maturing crops, particularly if the early sown crops fail (Ogbe-Michael undated)

Fig. 18.6 Animal traction direct sowing in Eritrea (Photo credit: de Araújo 2003)

18.5 Farmer Response to Change: A World Apart or Shaped by the Farming Environment?

While Eritrean farming practices appear to have changed little since well before European colonisation, farmer conservatism may well be a natural response to managing risk in adverse environments. Frequent droughts, compounded by years of war, have done little to provide Eritrean farmers with the required environment for change. In recent years, support programs from NGOs and other foreign aid have heightened potential opportunities for change. In Eritrean agriculture, local indigenous knowledge combined with the key elements of participatory-based learning and decision-making at local village and sub-zoba (district) levels have been important in maintaining current production levels and farmer choice for both cropping and livestock operations. However, this approach has not achieved full potential, as shown by the apparent lack of improvement in crop production.

A range of simple technologies and farming practices could be adapted to local Eritrean agriculture through a 'farming systems approach'. These would be aimed at improved crop establishment, improved fodder and pasture species, and availability of better quality seed. To support the introduction and adoption of new practices, the availability of finance to purchase improved seed varieties, fertilisers and other inputs needs to be addressed.

Given adequate funding, the participatory approach used in recognising and sharing local knowledge is also a critical factor in developing and adapting any new idea or farming practice; and should be followed as part of developing Eritrean farming systems. Recognition of the role that senior village elders and leaders play in influencing farmer decision making is an important consideration, as is the respect that is held for many progressive local farmers by the wider community. The issue of revolving land tenure (generally 7-year periods) amongst farmers however, remains a major challenge for developing sustainable farming systems, due to the lack of longer-term commitment and farmer 'connectedness' with the farming land. Adequate availability and training of extension officers, as well as access to information at the local village level are also important.

Involving farmers in the development of new practices (e.g. utilising the participatory approaches to which Eritrean farmers are accustomed) in adequately-resourced programs will improve food production, help to develop positive attitudes to the specific technologies, and provide a better understanding of agronomic techniques and management of risk.

Adequate support to such programs is critical in the development of Eritrean agriculture. The Government of Eritrea is committed to developing agriculture and new technologies. The recent establishment of the Hamelmalo College of Agriculture aims to produce graduates who will primarily work as extension officers across Eritrea, supporting both farmers engaged in traditional production systems and those making the transition to high-value irrigated agricultural enterprises. The mandate of the College is to assist in the achievement of food security for Eritrea through the provision of trained graduates who are actively engaged in the development of Eritrean agriculture at the farm level.

Sound, scientific principles must underpin the new technologies and opportunities that are identified for Eritrean farmers. These can incorporate basic crop monitoring activities by farmer groups centred on village communities (participatory focussed), and the identification of soil and plant characteristics (including sub-soil constraints) and management approaches (incorporating integrated pest management) which need attention.

18.6 Conclusions

Eritrean farmers have, for many of the last 50 years, received only limited support in developing their farming systems, a consequence of extended periods of war, frequent droughts and subsistence-based farming systems. The limited capacity of agricultural research and extension to introduce change has also been a major problem. The Government of Eritrea is committed to building a vibrant rural sector with the first priority food security and the second, generating opportunities for export of agricultural products.

Australian farmers have modernised their agricultural production systems and optimised water use efficiencies through the adoption of conservation farming systems – in conjunction with improved varieties and agronomic practice. This has been achieved through a participatory-based farming systems approach in which farmers have successfully identified and adopted new technologies.

Similarly, Eritrean farmers have adopted participatory approaches to managing their landscapes and farming operations. Examples include the selection of indigenous fodder species, specific plant types for grain production, and communal management of animal grazing. However, pressures on the landscape through increased populations of animals, and the desire to achieve food security are evident. There is now an opportunity to develop a better connection between research, extension and the farming communities, in order to identify, develop and introduce new conservation-based farming practices that will increase crop and fodder production, economic returns and food security.

There is great potential to adopt practices that achieve greater water use efficiency. This process needs to occur within an Eritrean farming systems context that respects local knowledge systems, social networks and constraints. It is evident that Eritrean farmers are resilient and already operate in a highly participatory manner, influenced by village elders and other respected farmers. This provides an ideal environment in which to develop improved farming systems collectively, and address potential barriers to adoption. Research and extension need to work in partnership, and to receive adequate resources, to achieve these outcomes.

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Chapter 19
Rainfed Farming Systems on the Canadian Prairies

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Abstract Agriculture on the Canadian Prairies is less than 130 years old. The Prairies account for 87% of the total cultivated land in Canada. The climate, continental in nature, consists of short summers with warm temperatures and very cold winters. The moisture regime ranges from semi-arid to sub-humid. Water and nitrogen are the factors most limiting to crop production. From the time the first plough turned over the rich prairie sod, soils have lost about 40% of their original nitrogen content because of losses from grain export, degradation from wind and water erosion, and leaching below the root zone-primarily from the use of a fallow-based cropping system. Since the 1980s, there has been a major shift away from fallow-cropping to more diversified systems combined with continuous cropping. Since the early 1990s, a shift to no-till as a result of advances in planting technology and chemical weed control has also made crop diversification and continuous cropping more profitable. These changes in cropping systems have also been shown to improve soil quality. Economically, however, current farming systems are characterised by a high debt-to-asset ratio. The year—year decline in the number of farms has important implications for rural development and the maintenance of

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_19,

infrastructure to support crop and livestock production. The future of Prairie agriculture rests on its ability to adapt to global conditions, and the key to success will depend on the adoption of new business models to address risk management as a function of climate, soils, geographic location, and domestic and international markets. The generation of new technology specific to the Prairies and the integration of livestock and cropping systems are the requirements for ensuring a competitive and sustainable Prairie agricultural industry in the future.

Keywords Crop diversity • Continental climate • Semi-arid • Sub-humid • Conservation tillage • No-till • Risk management • Energy production • Water availability • Nitrogen • Efficiency • Herbicide resistance

19.1 Introduction

19.1.1 Dominant Forces Shaping the Development of Agriculture on the Prairies

Settlement on the Canadian Prairies occurred over a period of 300 years, initially in association with the fur trade. Relative to other parts of the world such as Asia and Europe, agriculture on the prairies is recent – less than 130 years old. From the late 1880s to the 1950s, export of wheat supported building of infrastructure for a developing and expanding Canadian prairie economy. The increase in land planted to grain, mainly spring wheat,[1] barley and oat was rapid (Strange 1954), rising from 0.1 million hectares planted in 1880 to 1.1 million in 1910, 11.6 in 1920, and 30.1 million ha in 2001, where it remains today.

The evolution of agriculture on the Prairies did not progress according to principles of best land use as a function of climate, soils and geography, but according to the government policies of the day. However, the suitability of prairie soils for growing cereals was already recognised in 1889 from measurements of soil organic nitrogen at various locations across the Prairies (Janzen 2001). Unknown factors were the extent of soil heterogeneity in terms of texture, organic matter, topography and parent material, and the extent of climatic variability. The indiscriminate breaking of native prairie, combined with the cultural practices available at the time, resulted in severe land degradation and important losses in soil fertility – effects still noticeable today (Anonymous 1984; Janzen 2001). Within the prime agricultural region of the Prairies, moisture and nitrogen fertility are the major factors limiting crop production, and need to be protected for the long-term fertility of prairie soils.

[1] See Glossary for botanical names.

19.1.2 Extent and Importance of the Prairies for Canadian Agriculture

The Canadian Prairies cover three provinces, Alberta, Saskatchewan and Manitoba, a total area of 1.963 million km^2 of which 18% is under cultivation. The remaining area is not suitable for agriculture.

The Prairies encompass the northern limit of the North American Great Plains, and represent about 87% of the total area under cultivation in Canada. The landscape generally is gently rolling, sloping eastward from an altitude of about 1,200 m on the east side of the Rocky Mountains in Alberta to less than 300 m above sea level in the Red River Valley.

19.1.3 Overview of Climate and Major Soil Zones on the Prairies

The climate of the Canadian Prairies is classified as continental, characterised by long cold winters and short, but warm, summers. Diurnal fluctuations in air temperature are large, with frequent strong winds and a frost-free period ranging from 90 to 120 days. Precipitation is highly variable and unpredictable and, when combined with occasional frosts, these two factors have a large effect on agricultural production and economic risk (de Jong and Steppuhn 1983).

The agricultural portion of the Prairies can be subdivided into four distinct soil zones based on soil colour (Fig. 19.1), which stems from the interaction between native vegetation and climate on pedogenesis (Padbury et al. 2002).

1. The Brown soil zone (Aridic Borolls) (21% of the total agricultural area) occupies the most arid portion of the Prairies. The native prairie is composed of mixed short-grasses. The greatest limitation to crop production is inadequate precipitation with frequent severe droughts.
2. The Dark Brown soil zone (Typic Borolls) (22%) is less arid, originally under mixed prairie varying from short-to tall-grass. Moisture is still limiting but severe droughts are less frequent.
3. The Black soil zone (Udic Borolls) (37%) developed under the fescue prairie–aspen grove parkland vegetation and the true prairie grasslands. Moisture is higher and overall crop production is more consistent.
4. The Dark Gray and Gray wooded soils (20%) occur in the transition between typical prairie and forest. Moisture is adequate, but the growing season tends to be cooler and shorter than in the other soil zones.

Soil textures and moisture regimes within each zone are shown in Table 19.1; most prairie soils have good water-holding capacity. The climate of the Canadian Prairies ranges from semi-arid to sub-humid.

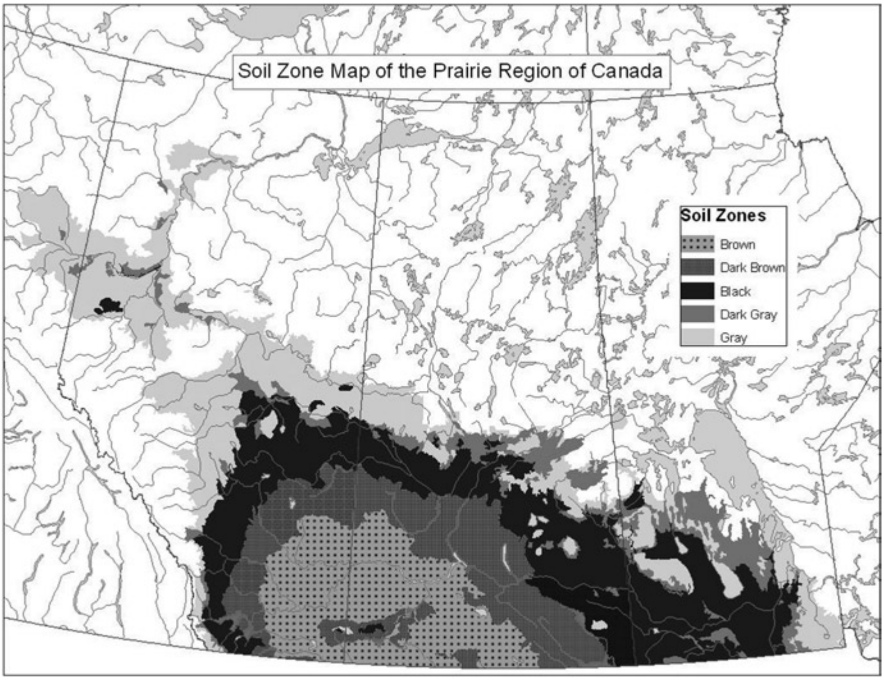

Fig. 19.1 Illustration of the distribution of the various soil zones on the Canadian Prairies

Table 19.1 Mean annual precipitation, potential evapo-transpiration, moisture deficit and predominant soil textures for the various soil zones of the Canadian Prairies

Soil zone	Precipitation[b] (mm)	Potential evapo-transpiration[a,b]	Water deficit[b]	Soil textures[c] Clay (%)	Loam	Sandy
Brown	334	729	395	59	24	14
Dark brown	413	681	268	49	36	12
Black	427	607	180	49	33	13
Gray and dark gray	467	470	3	54	22	11

[a]Based on free water evaporation from open pans using the conversion 0.71 to convert pan values to potential evapotranspiration (Grace and Quick 1988)
[b]From deJong and Steppuhn (1983)
[c]From Anonymous (2007a)

19.2 Development of Cropping Systems on the Prairies

19.2.1 The Beginning

Spring wheat was well adapted to the fertile prairie soils and climate, and quickly became established as the crop of choice for many agronomic and economic reasons, including world demand.

Annual cropping systems on the Prairies involve principally summer production. Planting starts in April and is usually complete by the end of May. Harvest starts in mid-late August and is usually finished by mid-October, depending on the crop grown and planting date. Prairie producers can also grow a few winter crops, e.g. winter wheat and fall rye. These are usually planted in the first 2 weeks of September and harvested the following year, starting in early August.

The early establishment of Experimental Farms after 1886 provided a unique benefit. As stated by Janzen (2001), "When the ploughs began to invert the prairie sod, scientists were already there to record the effects. And from the onset, preserving the soils was a priority." Over the next 20 years, extensive and detailed measurements of soil organic matter led Shutt (1905 in Janzen 2001) to report on its rapid decline and raise concerns about the 'permanence', now referred to as 'sustainability', of agriculture on the Prairies. Mitchell et al. (1944) reported that uncultivated soils contained from 0.2% to 0.7% nitrogen (oven-dry soil basis) and that, by the 1940s, 15–40% of it had been lost. This trend has continued so that, by the 1980s, most soils had lost more than 40% of their initial nitrogen.

19.2.2 Emerging Problems with Agricultural Sustainability on the Prairies

The importance of soil organic matter for crop growth and soil health had been well established. The rapid decline in soil organic matter was attributed to the fallow–wheat cropping system although this system allowed for water conservation, weed control, the conversion of soil organic N into mineral N and low production risks. Although its flaws were recognised in the early 1900s, the fallow–crop system persisted in most areas of the Canadian Prairies until the 1970s (Janzen 2001) because of the use of fallow for weed control and the lack of conservation tillage technology.

The fallow–wheat cropping system promoted the decomposition and loss of soil organic matter while the 'summer' bare fallow of 21 months made soils prone to wind and water erosion. In addition, the stationary threshers of the day resulted in the removal of most of the above-ground portion of the wheat plant to where it was processed in one part of the field. The remaining straw from the harvesting operation was not redistributed over the entire field; some was used for animal feed and bedding, but most was burnt.

The infamous 'Dust Bowl' of the 1930s is testimony to the negative aspects of summer fallow practices. It resulted in the re-settlement of more than 10,000 families to the northern fringe of the Prairies (Black and Gray soil zones) with its more reliable precipitation (MacEwan 1986). However, they brought the practice of fallow-cropping with them and perpetuated it over an even greater area. In the Black soil zone, summer fallow was used more for weed control and nitrogen mineralisation than for moisture conservation.

19.2.3 Improvements in Technology Lead to Changes in Farming Systems

Technologies such as the one-way disc planter allowed fallow–wheat cropping to extend to a fallow–wheat–wheat system and even to some intermittent continuous cropping. The introduction of the broadleaf herbicides 2,4-D[2] in 1947 and MCPA in 1953 were followed by the wild oat herbicides, diallate and later triallate, in the early 1960s (Timmons 2005; Appleby 2005) along with appropriate herbicide application technology (Holm 1992). Introduction of inorganic nitrogen and phosphorus fertilisers further increased the potential of continuous cropping and the movement away from fallow-cropping systems.

The 1970s and 1980s also saw a rapid increase in the introduction of new classes of selective herbicides for both cereal and broadleaf crops, which allowed for more continuous cropping. In the late 1970s, the introduction of air-seeding tine implements provided a means of planting through surface crop residues and was an important first step towards the wider adoption of conservation tillage[3] and continuous cropping. These technologies helped protect the soil from erosion and improved soil water conservation (Memory and Atkins 1990). The appearance of the non-selective herbicide glyphosate in the late 1970s and early 1980s encouraged an even greater expansion of conservation tillage and the first real opportunity to test and later adopt no-till cropping practices on a wide scale (Appleby 2005).

In the mid-1990s, the introduction of herbicide-resistant canola allowed for improved weed management along with other important economic and environmental benefits such as controlling weeds resistant to certain classes of herbicides (by the use of glyphosate) and reducing overall herbicide use (Beckie et al. 2006).

The extra soil moisture conservation resulting from no-till and the full retention of crop residues on the soil surface allowed greater diversity of crops including pulses (Zentner et al. 2001). The use of conservation tillage allowed for more successful establishment of shallow-sown crops such as canola because of better surface soil moisture at planting. All these technologies permitted the gradual elimination of fallow cropping across all areas of the Prairies, but especially in the drier Brown and Dark-Brown soil zones. A decline in summer fallow area occurred in all Provinces between 1981 and 2006 as shown in Table 19.2.

Table 19.2 Change in summer fallow area on the Canadian Prairies (1981–2006) (From Anonymous 2007b)

Year	Saskatchewan	Alberta	Manitoba
	'000 ha		
1981	6,677	–	635
1991	5,713	3,760	250
2001	3,156	1,255	240
2004	3,298	890	214
2006	2,428	753	127

[2] See Glossary for chemical details of herbicides.

[3] See Glossary for definitions.

Table 19.3 Change in area dedicated to the various crops grown in Saskatchewan (1981–2005) (From Anonymous 2007b)

		1981	1991	2001	2005
Crop	Species	'000 ha			
Spring wheat	*Triticum aestivum*	6,414	6,982	4,330	3,638
Durum	*Triticum durum*	1,396	1,589	1,740	3,197
Barley	*Hordeum vulgare*	1,518	1,343	1,862	1,943
Oat	*Avena sativa*	587	3,357	789	809
Canary seed	*Phalaris canariensis*	23	87	146	182
Canola	*Brassica napus*	546	1,359	1,922	2,671
Flax	*Linum usitatissimum*	101	220	473	656
Mustard	*Brassica juncea* and *Sinapis alba*	52	82	133	180
Field pea	*Pisum sativum*	16	179	696	1,091
Lentil	*Lens culinaris*	34	179	696	874
Planted forages	–	688	984	1,518	1,639

Over the same period, the area planted to spring wheat decreased, while the area for oilseed crops, such as flax and canola, and pulse crops, such as field pea and lentil, increased many fold, as demonstrated for Saskatchewan in Table 19.3.

19.2.4 The Current Basis for the Future

The continued investments in infrastructure on the Canadian Prairies in terms of roads, inland grain terminals, and agricultural research facilities (three universities with agricultural faculties and 11 federal research centres) combined with good access to machinery and crop input suppliers provide a sound basis for sustained agricultural development and the foundation for future innovation. The Canadian Prairies are now well diversified in terms of crop and animal husbandry, and this diversification can lead to new economic opportunities.

A major challenge facing agriculture is increasing freight costs because most production is exported. This involves the export of nutrients and increasing production costs to replace them. There is a strong effort to increase value-added processing in enterprises such as animal feeding, packing houses and biofuel production. Other value-adding opportunities tend to be smaller in scale and impact only a small number of farms.

19.3 Structure and Operation of Current Farming Systems on the Canadian Prairies

Describing the major farming systems of the Canadian Prairies is a challenging task given the breadth of its climate, soils and topography. However, one can get some appreciation of the major farming systems by examining the per-centages of farm types and the changes that have occurred from 1981 to 2006 (Table 19.4).

Table 19.4 The distribution of farm types (percentage) with gross receipts exceeding $2,500 CDN per year for the years 1981, 1991, 2001 and 2006 for the three Prairie provinces (Taken from Anonymous 2007b)

Province	Farm type	1981	1991	2001	2006
Manitoba	Dairy	6.8	5.0	2.7	2.4
	Cattle (beef)	21.4	21.2	34.1	34.6
	Hog	3.8	5.2	4.7	4.0
	Crop	57.1	57.8	43.4	42.3
	Other	10.9	10.8	15.1	16.7
Saskatchewan	Dairy	2.5	1.3	0.6	0.5
	Cattle (beef)	11.0	15.4	24.1	27.6
	Hog	1.0	1.3	0.6	0.5
	Crop	80.1	76.6	67.0	61.7
	Other	7.9	6.7	7.7	9.7
Alberta	Dairy	5.4	2.6	1.4	1.2
	Cattle (beef)	31.5	41.4	42.9	41.5
	Hog	2.7	3.1	1.7	1.2
	Crop	48.8	39.8	34.6	34.1
	Other	17.0	13.1	19.4	22.0

Adapted from Statistics Canada Website:
For Manitoba: http://www40.statcan.gc.ca/l01/cst01/agrc35h-eng.htm
For Saskatchewan: http://www40.statcan.gc.ca/l01/cst01/agrc35i-eng.htm
For Alberta: http://www40.statcan.gc.ca/l01/cst01/agrc35j-eng.htm

19.3.1 Dairy Farming System

The number of dairy farms has decreased in all three Provinces because of consolidation. Although the total number of dairy cows has decreased, overall production has increased slightly as a result of advances in herd health, nutrition, genetics and dairy technology. The larger dairy operations are usually self-contained family operations with enough land (leased or owned) for producing forages and annual crops for fodder, silage or feed grain to meet most of their feed needs. The wastes are then recycled on the land. This type of operation provides numerous options for crop rotation, soil fertility improvement and pest management. It results in a healthier soil resource and the potential for reduced inorganic fertiliser and pesticide use over time. The total amount of nutrients exported from this farming system in the form of milk is lower than from grain-only farming systems.

19.3.2 Hog Farming Systems

The proportion of farm types dedicated to pork production has decreased in Alberta and Saskatchewan since 1981, but has remained fairly constant in Manitoba (Table 19.4). The decreases indicate consolidation and adoption of new business models; fewer hog operations are part of the more traditional farm. However, hog numbers have increased in Alberta and Saskatchewan since 1991 even though the total number of hog farms has decreased (Anonymous 2006c). In Manitoba, the number of hogs per operation increased because of geographical advantages – for example, proximity of feed grains and easier access to continental markets. Unlike the dairy operations, most hog operations on the Prairies do not produce their own feed but purchase it directly from feed suppliers. Thus, a large number of these types of operations are not integrated into farming systems.

With larger units, manure disposal remains an issue. Enough land needs to be available to dispose of it in an environmentally sustainable way. The development of bio-gas units may also provide a more concentrated product and allow transport for longer distances. There is also a limited move towards raising hogs in a more traditional method by using straw bedding and composting the straw.

Although hogs cannot use forages, they can utilise by-products from the processing of milk, canola, soybean, corn and wheat in the brewing and distilling industry, and also low-quality grains from adverse weather conditions. This avoids the need to dispose of these by-products into landfills and thereby create other potential environmental hazards.

19.3.3 Beef Cattle Farming Systems

More recently, an increase in cow–calf operations has been observed in all Provinces. This is reflected, for example, in the increased area planted to perennial forages in Saskatchewan (Table 19.3). This major shift in farming systems was motivated in large part by a change in transportation policy (Vercammen et al. 1996). Since 1996, producers have had to absorb the full cost of grain transportation from the farm to the ocean ports, which has made the production of certain crops less economical. It may also be a reflection of declining soil fertility. As soil degrades, it becomes too risky for crop production and is, therefore, planted to forage species for grazing.

As a rule, beef cattle production is integrated with annual cropping in a mixed farming system over most of the Prairies. The exceptions are the south-west portion of Saskatchewan, the south-east portion of Alberta and the foothills of the eastern Rocky Mountains in Alberta. In those areas, large tracts of native pastures remain and support beef-only farming systems.

The beef cattle component of mixed-farming operations varies with farm and geographical location. The more northerly fringes tend to have a greater proportion of beef cattle because of higher crop production risks, resulting from an overall shorter growing season. The integration of beef farming with annual crop farming provides many opportunities. Permanent forages can be included in cropping systems for grazing and as a source of hay, with the former less exhaustive of soil nutrients. New bloat-combating technologies allow the direct grazing of alfalfa, which reduces the dependence on inorganic nitrogen to sustain forage productivity.

However, since administration of these substances to grazing animals can be difficult, the adoption has been limited to high-intensity grazing systems. Including forages in annual cropping systems can improve crop yields (Entz et al. 2002) and reduce the dependence on herbicides (Ominski et al. 1999). In the early 2000s, 5–15% of the arable cropland was being rotated with forages (Entz et al. 2002). Short-term rotations with timothy grass (*Phleum pratense*) or alfalfa for the export hay market have been adopted on farms with irrigation in the dry areas and to a limited extent in the wetter areas. Most hay production for beef cattle is based on a grass–alfalfa mixture. The most common grass species for hay production are brome grass (*Bromus* spp.) in moist areas and crested wheat grass (*Agropyron desertorum*) in drier areas. Much of the 'permanent' hay and pasture is on land not suited to annual cropping because of low water-holding capacity, excess water, extreme slopes or rocks (Padbury et al. 2002).

19.3.4 Annual Crop Farming Systems

The number of cropping farms (Table 19.4) has declined in all provinces as farm size has increased. In general, the grain farm systems of the early 1970s were dedicated to one or two crops only, with a high proportion of fallow. Now cropping is being diversified, with cereal (spring and winter wheat, barley, oat, durum, rye and triticale[4]), oilseed (canola, flax, mustard and sunflowers) and pulse crops (field pea, lentil and chickpea and to a limited extent, faba bean). Most annual crop farming systems on the Prairies now incorporate between three and six crop types each year.

This diversification provides many opportunities for flexibility of crop rotation, to address issues of pest and soil fertility management, and to provide better economic and risk management. It allows for a greater range of herbicides for more effective weed control and also greatly reduced resistance to certain groups of herbicides (Beckie 2007). Moreover it reduces the impact of soil-borne plant diseases (Bailey et al. 1992, 2001).

The ability to grow both spring crops (cereal, oilseed and pulse) and winter crops (cereal) in all soil zones is unique to the Prairies of Canada and the north central areas of Europe and Asia, compared to other rainfed areas of the world. Winter cereals take advantage of early spring soil moisture, provide competition against grassy weeds such as wild oats (*Avena fatua*) (Schwerdtle 1983), and allow an extended harvest season. Winter crops such as fall rye have been shown to reduce the potential for nitrate leaching below the rooting zone even when grown on fallow[5] (Campbell et al. 2006). The wide diversity of annual spring crops gives prairie farmers the ability to adjust their cropping systems easily to changing market conditions without disrupting their basic crop rotations.

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[4] See Glossary for botanical names.

[5] Wheat following a fallow phase.

No-till farming with full stubble retention reduces soil degradation and nutrient loss from wind and water erosion. However, crop-only farming systems export nutrients in their products; Doyle and Cowell (1993) estimated that, between 1965 and 1989, there was an overall negative balance of 24, 2.2 and 15 kg/ha/year for nitrogen, phosphorus and potassium respectively on the Canadian Prairies. An important challenge for annual crop farming systems is to reduce nutrient losses from this system.

19.3.5 Summary of Prairie Farming Systems

The major feature of Prairie agriculture is diversity. This diversity is seen in the variation in the types of crops grown and the livestock operations. In 2006 in Manitoba, the percentage of farms dedicated to livestock operations were 41% and to crops 42%, while in Saskatchewan the proportions were 29% and 62% and in Alberta 44% and 34%, respectively. The difference in proportion among Provinces is a reflection of differences in transportation costs and factors related to climate and soil type. Another recent feature of Prairie agriculture is the rapid adoption of no-till for the management of annual cropping systems. Future directions for Prairie farming systems are discussed in Sect. 19.7.

19.4 Achieving Efficiency, Productivity and Sustainability

Efficiency, productivity and sustainability can only be achieved in an environment that encourages and rewards investment in new technologies and ideas. To achieve this, Prairie agriculture must be able to compete with other industries, such as oil and gas or pharmaceuticals, for public and private investment. To be sustainable, agriculture must be adaptable and flexible enough to change what is produced and how it is produced in response to changing markets, climate and other external factors, and to address problems arising within the industry.

Although the overall land area of the Canadian Prairies is vast, only a small proportion of our soil is suitable for agriculture. For this reason it is critical that we conserve and, when possible, enhance the productivity of agricultural soils. Within the agricultural land base, water and nitrogen are the two principal factors limiting crop production. Advances in crop production are directly related to how efficiently water and nitrogen are managed and how the supply of one is matched with the other.

Food, feed and fibre production are capital-intensive industries with historically very low margins and rates of return. In order to sustain a profitable industry, attention has to be focused on efficiency and productivity. The development of a sustainable agricultural industry from a resource and energy perspective will only be possible if the industry is economically viable.

Pimentel and Pimentel (2000) estimated that 99% of food consumed by humans comes from the land. Every year, 2–12 million hectares or 0.3–0.8% of the world's arable land is rendered unsuitable for agricultural production through soil degradation, with wind and water erosion accounting for 84% of this (den Biggelaar et al. 2004a). Thus, good management to protect the soil against degradation and sustain long-term productivity is imperative for meeting the world's future needs for food and fibre (den Biggelaar et al. 2004b) and now energy.

The challenge for Canadian agriculture is to ensure economic viability while both satisfying society's need for safe and nutritious food and conserving or enhancing the environment for future generations (Gilson 1989). Sustainable development has been defined by Brundtland (1987) as: "economic growth that meets the needs of the present without compromising the ability of future generations to meet their own needs". At the 2002 Earth Summit on Sustainable Development held in Johannesburg, this definition was broadened and strengthened by linking global poverty, the environment and the use of natural resources to sustainable development (Anonymous 2002). The above goal and enhanced definition of sustainable development provides the context of how rainfed agriculture needs to evolve on the Canadian Prairies. Sustainable development is also the cornerstone of government policy in Canada.

19.4.1 Addressing Soil Degradation and Loss of Soil Fertility on the Prairies

Three forces came together in the late 1970s to address the issue of rapid soil degradation and the long-term decrease in soil organic matter (Lafond 2003).

The first was the vision and determination of a group of producers on the Prairies who took it upon themselves to show that it was possible to protect the soil and remain economically viable. This led initially to the creation of informal producer groups and later more formal associations such as the Manitoba-North Dakota Zero Tillage Farmers Association, the Saskatchewan Soil Conservation Association and the Alberta Conservation Tillage Society. These associations provided a forum for the exchange of ideas on issues pertaining to conservation tillage.

The second force was policy. In 1984, the Standing Committee on Agriculture, Fisheries and Forestry presented its report on soil conservation to the Senate of Canada (Anonymous 1984). This report outlined the extent of soil degradation in all regions of Canada, the lack of awareness of this problem and the increasing danger of losing a large portion of agricultural capability unless a major commitment was made to conserving the soil. The report led to the creation of important soil conservation programs – the National Soil Conservation Program (NSCP), the Environmental Sustainability Initiative, the Save our Soils (SOS) program, the Green Plan program and more recently the Environmental Farm Plan program. These programs, combined with increased research activities at both the federal and

Table 19.5 The percentage of cultivated area using no-till as the primary soil and crop management practice on the Canadian Prairies from 1991 to 2006[a]

Year	Saskatchewan	Alberta	Manitoba
1991	10	3	7
1996	19	10	15
2001	39	27	13
2006	60	48	21

[a]Taken from McClinton 2007 and B. McClinton, personal communications, executive director with the Saskatchewan Soil Conservation Association (www.ssca.ca)

provincial levels, provided the framework necessary to make conservation tillage (full surface soil disturbance but with a minimum of 30% residue cover) and no-till[6] (no-tillage and full stubble retention) a reality on the Canadian Prairies. The SOS program in Saskatchewan provided awareness and gave producers first-hand experience with conservation tillage practices through a combination of on-farm demonstrations, access to no-till planting equipment for limited land areas, and local and regional conferences, symposiums and trade shows.

The third force was the integration of key technologies such as appropriate planting equipment, non-selective herbicides, crop diversification, knowledge, experience, confidence and applied research in no-tillage (Lafond et al. 1997).

The noticeably small amount of damage from wind erosion over a large area of the western Prairies during the droughts of 2002 and 2003 is testimony to the progress made in the last 20 years. Yet, despite the greater adoption of no-till cropping techniques, especially in Saskatchewan, even more adoption of no-till is needed to protect soils against wind and water erosion and sustain soil fertility in the long term (Table 19.5).

19.4.2 Enhancing Crop Water Use Efficiency

19.4.2.1 Dynamics of Water in Rainfed Farming Systems on the Prairies

The relationship between biomass production and transpiration is well recognised (deWit 1958 in Taylor et al. 1983). This relationship implies that the more water is available for transpiration, the more biomass can be produced through better support of photosynthesis – assuming nutrients are not limiting. In the rainfed cropping system of the Prairies where growing season moisture deficits are the norm, not all precipitation is available for transpiration. Water is also lost through evaporation at the soil surface (dominant pathway), surface runoff and deep drainage (minor pathways).

[6]These terms are used differently in different countries. These definitions apply to the Canadian Prairies. See Glossary.

The ratio of potential evapo-transpiration to precipitation ranges from 2.2 in the Brown soil zone to 1.4 in the Black soil zone (Table 19.1).

On the Canadian Prairies, two-thirds of annual precipitation normally falls in the April to September growing season with half of this falling in June–July, the critical period of crop development. Thus, one-third of precipitation falls outside the growing season as a combination of rain and snow.

19.4.2.2 Strategies to Increase Crop Water Use on the Prairies

The obvious strategy to increase crop water use is to increase the availability of precipitation for crop transpiration. The early practice of summer fallowing resulted in more water being available for a crop after fallow compared with after another crop, but the overall efficiency of rainfall conserved was low. During the 21-month fallow period, only about 25% of the precipitation was stored in the Brown soil zone and about 10% in the Black soil zone (deJong and Steppuhn 1983) because of losses due to overall evaporation as well as evaporation from cultivation for weed control, from weed growth and from runoff.

When herbicides are used (chemical fallow) rather than tillage to control weeds, there may be a small increase in soil moisture storage, with less in Black soils than in Brown (Lafond et al. 1996) or no difference (deJong 1990). Although tillage in the fall was once thought to save water by controlling weeds and improving water infiltration from snow melt, research has now shown that this is not so in any soil zone (Lal and Steppuhn 1980).

The poor water storage efficiency of fallowed soil, whether tilled or managed with herbicides, shifted emphasis to developing methods to encourage water storage for continuous cropping. It had been observed that, in many years, soil water levels were similar in cultivated fallow and stubble fields at sowing (deJong 1990). This was thought to be because snow was an important source of soil water recharge between crops, given that about one-third of the total yearly precipitation falls during the September–April period (deJong and Steppuhn 1983).

The benefits of surface residues and standing stubble for trapping snow, reducing soil evaporation losses, and protecting the soil against wind and water erosion are well known. Smika and Unger (1986) in a review reported that soil with 4.5 t/ha of straw left on the surface stored 40% more of the precipitation during the April to September period than when the same amount of residues was disced-in. The improved soil moisture conservation with no-till explains the observed increase in yield for the Black and Gray soil zones. In these soils, the average increase in soil moisture with no-till is around 10–15 mm. The reason for these observed low levels of water conservation is that snowmelt infiltration is inversely related to the soil moisture (ice) content of the 0–30 cm soil layer at time of snow melt (Gray et al. 1984).

The yield increases with no-till have been less consistent in the Brown and Dark Brown soil zone due to inconsistent increases in soil moisture as a result of more variable precipitation and higher soil drying potential (Lafond and Fowler 1990; Lafond et al. 1996, 2006).

The lower soil water conservation in the Brown and Dark Brown soil zones is due to (i) the limitations to infiltration by the freezing soils (ii) the lower overall residue production and (iii) the periodic warm 'chinook' winds that can occur during the winter months and encourage snow melt and sublimation. Further, the time interval between the end of snow melt and the start of planting is longest in the Brown soil zone. Together, these factors result in higher water losses from evaporation, in Brown and Dark Brown soils, which can exceed the amount of water conserved from snow melt.

One of the first proposed methods to increase moisture conservation in the Brown soil zone was to increase snow capture by snow ridging (deJong and Steppuhn 1983). This method involved creating ridges 2–3 m apart perpendicular to the prevailing winds to increase surface roughness and encourage snow trapping. However, the value of this approach is highly dependent on available snow; it incurs extra financial and energy costs and the losses from sublimation and wind action can be fairly high. Another proposed method of trapping snow was to create vegetative shelterbelts or trap strips of permanent grass (McConkey et al. 1990) usually spaced 15 m apart. Although effective in increasing soil moisture storage, they require much effort to establish and maintain.

Standing stubble, preferably more than 30 cm tall was found to be the most efficient way to increase soil water from snow (Campbell et al. 1992). Sculpturing alternating strips of high and low stubble at the time of swathing or harvesting in the Brown soil zone increased snow trapping by 20–30% over even height stubble. This was translated into an average increase of 13 mm of extra soil moisture. The combined effects of sculptured/standing stubble and surface residue retention in increasing soil moisture may improve the economic opportunity for continuous cropping, especially for the drier areas of the Prairies (Zentner et al. 2001).

Although the net amount of soil moisture conserved with no-till, 10–15 mm on average, is not large regardless of soil zone, these increases are critical for crop establishment. No-till allows for more uniform emergence and shallow planting without the need for rainfall after sowing. Under conventional tillage, the need for cultivation to control weeds can result in excessive drying of the surface soil. This can make establishing small-seeded crops such as canola difficult and highly dependent on follow-up rainfall. Waiting for rain to promote crop emergence is synonymous with delayed planting – which carries a yield penalty. It also reduces the ability of crops to emerge before weeds, a critical element of crop competition against weeds (O'Donovan et al. 2005).

19.4.2.3 Strategies to Increase Crop Water Use Efficiency (WUE)

Water Use Efficiency as used in this chapter is simply defined as grain yield (kg/ha) divided by the difference in soil water at the start and end of the cropping season plus the rainfall during the period. WUE and associated terms are defined and discussed extensively in Chap. 1. WUE is affected by the cropping system: sowing on fallow is better than sowing on stubble in the drier Brown soil zone (Steppuhn and Zentner 1986) but not in the Black soil zone (Lafond et al. 2006).

WUE can also be affected by:

- Crop species – values of 8.3 ± 0.84(SE), 5.4 ± 0.37, 9.1 ± 0.25 kg/ha/mm have been obtained for field pea, flax and wheat respectively (Lafond et al. 2006) reflecting differences in growth habit, inherent yield potential, energy content of the seed (oilseeds have higher energy levels per kg and thus require more photosynthate to produce a kg of seed) and depth of rooting. The higher variation in WUE for flax and field pea relative to spring wheat is a function of their shallower rooting habits.
- Crop type – wheat genotypes with winter habits have shown increases in WUE of about 26% over spring types (Gan et al. 2000).
- Crop rotation – spring wheat on field pea stubble (7.7 kg/ha/mm) had higher WUE than spring wheat on spring wheat stubble (7.0 kg/ha/mm), and winter wheat on flax stubble (10.4 kg/ha/mm) had a higher WUE than winter wheat on spring wheat stubble (9.0 kg/ha/mm) (Lafond et al. 2006).
- Tillage practices – flax grown under no-till had a higher WUE than on conventional tillage (5.4 vs. 4.9 kg/ha/mm) (Lafond et al. 2006).
- Soil fertility – especially nitrogen, which promotes the growth of roots and shoots and allows the plants to explore the available soil water in the root zone more effectively (Henry et al. 1986).

WUE in the dry areas of the Prairies can be increased by planting the crops in stubble more than 30 cm tall. This reduces wind speed near the soil surface by two thirds; such reduction minimises water losses through evaporation and makes more of the soil water available for plant transpiration. WUE in spring wheat, pulses and canola was increased by 12%, 16% and 11%, respectively by this treatment (Cutforth and McConkey 1997; Cutforth et al. 2002, 2006).

WUE can also be improved simply by employing the best agronomic practices (e.g. planting rates, planting dates, fertiliser rates and types, choice of cultivars, crop rotations, tillage systems, pest management, and timing of various agronomic treatments) which are almost entirely under the control of the producer. Total amount and timing of rainfall will also affect water use efficiency.

19.4.2.4 Factors under the Control of Prairie Grain Producers that affect WU and WUE

Water is lost from cropping systems through evaporation at the soil surface, surface run-off and drainage below the root zone. Thus, grain producers need to adjust production practices to increase water conservation, make more water available for crop growth, and use it more efficiently (see also Chap. 4). Table 19.6 identifies the relevant factors that are under the control of producers. The best opportunity comes from a no-till continuous cropping system involving tall (>30 cm) stubble and full surface residue retention.

Table 19.6 List of factors under the control of producers to enhance crop water use and crop water use efficiency

Factors	How are they controlled?	What is the effect?
Surface runoff of water	Full stubble and crop residue retention at the soil surface using a no-till production system	Improved water infiltration by minimising the impact of raindrops on soil aggregates, thereby increasing the availability of soil water to the crop.
Evaporation losses of soil water	Tall stubble with full crop residue retention at the soil surface using a no-till production system	Reduced wind speed at the soil surface reduces evaporative losses and ensures more water near the soil surface for crop establishment and growth
Residue amount	Even spread of crop residues on the soil surface by using appropriate technology on harvester-threshers	Improved ease of planting to ensure proper seed to soil contact and uniform depth of seed placement
Long-term soil organic matter	Prevent wind and water erosion combined with continuous cropping using a no-till production system	Improved soil health by ensuring continual carbon input into the soil system while minimising soil organic carbon losses
Crop nutrition and agronomy	Adjust inputs of inorganic fertilisers and employ the best agronomic practices for each specific crop according to soil type, regional climatic condition and available water.	Optimum economic returns
Pests and diseases	Crop rotation, trap strips	Minimised impact of plant diseases, weeds and insect pests
Soil degradation	Prevent wind and water erosion	Sustained long-term fertility of the soil
Tillage system	Adoption of no-till system	Long-term benefits of increased soil organic matter and the elimination of soil degradation
Crop rotation	Avoid planting crops into their own stubble and alternate between cereal, oilseed and pulse crops	Reduced impact of pests, enhanced productivity of crops and improved economic returns

19.4.3 Nitrogen Use Efficiency

Nitrogen is the nutrient that is most limiting to crop production in Prairie rainfed systems and the one applied in greatest amounts. Appropriate nitrogen use improves not only crop yield but also production of residues which, if retained, improve the physical properties and water-holding capacity of the soil, soil organic matter content and the re-cycling of nitrogen and other nutrients (Zentner et al. 1992a, b; Campbell et al. 1996). Higher nitrogen fertiliser use can affect greenhouse gas emissions by increasing nitrous oxide production (Liebig et al. 2005). Nitrogen fertilisers (which take large amounts of energy to manufacture) also represent 65–70% of the total energy input for crop production on the Prairies (Zentner et al. 2004b). Nitrogen use efficiency (NUE) is therefore important and can be maximised by minimising losses and waste of applied N.

NUE for crop production in Western Canada ranges from 50% to 70% (Malhi et al. 2001) and world-wide about 33% (Raun et al. 2002). Nitrogen management on the Prairies aims to synchronise a crop's needs for nitrogen with its availability (concept of just-in-time) and to minimise any potential losses. Prediction of nitrogen requirements in semi-arid areas is difficult because of uncertainty in predicting available moisture, and also temperature.

19.4.3.1 Nitrogen Forms, Timing and Placement

The principal forms of nitrogen fertiliser used on the Prairies are urea, followed by liquid urea ammonium nitrate (UAN or nitrogen solution) and anhydrous ammonia – except in Alberta where ammonium sulfate and ammonium nitrate are more common than UAN. Ammonium nitrate, a dry granular product, is no longer sold in bulk in Western Canada, which means an even greater shift to other forms of N fertiliser (Table 19.7).

Spring application is by far the most common timing for all forms of nitrogen. In the case of anhydrous ammonia however, about 30% is applied as an in-soil band in the fall after harvest, before the soil freezes (Table 19.8).

Table 19.7 Total nitrogen fertiliser use ('000 tonnes) and percent by fertiliser form for each Prairie Province in 2005

Nitrogen form	Alberta	%	Saskatchewan	%	Manitoba	%
Urea	480.0	55.7	540.5	49.7	200.8	38.8
Ammonium sulfate	148.2	17.2	135.7	12.5	60.4	11.7
Ammonium nitrate	62.1	7.2	13.9	1.3	9.2	1.8
Anhydrous ammonia	143.6	16.7	173.7	16.0	112.4	21.7
Nitrogen solution[a]	27.9	3.2	224.0	20.6	134.7	26.0
Total	861.9		1,087.8		517.6	

[a]Nitrogen solution refers to liquid urea-ammonium nitrate (UAN) (Anonymous 2006a)

Table 19.8 The timing of fertiliser application for the various nitrogen fertiliser forms as a percent of the total number of farms based on the 2001 census of agriculture for the three Prairie Provinces

Nitrogen form	Spring	Summer	Fall
Urea	90.4	1.8	7.8
Ammonium sulfate	91.7	1.0	7.2
Ammonium nitrate	89.7	3.6	6.7
Anhydrous ammonia	69.9	0.2	29.9
Nitrogen solution[a]	87.5	4.6	8.0

[a]Nitrogen solution refers to liquid urea-ammonium nitrate. (Korol 2004)

Adapted from statistics Canada publication fertiliser and pesticide management in Canada, Catalogue 21-021, 2004, Vol. 1, No. 3, page 20, http://www.statcan.gc.ca/pub/21-021-m/2004002/pdf/4193745-eng.pdf

Table 19.9 The method of nitrogen fertiliser application for the various nitrogen fertiliser forms for each of the three Prairie Province as a percent of the total number of farms, based on the 2001 census of agriculture (Korol 2004)

Nitrogen application	Alberta	Saskatchewan	Manitoba
Broadcasting (spring)	27.5	8.8	26.3
Banded (at time of planting, or pre-planting)	18.3	20.6	19.6
Applied with seed	41.4	57.7	39.9
Post-plant and top dressing	1.0	1.0	1.6
Knifed-in (fall or pre-planting)	10.2	10.7	11.3
Other	1.6	1.1	1.3

Adapted from Statistics Canada publication *Fertilizer and Pesticide Management in Canada, Catalogue 21-021, 2004, Vol. 1, No. 3, page 15,* http://www.statcan.gc.ca/pub/21-021-m/2004002/pdf/4193745-eng.pdf

Fertiliser is most commonly applied at the time of planting followed by broadcasting on the soil surface (broadcasting is used infrequently in Saskatchewan) (Table 19.9). The relatively high proportion of broadcasting in Alberta and Manitoba reflects the higher proportion of non-legume forages relative to annual crops.

Nitrogen losses can be minimised by applying N as close to the time of crop needs as possible. Most nitrogen fertiliser is applied in the spring either at or before planting, with less than 2% applied after planting. Reducing the time from application to time of maximum crop uptake and placing the fertiliser in the soil (rather than on the surface) can significantly reduce potential losses of nitrogen and emissions of nitrous oxide.

19.4.3.2 Major Pathways of Nitrogen Losses

There will always be some nitrogen losses through volatilisation, immobilisation, denitrification and leaching (Tisdale et al. 1985). Ammonia-based fertilisers such as urea or UAN can volatilise when placed on the soil surface or in bands that do not close properly because of wet soil conditions. This occurs particularly in clay-textured soils and under no-till conditions with crop residues on the soil surface. Urease enzymes occur widely on the surface of crop residues as well as in the soil.

Immobilisation can occur if large amounts of crop residues with carbon/nitrogen (C/N) ratios above 15 are incorporated into the soil. Under these conditions, the nitrogen is not necessarily lost from the soil system but temporarily unavailable.

Denitrification occurs when the residual nitrate levels are high in the surface soil layers and soils are wet with low oxygen levels. Such losses can be significant on the Prairies during the spring thaw and the extent of the losses will also be influenced by soil texture and landscape position. Application of N fertiliser in the fall increases the potential for nitrification because of suitable soil temperatures prior to soil freezing (Malhi and Nyborg 1979; Malhi and McGill 1982; Malhi and Nyborg 1984). Once N is in the nitrate form, winter and/or early spring losses from denitrification can be significant (Malhi and Nyborg 1983; Malhi et al. 1990; Nyborg et al. 1990, 1997). Nitrification can be inhibited when urea is banded or nested to create high concentrations of ammonium (Malhi and Nyborg 1985; Yander-Singh et al. 1994). High ammonium concentrations resulting from banding, nesting or nitrification inhibitors limit the microbial conversion of ammonium to nitrate. Thus denitrification is reduced and fertiliser recovery from fall applications is improved.

Leaching is more of an issue in fallow than with continuous cropping systems and with coarse-textured soils. Placing the ammonia-based nitrogen fertilisers in the soil greatly minimises the potential for volatilisation losses.

Therefore the major pathways of potential nitrogen losses on the Prairies are firstly denitrification and secondly short-term immobilisation, the latter depending on the amount of, and the C/N ratio, of the residues.

19.4.3.3 Factors Affecting Nitrogen Use Efficiency

Nitrogen use efficiency (NUE) is defined here and measured by the relationship *((N uptake for treatment – N uptake of control) / (N fertiliser applied) x100).* NUE is influenced by such factors as the inherent fertility of the soil, climate, tillage practices, crop rotations and rates of nitrogen used (Malhi et al. 2001). Soils with low levels of potentially mineralisable nitrogen (that is low soil organic matter and a low level of rapid cycling organic matter) tend to have higher NUE than soils with high levels because they respond more efficiently to applied nitrogen at low nitrogen rates (Stevens et al. 2005).

In a comparison of nitrogen forms, placement, timing and rates in different soil zones, NUE decreased with increasing rates of applied nitrogen in the Brown, Black and Gray soil zones, but remained constant in the Dark Brown soil zone (Thavarajah 2001). Provided the nitrogen fertiliser was placed in-the-soil as opposed to on-the-soil, fertiliser form and placement relative to the seed had little effect on NUE. Prolonged periods of moist surface soil, combined with warm temperatures, result in high levels of mineralisation of organic N. This reduces the difference in nitrogen uptake between the control treatments (no nitrogen applied) and the treatment receiving nitrogen, resulting in lower estimates of NUE for the above formula.

19.4.3.4 Strategies to Improve Nitrogen Use Efficiency

The obvious strategy for the Canadian Prairies to ensure efficient use of nitrogen is to apply nitrogen fertiliser as close as possible to the time of maximum crop uptake and to use a rate that matches crop needs as a function of soil and climatic conditions.

With canola, spring wheat and flax in the Brown, Dark Brown, Black and Gray soil zones, it was found that: (1) spring applications were superior to fall applications, (2) anhydrous ammonia was as effective as urea, and (3) placing the nitrogen fertiliser in the soil at the time of planting was superior to a surface broadcast application immediately before planting (Lemke et al. 2003). Nitrous oxide emissions, estimated to be 1.25% of nitrogen fertiliser applied, were lower than estimates of the International Panel on Climate Change, regardless of soil zone, nitrogen form, placement and timing (Helgason et al. 2005).

It may be possible to minimise further losses from volatilisation and denitrification by using urease and/or nitrification inhibitors (Malhi et al. 2001) and controlled-release urea in which the granules are covered with a thin polymer coating (Anonymous 2006b). This technology allows most of the nitrogen to be placed in the soil at the time of planting; the slower conversion of ammonia to nitrate ions then allows more of the nitrogen to become available closer to the time of maximum crop uptake.

The current practice for choosing a nitrogen application rate is to test the soil for residual nitrate levels and then determine a yield goal based on historical production using average climatic conditions. The rate is then adjusted for spring soil moisture levels, nutrient removal by previous crops, whether the preceding crop was a grain legume, the crop to be grown, and the expected price for the crop. Uncertainty comes from the inability to predict accurately precipitation, temperature and nitrogen mineralisation during the growing season.

Active optical sensors that emit light in two specific wavebands and measure their reflectance off the crop canopy may further refine the ability to match nitrogen fertiliser rates with crop needs (Raun et al. 2002; Anonymous 2006d). Yield potential of a crop can be predicted early in the growing season from indirect estimates of crop biomass, using the Normalised Difference Vegetative Index (NDVI) (Rouse et al. 1974). This approach measures crop characteristics rather than soil attributes. By combining this sensor technology with non-limiting nitrogen fertiliser reference strips in the field, it is possible to determine if the amount of nitrogen fertiliser added is adequate to meet the potential of the crop. This approach can reduce the economic risks associated with nitrogen applications and avoid over or under application of nitrogen. However, it relies on in-crop, surface application of nitrogen, which is not always as efficient as in-soil application. Rainfall is needed to move the nitrogen into the root zone for uptake (Holzapfel et al. 2007).

The importance of nitrogen fertility for crop production is well recognised but it also has important environmental implications. The production of nitrogen fertilisers is energy intensive and their use contributes to emissions of nitrous oxide, a potent greenhouse gas. Over-use can also lead to surface and ground water contamination with nitrates. By matching nitrogen fertiliser rates more precisely to crop needs, placing the fertiliser in the soil and minimising the time between placement in the soil and the period of rapid uptake by the crop, it will be possible to achieve higher levels of NUE on the Prairies.

19.4.4 Management of Plant Diseases and Weeds

19.4.4.1 Plant Diseases

Prairie cropping systems have moved from monoculture cereal cropping with or without fallow to diversified continuous cropping rotations using reduced tillage or no-till. This crop diversification reduces the build-up of plant pathogens.

Annual grain crops on the Prairies can be classified as cereal, oilseed or pulse. Within the oilseed and pulse group, common root diseases include *Rhizoctonia* spp., *Pythium* spp. and *Fusarium* spp. The foliar disease *Scerotinia sclerotiorum* affects most dicotyledon crops grown, with sunflower being the most susceptible and flax and buckwheat the least susceptible. A number of the cereal root diseases such as common root rot (*Cochliobolus sativus*) are common to all cereals, but there is little commonality among the major leaf diseases of barley, rye, wheat or durum, and oat. There are few diseases affecting both cereals and dicotyledonous crops.

Crop rotation is the most effective biological control option for crop diseases. Alternating between cereals and non-cereals will reduce the impact of residue- and soil-borne diseases. For example, a pulse crop in a cereal rotation, using no-till enhances the populations and activity of beneficial organisms that reduce the effects of cereal root pathogens (Krupinski et al. 2002). Lupwayi et al. (1999) showed that soil microbial biomass and diversity were greater in wheat when following a legume crop than following fallow. Crop rotation is less important for wind-blown and seed-borne diseases. In these situations, the logical strategies are to have clean seed, seed treatments, foliar fungicides and/or resistant cultivars (Krupinski et al. 2002).

The effects of tillage systems on the incidence and severity of plant disease are small relative to the effects of environment and crop rotation (Bailey et al. 2001; Turkington et al. 2006). Nonetheless, no-till was shown to reduce the severity of common root rot in cereals (Bailey et al. 2001). Reduced tillage and no-till reduce many crop diseases because of their direct and beneficial effects on soil biology (Krupinski et al. 2002). A healthy soil with diverse and balanced populations of soil micro-organisms will provide substantial competition against root pathogens as these often use the same organic carbon substrate. Soil microbial biomass and diversity in wheat, for example, were greater with reduced tillage than in the conventional tillage (Lupwayi et al. 1998). No-till has been shown to increase the specific bacteria that can decompose the over-wintering fruiting bodies of *Sclerotinia* spp. (Nasser et al. 1995) (see also Chap. 6).

The best strategy to minimise plant diseases in cropping systems on the Canadian Prairies is to adopt reduced tillage or no-till practices combined with diverse crop sequences that include cereal, oilseed and pulse crops. The temporal variability of climate on the Prairies also reduces the risks of certain diseases from becoming dominant. Attention also needs to be given to other disease control methods such as providing disease-resistant cultivars, disease-free seed with high vigour, use of seed treatments or foliar fungicides if warranted, balanced soil fertility, control of weeds and volunteer crops to break pathogen cycles, and careful record keeping of disease incidence (Krupinski et al. 2002). One major weakness in our approach to plant disease management lies in our inability to predict losses due to diseases and to predict how much of that loss can be averted by applying fungicides. The integration of climatic data with estimates of disease inoculum levels could help address these concerns (see also Chap. 9).

19.4.4.2 Weed Management

Weed control by tillage was the reason for the continuation of the fallow-crop system on the Prairies. Continuous cropping and more diversified rotations have been made possible by: (i) the use of selective herbicides for a wide range of crops since the 1980s; (ii) non-selective herbicides such as glyphosate (Appleby 2005); and (iii) changes in tillage practices to increase spring soil moisture (Lafond and Fowler 1990).

The basic approaches to weed management – herbicides, tillage and agronomic practices – interact strongly with environmental conditions (Lafond and Derksen 1996) to determine the extent of changes in weed communities. Under no-till, weed management becomes entirely dependent on herbicides and crop production practices.

An initial concern with no-till was the potential for rapid shifts in the density and composition of weed populations. More recently, there has been a major concern over both the increase in weeds becoming resistant to herbicides and also the overall potential increase in herbicide use. On a global basis, Canada uses 3% of pesticides produced. Herbicides account for 77% of all pesticides used in Canada, followed by 9% for fungicides and 8% for insecticides. The Prairies, with 87% of the total cultivated area in Canada, use 77% of all pesticide used in Canada, and the majority are herbicides (Anonymous 2006e).

There was initial concern that selection pressure by the continued use of particular herbicides might change weed communities (Lafond and Derksen 1996; Derksen et al. 2002), and this prompted a counter strategy of varied selection pressure.

Species such as Canada thistle (*Cirsium arvense*) and perennial sowthistle (*Sonchus arvensis*) are more associated with minimum- or no- tillage practices, whereas annual species tend not to be associated with any particular tillage practice (Thomas et al. 2004). Some species such as field pennycress (*Thlaspi arvens*) were more associated with conventional tillage whereas Russian thistle (*Salsola iberica*) was associated more with no-till. There do not appear to be functional traits amongst weed species that can be associated specifically with changes in tillage practice.

However, no major shift in weed species has occurred, possibly because no-till and crop diversification together allowed for a broader range of herbicide chemistries with more diverse crop types and growth habits (spring or winter crops).

At the same time, one-pass planting and fertilising allowed precise placement of nitrogen fertilisers to increase the competitive ability of crops over weeds (O'Donovan et al. 1997). Large differences in weed communities on the same plot from year to year can be due to temporal variability in rainfall (Thomas, personal communication). The temporal variability of temperature and moisture on the Prairies represents an important source of varied selection pressure to prevent dominance of particular weeds. The combined impact of planting rates, crop rotations, crop types, planting dates and herbicides in lowering weed seed recruitment in the soil seed bank can be large when used strategically (Harker and Clayton 2003).

In 1996, the introduction of canola varieties resistant to herbicides (glyphosate, glufosinate, and imazamox and imazethapyr) with different modes of action provided a new tool against annual grassy weeds such as wild oats (*Avena fatua*) and green foxtail (*Setaria viridis*). These weeds were showing resistance to the ACCase (Group 1) and ALS/AHAS (Group 2) group of herbicides (Saskatchewan Agriculture and Food 2008). The introduction of canola varieties resistant to glyphosate (Group 9) and glufosinate (Group 10) provided a means to control annual weeds resistant to Group 1 and 2 herbicides, and causing problems in cereals and broadleaf crop. Such weeds include cleavers (*Galium aparine*), chickweed (*Stellaria media*), hempnettle (*Galeopsis tetrahit*), kochia (*Kochia scoparia*), ball mustard (*Neslia paniculata*), wild mustard (*Brassica kaber*), Persian darnel (*Lolium persicum*), red root pigweed (*Amaranthus retroflexus*), Russian thistle and field pennycress (Saskatchewan Agriculture and Food 2008).

For pre-planting weed control, a decrease in the cost of glyphosate allowed application rates to be increased. This reduced the selective pressure operating at low rates on certain weeds, such as wild buckwheat (*Polygonum convolvulus*). In essence, this made glyphosate more non-selective rather than mildly selective (Derksen et al. 2002).

For perennial weeds such as Canada thistle, quackgrass (*Agropyron repens*) and dandelion (*Taraxacum officinale*), pre-harvest applications of glyphosate have given excellent weed control in a wide range of annual crops other than canola resistant to glyphosate.

Weed surveys in 2000 showed that green foxtail was the most abundant weed with wild oat ranking second, wild buckwheat, third, and Canada thistle, fourth (Leeson et al. 2005). Since weed surveys started in 1973, six high-ranking weed species have declined while five new species – (cleavers, spring wheat, kochia, barnyard grass (*Echinochloa crusgalli*)) and dandelion have appeared. The appearance of spring wheat could be due to its lower frequency in crop rotations, thus making volunteer plants more obvious. As a group, annual and perennial grasses have increased while annual broadleaf weeds and facultative winter annuals have decreased. Overall densities of weeds have decreased in the most recent survey, implying less weed seed recruitment in the soil seed bank under the current tillage and cropping systems.

In conclusion, changes in weed communities occur slowly. With integrated weed management, producers on the Prairies have numerous strategies at their disposal to continually vary selection pressure and thus prevent particular weed species from becoming dominant well into the future. In addition, the effectiveness of current crop production practices for weed management is reflected in the overall reduction of weed densities. The long-term weed management strategy for the Prairies is to employ a diversity of weed management tools and to ensure that no one tool gets a disproportionate amount of use lest its effectiveness be greatly diminished (Harker and Clayton 2003). The adoption of integrated weed management strategies will also enhance economic returns (Smith et al. 2006) (see also Chap. 8).

19.5 Economic and Energy Considerations

19.5.1 Overview of Economics of Cropping Systems

With the decline in fallow-cropping practices on the Prairies and the increase in continuous cropping, the economic debate shifted to comparing the economic merits of increased cropping intensity with those of a crop–fallow system. Most of the economic research on cropping systems on the Prairies is based on long-term studies located at Agriculture and Agri-Food Canada Research Centers (Ripley 1969; Campbell et al. 1990). It is also particularly related to crop production in the drier areas where lower rainfall and higher potential evapo-transpiration create greater uncertainty for continuous cropping.

19.5.1.1 Brown Soil Zone (Mean Annual Precipitation 334 mm)

Crop–Fallow vs. Continuous Cropping

Over 18 years (1967–1985), a study at Swift Current compared intensities of wheat cropping under conventional tillage[7] (as summarised in Table 19.10). Precipitation was below the long-term average in 12 of the 18 years. Yields of wheat[8] on fallow were 25–30% higher than on stubble, and yields of wheat on fallow were similar for the fallow–wheat (F–W) and fallow–wheat-wheat (F–W–W) rotations when fertilised according to soil test recommendations (Zentner and Campbell 1988). Yields of wheat on stubble were not affected by rotation length and preceding crops.

Table 19.10 shows the most profitable rotations for the 18-year period, under different wheat price scenarios. Overall income variability was lowest for F–W and highest for continuous wheat (Cont–W). The economic analysis supported fallow in the cropping system for the brown soil zone but the intensity of cropping could

[7] Conventional tillage involves a number of cultivations to control weeds and prepare a seedbed, usually a minimum of once in the fall and once in the spring prior to seeding.

[8] Mean yields for individual harvests.

Table 19.10 Profitability of alternative wheat rotations at various wheat prices, on brown soils (After Zentner and Campbell 1988)

Wheat price	Most profitable rotation
High	Continuous wheat
Above normal	Fallow–wheat–wheat
Normal	Fallow–wheat and fallow–wheat–wheat
Low	Fallow–wheat

be increased from F–W to F–W–W without incurring additional risk. This finding was also confirmed by Walburger et al. (2004).

An economic analysis was also conducted for the period 1985–2002 using the same crop rotations (Zentner and Campbell 1988) plus the inclusion of stubble mulch tillage techniques and more diversified continuous cropping rotations involving lentil (LENT) and flax (FLX).This period was characterised by above-average precipitation. The highest returns of all treatments were observed for the W–LENT and the least returns for F–FLX–W (Zentner et al. 2007). Flax is not well adapted to the dry areas and is best suited for planting on stubble, preferably after a cereal because of the strong mycorrhizal associations which it forms and which are reduced when planted on fallow. With the higher fertiliser rates used, in keeping with the higher rainfall, the benefits from N and P were greater in this period than during the previous lower rainfall period, especially for the Cont–W rotation (Zentner and Campbell 1988).

The conclusion was that producers less averse to risk would change to continuous cropping and diversified rotations while more risk-averse producers would still include some summer fallow in their cropping systems as a risk management strategy.

Decisions on whether to sow a crop or put the land to fallow are assisted by knowing the spring available soil moisture level (Weisensel et al. 1991). A flexible continuous wheat rotation is then one where fallow is substituted for a wheat crop when spring available soil moisture level is less than a given amount. These authors also found that the available water needed to allow a crop to be planted without fallowing depended on the price of wheat. Using this relationship, Zentner et al. (1993) showed that income variability with the flexible continuous wheat (Cont–W–IF), i.e. using the above decision rule, was less than with a fixed Cont–W rotation and similar to the F–W rotation, the rotation with the least income variability. Actual net incomes were also higher for the Cont–W–IF than even the Cont–W and F–W rotations. With the Cont–W–IF rotation, a crop was sown only if the available soil moisture in the 0–120 cm soil layer was greater than 76 mm.

The positive results of the W–LENT rotation encouraged further grain and soil analyses with respect to long-term sustainability of this cropping system (Zentner et al. 2001). The first observation was that nitrate leaching was lower for Cont–W than F–W or F–W–W and lowest for W–LENT. Wheat grown on lentil stubble had similar grain yields to Cont–W, but higher grain protein content, which provided an incremental economic benefit.

Soil quality measurements included soil organic carbon, light fraction organic carbon, mineralisable carbon and N, and proportion of water stable aggregates.

Soil quality was highest in W–LENT followed, in descending order of magnitude, by Cont–W, F–W–W, and F–W. Including lentil in the rotation reduced overall energy requirements because N fertiliser is not required and carbon dioxide emissions were 19% less than for Cont–W.

When financial risk is considered i.e., total income and year-to-year variability, the W–LENT rotation provided lower risk than Cont–W, but higher than F–W and F–W–W. As long as the price of lentil was above $350 per tonne, the W–LENT rotation was deemed economically successful. These results are in keeping with the observation that producers are successfully extending their farm systems in the Brown soil zone by including pulse crops and using rotations such as W–LENT with good success. Other more recent research in the Brown soil zone has also demonstrated the economic benefits of including grain legumes in the rotation to permit a higher intensity of cropping (Walburger et al. 2004).

Green Manure vs. Fallow

Another important question regarding cropping systems in the Brown soil zone was the feasibility of using legume green manure (GM), i.e. lentils ploughed-in at the start of flowering or end of June – which ever comes first – as a partial fallow substitute (Zentner et al. 2004a). When combined with conservation tillage practices, tall stubble to maximise snow trapping, soil water conservation and recommended rates of N and P fertilisers, costs were similar for F–W–W and GM–W–W. The extra costs of managing the green manure crop were offset by the savings in nitrogen fertiliser costs for the subsequent wheat crop and savings from weed control costs incurred during the regular fallow phase of F–W–W. The precipitation was above average for this period of the study and the net returns were highest for Cont–W, despite this having the highest cost. This is in contrast to the results presented earlier (Zentner and Campbell 1988). This more recent study provides good evidence of the positive, incremental impact of new management practices on crop production – in this case snow trapping and conservation tillage. The next most profitable rotation was F–W–W–W–W and the least profitable rotation was F–W–W and GM–W–W.

Producers with the lowest aversion to risk would choose Cont–W while the producers averse to risk would still choose cropping systems that included fallow at least once in 3 years. The recent increases in nitrogen fertiliser prices may make green manure crops more financially attractive.

Impact of Conservation Tillage

The last factor to consider in the economics of cropping systems for the Brown soil zone is the impact of conservation tillage. A comparison was made of wheat under F–W and Cont–W cropping systems, using conventional tillage (CT), minimum tillage (MT) and no-till (NT) in three soil types (silt loam, sandy loam and heavy clay). There was no economic benefit for any treatment during the period 1982–1993

(Zentner et al. 1996b). The savings that MT and NT offered in terms of labour, fuel and oil, machinery repairs and machinery overhead were more than offset by the increase in herbicide costs. Production costs were higher for NT than CT – 10–13% for Cont–W and 14–29% for F–W.

The poor overall economic performance of NT was due to a combination of higher input costs, specifically herbicides, and the lack of yield increase with NT over CT. A reduction of 50% in herbicide costs was deemed necessary to make NT equivalent to CT in terms of production costs. The continued expansion of no-till combined with continuous and diversified cropping, and improved snow management techniques in the Brown soil zone, is a strong indication that the economics for no-tillage have improved since the mid-nineties, in addition to the decrease in the price of glyphosate herbicide.

19.5.1.2 Dark Brown Soil Zone (Mean Annual Precipitation 413 mm)

As discussed in Sect. 19.1.3, although there were moisture deficits in most years in the Dark-Brown soil zone, severe droughts are less frequent. A 12-year study (1978–1990) at Scott, SK compared the agronomic and economic performance of two crop rotations (F–Oilseed(O)–W, and O–W–W) under two tillage systems (CT and NT) (Zentner et al. 1992a, 1996a). In 75% of the years, gross returns were 46% higher for the O–W–W rotation than for F–O–W one. The use of NT increased gross returns in 25% of the years as a result of improved grain yields – because of more available soil moisture. Significant differences in overall production costs, based on 1990–1991 input and grain prices, were: O–W–W > F–W–W and NT > CT. Based on the economic analysis of this study, producers less averse to risk would choose continuous cropping and NT while producers with a high aversion to risk would still choose CT and some fallow in their cropping system.

A study based out of Lethbridge, AB, also in the Dark Brown soil zone, compared different fallow management systems which included combinations of reduced tillage and herbicide management; the study concluded that other than good protection against wind erosion, reduced tillage for fallow management did not improve the net returns (Smith et al. 1996). The paper did not consider the long-term economic benefits of reduced tillage on soil physical and chemical properties.

More recently, Holm et al. (2006) in a study located in Saskatoon, SK in the Dark Brown soil zone demonstrated the superior economic performance of NT over conventional tillage under a continuous cropping scenario. Their study was based on input costs and product prices evaluated at 2000 levels. When using a spring wheat–canola–barley–field pea rotation under six different integrated weed management systems and two tillage systems (NT and CT), the highest net returns were observed with high, medium and low herbicide use combined with no-till. This is a further strong indication that the long-term economic and environmental sustainability of cropping systems in the Dark Brown soil zone depends on a diversified crop rotation with no-till practices, even for producers with high aversion to risk. This is reflected in the increase in no-till area since the 2006 agriculture census (Table 19.5).

19.5.1.3 Black and Gray Soil Zones Mean Annual Precipitation 427–467 mm

In the Black and Gray soil zones, the benefits of diversified continuous cropping rotations and conservation tillage on improved agronomic and economic performance have been well demonstrated under a wide range of climatic conditions and locations (Gray et al. 1996; Nagy 1997; Zentner et al. 2002a; Lafond et al. 2006). The various economic analyses have concluded that most producers will opt for diversified continuous cropping systems and no-till, regardless of the level of their risk aversion. This represents a clear advantage for both producers and the environment because soil degradation is arrested, soil organic carbon content is increased (McConkey et al. 2003), and the economic performance is improved (Zentner et al. 2002b).

19.5.1.4 Summary of Economics Findings

The evolution of planting methods, fertiliser and pesticide (specifically herbicide) technologies, combined with advances in crop diversification and production have stimulated interest in the economic potential for continuous cropping, especially in the drier areas of the prairies. Many of the economic studies cited focused on the drier areas due to greater uncertainty with growing-season precipitation leading to more income variability and risks with net returns.

In the Brown soil zone, the frequency of fallow cropping was reduced and continuous cropping was found possible provided that stubble mulch techniques, tall stubble and diversified cropping were used and commodity prices were average to above average.

In the Dark Brown, Black and Gray soil zones, the economic analyses favoured diversified and continuous cropping systems combined with no-till practices.

19.5.2 Energy Use and Energy Use Efficiency

19.5.2.1 Historical Perspective of Energy Use for Crop Production

Crop production on the Prairies is highly dependent on non-renewable energy, and agriculture accounts for about 10% of total greenhouse gas (GHG) emissions in Canada (Janzen et al. 1999). The development of sustainable rainfed production systems must be concerned about energy use and energy use efficiency, as well as economics.

Energy use efficiency is usually measured as the ratio of energy output to energy input, or the amount of grain produced (kg) per gigajoule (GJ) energy input. It could also be expressed as the ratio of product energy output per unit of GHG emitted. Hopper (1984) estimated the energy requirements for wheat production at 2,500 MJ/ha in 1948 and 8,400 MJ/ha in 1981. Other studies, based on surveys of

Saskatchewan farms, reported increases in energy use of 61% for the period 1961–1976 (Stirling 1979), with a further 11% increase for the period 1990–1996 (Coxworth 1997). The growth in energy use for crop production on the Prairies is partly explained by the increase in mechanisation, and the use of inorganic fertilisers, herbicides, and electricity in farm operations. 'Energy use' in the context of this discussion also includes the energy required for both the manufacture and utilisation of these inputs. It excludes solar energy used in photosynthesis. The rise in energy use for wheat production since the early 1950s also resulted in higher grain yields.

19.5.2.2 Estimates of Energy Use and Energy Use Efficiency on the Canadian Prairies

In this section, the impact of recent movements towards continuous cropping, crop diversification and the adoption of no-till on energy use and energy use efficiency are discussed. Data are presented (Table 19.11) from long-term tillage and crop rotation studies conducted at Agriculture and Agri-Food Canada Research Centers, on two soil types in the Brown soil zone and one in the Black soil zone. The results are reported on a yearly, crop rotation basis.

Energy output per hectare: Comparing crop rotations in the Brown soil zone, mean annual energy output was higher for Cont–W than for F–W because of overall higher grain production in the former, from more harvested crops. In the Black soil zone, there were higher energy outputs from the continuous cropping rotations, and when fallow was used only 1 year in four. When tillage systems are compared for the Brown soil zone, there were only a few, inconsistent differences between NT and CT. In the Black soil zone, the only significant differences were the superior energy output of NT in the wheat–flax rotation.

Energy input per hectare: In comparing rotation types for both soil zones, continuous cropping rotations had consistently higher mean annual inputs of energy than where a fallow was included. The main reason was the lower amounts of nitrogen fertiliser needed with crops grown on fallow, thereby lowering the overall amount of energy input. When field pea was included in a 4–year continuous cropping rotation in the Black soil zone, mean annual energy use was increased by only 13.5% relative to the fallow–containing rotation. This is because nitrogen fertiliser is not necessary for field pea, provided that the crop is well inoculated with an appropriate strain of nitrogen-fixing bacteria (*Rhizobium* spp.).

Comparing tillage treatments: In the Brown soil zone, there were consistently higher inputs of energy for NT than for CT, regardless of cropping system and soil type. However in the Black soil zone, there was no difference in energy use between CT and NT. In the Black soil zone, more tillage operations are required for CT than in the Brown soil zone. This means that the energy required for CT cultivation in the Black soil zone is about as much as that required for herbicide production and application in NT, although not in the Brown soil zone.

Table 19.11 Effect of tillage and crop rotation on mean annual energy output, energy input, the contributions of fertilisers, herbicides, fuel and oil to energy consumed, the energy output to input ratio and grain produced per unit of energy for Brown (two soil types) and Black soil zones

	Brown soil zone (1982–1993)[a]				Black soil zone (1987–1998)[b]					
	Cont–W[d]		F–W[d]		F–W–W–Ww[c,e]		W–W–Fx–Ww[c,e]		W–Fx–Ww–P[c,e]	
Soil type	CT	NT	CT	NT	CT	NT	CT	NT	CT	NT
Energy output (MJ/ha/year)										
Clay	21,840a	22,952a	17,897b	19,988a	32,296d	32,711d	39,295c	42,014b	42,377ab	42,603ab
Silt loam (SL)	25,497a	25,947a	16,646a	15,765b	–	–	–	–	–	–
Energy input (MJ/ha/ year)										
Clay	4,888b	5,268a	–	2,548	6,227c	6,235c	8,116a	8,037a	7,128b	7,018b
Silt loam (SL)	5,479b	5938a	2,597b	2,810a	–	–	–	–	–	–
Relative contribution of selected production inputs to total energy input (%)										
Clay fertiliser	61	61	44	37	66	69	70	73	64	68
Clay herbicides	4	8	4	21	6	11	6	8	6	8
Clay fuel and oil	23	20	33	26	23	16	20	15	25	19
S–L Fertiliser	62	61	36	36	–	–	–	–	–	–
S–L herbicides	5	10	6	26	–	–	–	–	–	–
S–L fuel & oil	21	19	38	24	–	–	–	–	–	–
Ratio of energy output to energy input										
Clay	4.1	4.0	8.0	7.7	5.2c	5.3c	4.8d	5.2c	6.0b	6.1a
Silt–loam	4.7	4.4	6.4	5.7	–	–	–	–	–	–
Grain production per unit of energy (kg grain/GJ)										
Clay	298a	290a	581a	489b	310c	290d	293d	307c	359b	379a
Silt–Loam	343a	316b	468a	412b	–	–	–	–	–	–

[a]Zentner et al. (1998)
[b]Zentner et al. (2004b)
[c]F–W–W–Ww refers to Fallow–Spring wheat–Spring wheat–Winter wheat; W–W–Fx–Ww refers to Spring wheat–Spring wheat–Flax–Winter wheat; W–Fx–Ww–P refers to Spring wheat–Flax–Winter wheat–Field pea
[d]Within individual soil types, means followed by different letters are significantly different ($p<0.10$) for comparison of tillage systems within Cont–W and F–W
[e]Within individual soil types, means followed by different letters are significantly different ($p<0.10$) for comparison of tillage systems and crop rotations

Comparing proportions of energy use associated with fertiliser, herbicides, fuel and lubricants: In the Brown Soil Zone, fertiliser accounted for 61% of total energy use in Cont–W vs. about 40% for F–W, while herbicides accounted for 4–26%, depending on the tillage system. In the Black soil zone, fertiliser accounted for 64–73% of total energy used, depending on the rotation, and herbicides 6–11%. Energy for fuel and lubricants was lower for NT than CT regardless of soil zone, soil type or crop rotation.

Energy use efficiency: In the Brown soil zone, this was higher for F–W than for Cont–W and higher for CT than for NT. In the Black soil zone, the ratio was higher for NT than CT combined with continuous cropping, and the rotation which included field pea had the highest ratio because of the energy savings. The higher ratio for field pea is the result of not having to use nitrogen fertilisers.

The technological and agronomic advancements made in crop production on the Prairies during the last 25 years have increased the energy use efficiency of grain production based on results from long-term field studies in the Brown and Black soil zone. From the early 1950s to the early 1990s, energy use efficiency increased from 220 kg grain per GJ to 312 (range 290–343) for Cont–W and to 488 (range 412–581) for F–W in the Brown soil zone. In the Black soil zone, the energy use efficiency has increased from 220 to 323 (range 290–379) for the same time period. The energy use efficiency is similar for the Brown and Black soil zones for continuous cropping. Although energy use efficiencies are higher for F–W than Cont–W in the Brown soil zone because of the lower levels of nitrogen fertiliser used with F–W, it is important to note that these improvements have occurred at the expense of soil quality, including organic matter and soil nitrogen contents. A negative nitrogen balance occurs where the removal of nitrogen is greater than the input, a common situation where fallow occurs in the rotation. However, it can also occur where no-till and continuous cropping is used (Campbell et al. 2007).

Overall, the best strategy for Energy Use Efficiency is to increase the energy from crop production by improving water conservation and water use efficiencies. Many of the suggested innovations require little additional energy (Table 19.6). In addition, continuous cropping, combined with no-till and crop diversification, has been shown to improve long-term quality of Prairie soils (McConkey et al. 2003). There is also an urgent need to find ways to reduce the reliance of cropping systems on inorganic nitrogen fertiliser by introducing more nitrogen-fixing species into the cropping system. Site specific approaches to nutrient management and integrated pest management will improve energy use efficiency. Pest management approaches that only apply pesticides spatially and temporally according to economic thresholds will also improve energy use efficiency by reducing the energy input associated with the production of pesticides.

19.5.3 Agriculture as a Renewable Energy Source

There are two basic approaches to generating energy from agricultural products: (1) combusting biomass to produce heat and electricity and (2) producing either ethanol or biodiesel. Most comparisons are made using (a) the net energy gains (E_g)

after subtracting all fossil fuel energy used and (b) in the ratio of fuel energy produced to complete fossil energy input (ER).

Main et al. (2007) examined both situations. When grasses and coppiced willows were used to generate heat and electricity, the E_g values were 29–117 GJ/ha/year and the ER 4–17. If these same products were processed to lignocellulosic ethanol, the E_g values were 22–114 GJ/ha/year and the ER 5–13. This means that E_g and ER values were maintained. When the same analysis was done for ethanol and biodiesel using grains as the feedstock, the E_g values were between –15 and +32 GJ/ha/year and the ER values 0.8–3.7. Other energy analyses for biodiesel production using soybean and canola showed ER values of 2.08–2.41 with essentially no difference between the two crops (Smith et al. 2007). Although soybean requires less overall energy to produce it because of its nitrogen-fixing capabilities, it produces only about half the oil that canola produces.

These results provide an interesting dilemma with respect to future cropping systems when energy efficiencies for different feedstocks are taken into consideration. The results favour the production of biomass rather than grain as an energy source. This would allow the introduction of more diversity into Canadian prairie production systems. Additionally, there are the questions raised by using prime agricultural soils for energy production rather than for food.

19.6 Prairie Farming Systems – Overview

19.6.1 Productivity and Sustainability

Based on the proportions of farm types on the Prairies, beef cattle production and annual cropping represent the dominant farming systems. Although their proportions vary with geographical location, annual cropping systems account for the largest proportion.

The climate of the Canadian prairies is classified as semi-arid to sub-humid. The ratio of potential evapo-transpiration to precipitation ranges from 1.4 to 2.2 for the Black and Brown soil zones, respectively. The high ratio combined with variable growing-season precipitation represents an important crop production risk. Canadian prairie soils have lost 40% of their original nitrogen content through various forms of degradation since their initial cultivation. This loss in fertility also adds to production risk. When considered across the major soil zones, 76–85% of the soils are either fine- (clay) or medium-(loam) textured with 50% or more falling in the fine-textured category. This implies that prairie soils have good overall production potential and water-holding capacity with good rooting profiles, and need to be conserved. Water and nitrogen are considered the most limiting factors to crop production. The key to the long-term productivity and sustainability of Canadian Prairie agriculture rests on effective management of soil, water and nitrogen.

The last 20 years on the Canadian prairies has been characterised by the rapid adoption of planting, fertiliser, herbicide technologies, crop diversification, improved crop and livestock husbandry and benefits from the application of crop and livestock genetics. The adoption of genetically-modified canola varieties resistant to different groups of herbicides has provided relief from the problem of grass and broadleaf weeds becoming resistant to Group 1 and 2 herbicides. It has also contributed to more diversified rotations beyond the traditional canola growing areas.

The movement to no-till since the early 1990s is protecting soil fertility from degradation caused by wind and water erosion. Due to improved water conservation and water use efficiency, no-till is improving overall crop production, and this has led to higher levels of soil organic carbon and nitrogen content (McConkey et al. 2003). Some of this recently-stored carbon and nitrogen is subject to rapid mineralisation, thereby providing a ready supply of available nitrogen to the crop during the growing season and a fertility buffer when above-average growing conditions are encountered. The increase in soil organic matter also has beneficial effects on soil physical, chemical and biological properties. The adoption of no-till has also allowed the replacement of fallow cropping systems with more diversified continuous cropping rotations. Fallow-cropping systems were a key contributor to soil degradation on the Prairies. When these no-till production practices are combined with appropriate agronomic practices, they can be viewed as contributing to the future sustainability of Canadian Prairie agriculture.

The adoption of no-till has also led to changes in nitrogen management. The most widely used approach is to band the nitrogen fertiliser in the soil away from the seed at time of planting. This greatly reduces the time between application and time of maximum crop uptake and the potential for losses; and the end result is increased nitrogen use efficiency. The greatest challenge still remaining is deciding on an appropriate nitrogen rate to match crop needs with soil and climatic conditions. The recent advances with optical sensors of crop N status provide a solution to temporal and spatial variability at the field level and a better way to optimise the rate of nitrogen application. This alleviates potential negative environmental and energy consequences from overuse of nitrogen fertilisers and lower economic returns from sub-optimal rates.

Another important aspect of productivity and sustainability is energy outputs relative to energy inputs. Prairie agriculture is highly dependent on non-renewable energy. Energy use for agriculture has increased 70% for the period 1948–1996. This rise in energy use also resulted in higher grain yields so that energy use efficiency was maintained at 220 kg per GJ of energy for spring wheat. This represents an energy output to energy input ratio of 3.5. Recent advances in crop production have increased this ratio to 4.0–4.7 for continuous cropping in the Brown soil zone and 4.8–6.1 in the Black soil zone. The largest contributor to energy use for continuous cropping is fertiliser at 61% and 71% for the Brown and Black soil zone, respectively followed by fuel at 21% and 20% and then herbicides at 6% and 7%. Of interest is the fact that there was essentially no reduction in overall energy use with the adoption of no-till. The savings in fuel with no-till were taken up by energy associated with producing and applying herbicides. The strategy to improve energy use efficiency is to employ the best crop management practices, with emphasis on fertiliser management because of its large contribution to overall energy use.

Beef cattle farming systems tend to be integrated with annual cropping systems; however, the relative contribution of each system to overall economic activity varies with geographical location. This level of integration allows for marginal or degraded soils to be planted with forages for hay and pasture, improving economic returns and reducing risk. This approach is less exhaustive on soil fertility and even results in long-term soil improvement. Inclusion of forages as part of an annual cropping system will improve annual crop yields, allow for unique weed management strategies and reduced overall pesticide use. In the long-term, this level of integration is desirable to sustain productivity and contribute to long-term sustainability.

From a global basis, Lal (2007) stresses the urgency to improve degraded soils and ecosystems and the depleted organic carbon pools so that soils can respond fully to crop production inputs – especially in the developing countries where most of the population growth is occurring. To accomplish this goal "the strategy requires the adoption of a holistic approach based on sound scientific principles of managing the soil and water resources in accord with the social, economic, and political realities of the region".

19.6.2 Profitability and Flexibility

Canadian prairie producers rely heavily on export markets as their main source of revenue, but the costs incurred by producers to bring their products to ocean shipping ports represent their largest expense. When this expense is combined with the volatility of world grain markets and the highly variable climatic conditions, prairie producers operate under a great deal of uncertainty.

Even under conditions of volatile markets and variable climate, Prairie producers have the flexibility to adjust their cropping programs to better reflect market conditions. One of the unique aspects of Prairie annual cropping systems is the diversity of spring and autumn sown crops (cereals, oilseed and pulse) that can be grown in all regions of the prairies. In order to support this diversity of crops, marketing expertise, crop processing infrastructure and crop-specific research were developed across the prairies. This provides producers with marketing and processing choices and the required knowledge for successful crop production. Another important aspect of crop diversity is the ability to maintain appropriate crop rotations for reasons of pest management and soil fertility, even though the mix of crops can change dramatically on an annual basis. This is in contrast to many other parts of the world where this level of crop diversity has not been possible or yet achieved.

The adoption of no-till has also allowed for better returns and better overall risk management, especially in the Dark Brown and Black soil zone. The economic advantage of no-till was further enhanced with the use of diversified continuous cropping systems. In the Brown soil zone, the benefits of no-till and continuous cropping were not as consistent. The semi-arid conditions are such that no-till may not always result in the desired water conservation due to variability in precipitation and the high potential for soil water loss between the end of the snow-melt period and the start of planting. However, more recent research has demonstrated that no-till combined with planting into tall stubble can enhance crop production and water use efficiency and tip the balance in favour of no-till and continuous cropping. The recognised improvement in long-term soil fertility with use of no-till implies that production risks will be lowered over time.

Beef cattle production systems, given their integration with annual cropping systems, allow for more optimum land use, especially in situations of marginal or degraded soils. This in turn provides for better economic returns and less risks. The inclusion of forages in annual cropping systems e.g. for the export hay market, provides flexibility to capture economic opportunities.

From the outside, it would appear that Precision Farming systems have attained a desired level of productivity, sustainability, profitability and flexibility. The reality is that returns on investments remain low and capital requirements are high for the level of risks. More integration of livestock and annual cropping farming systems could improve overall net returns and reduce the risks associated with food, feed and fibre production.

19.6.3 Sustainability of Rural Areas

Although one could argue that technological advances in Prairie agriculture have made it more sustainable, the outcome has been the creation of fewer, but larger, farming units, directly affecting rural demographics. The Canadian Prairies are undergoing rural depopulation which, in turn, affects the various services necessary to sustain rural areas – medical, educational, social, general, commercial and access to labour. Federal, provincial and local governments have supported, through policy changes and financial incentives, the development of value-adding processing as a means to curb rural depopulation.

19.7 What Does the Future Hold for Rainfed Production Systems on the Canadian Prairies?

Prairie farming systems are not static, and will continue to evolve as climate, markets, economic opportunities, demographics and technologies change. The gradual reduction of world grain stocks combined with competition for grains, not only in the food and feed markets but also in the bio-energy sector, is creating new requirements and opportunities for changes in cropping systems. The development of technologies for converting biomass, such as switchgrass (*Panicum virgatum*), to biofuels and other co-products is adding to future crop diversification. The introduction of new industrial crops and the introduction of improved agronomic traits into existing crops will help shape the farming systems of the future. Attention will also need to be given to net energy production in agriculture, not just total energy production (Main et al. 2007; Smith et al. 2007). To reduce energy input from fertiliser N, more annual or perennial N-fixing species must be included. Some woody perennials may be desirable for cellulosic ethanol production. The woody perennial legume caragana (*Caragana arborescens*) is well adapted to the Canadian Prairies and also fixes nitrogen. However, its potential as a feedstock for cellulosic ethanol production has not been evaluated.

World-wide acceptance of genetically-modified crops needs to be resolved so that prairie producers can explore more fully the potentials of this technology. The experience with herbicide-tolerant hybrid canola has clearly demonstrated how genetic yield improvement can be enhanced with improved agronomic practices, to provide more flexibility and sustainability in farming systems.

The future developments of farming systems on the Prairies will also need to be guided by risk management. The integration of livestock and crop farming systems offers the most opportunities for this. However, these developments will only be possible with the adoption of new business models that accommodate better integration and financial risk-sharing. The risks associated with annual cropping can be addressed through the development and adoption of more predictive crop production models which allow for a better matching of crop inputs with climatic conditions, and pest management models that can more easily predict pest occurrences. The key will be to manage costs and crop inputs more effectively in order to react better to market and climatic conditions. The development of site-specific sensing technology for nutrient applications and crop management in highly variable soils and climates will be necessary if farming is to become more sustainable. Government policy will also have a significant impact on future developments – for example through biofuels and biomass initiatives. Both local and global policy will continue to impact Canadian agriculture

19.7.1 Economic and Energy Realities

The economic climate for the Prairie farmers has been such that realised net income has been falling since the late 1970s. The accumulated farm debt for Canada as a whole increased from \$9.1B in 1970 to \$32B in 1998, and the Canadian farm debt-to-asset ratio was still increasing in 2006 (Fulton et al. 1989; Schmitz et al. 2002; Anonymous 2006f). The debt-to-income ratio in 1981 was 4.4 whereas, for the period 1997–2005, the ratio has averaged 15.3 (Brinkman 2007). During that same period, the ratio for American farms has increased only slightly to 3.7. The decrease in realised net farm income is due, in part, to increases in input costs and decreases in commodity prices. Changes in transportation policies have also significantly increased the overall cost of production (Schmitz et al. 2002). Within this economic climate, we are also observing rapid consolidation in agricultural production. This, in turn, is causing rural depopulation and labour shortages in rural areas, which makes it difficult to maintain essential services such as health care, education and commerce. There is urgent need to investigate more innovative business and investment models that allow for more economic integration between livestock and annual cropping farming systems as a way to provide more financial stability and better risk management associated with food, feed and fibre production. The development of robotic applications could also help address labour shortages and also allow for more farming units as opposed to fewer larger units as the current trends show.

The rapid increase in world fossil fuel use and the effect of this on global warming and pollution is focusing attention on agriculture as a source of renewable energy. Agriculture is also seen as a potential player for reducing greenhouse gases through the sequestration of carbon dioxide into soil organic carbon. The Canadian Prairies can be viewed as a large solar collector capable of converting the sun's energy into various energy products, i.e. grain and/or crop residues for producing ethanol, vegetable oil for biodiesel or burning crop biomass for electricity. However, energy is still required to support this 'solar collector'. Thus fossil fuel is needed to operate equipment, to manufacture and distribute crop inputs, and to store and transport grains to the end-user. As indicated in Table 19.11, fertiliser, fuel and oil account for at least 90% of total energy requirements, fertilisers alone accounting for 60–70%. Greater efficiency in the use of these components and of N-fixing crops will be required to reduce the use of non-renewable energy in Prairie agriculture. In the case of fertiliser, site-specific applications that take into consideration temporal and spatial variability at a field level offer important opportunities for improving efficiency. In the case of fuel use, consideration has to be given to the concept of using smaller field equipment with more robotic capability as a way to reduce both labour use and fuel consumption.

19.7.2 Farming Systems

Cropping systems on the Prairies have evolved over the last 25 years to incorporate more continuous cropping, crop diversification and no-till. These systems are also addressing the issue of soil degradation from wind and water erosion while contributing to a more productive and sustainable soil resource with improvements in air and water quality.

The decreasing realised net farm income combined with the high cost of transportation of bulk commodities is causing shifts in land use towards animal production. The implication is that the more marginal areas, or areas incurring high transportation costs, are being converted to forage production. In the animal and cropping sectors, we are seeing fewer, but larger, operations. However, the present shift is towards more specialisation rather than integration of cropping and animal production systems. This reduces the opportunities for developing innovative and sustainable farming systems. There is urgent need to develop more comprehensive farming systems that integrate crop and animal production in order to exploit their synergy and enhance the sustainability of Prairie farming.

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Chapter 20
Rainfed Farming Systems in the USA

Alan Franzluebbers, Jean Steiner, Doug Karlen, Tim Griffin, Jeremy Singer, and Don Tanaka

Abstract This chapter describes characteristics of four major rainfed farming regions and systems in the USA: Great Plains wheat-sorghum-cattle; midwestern corn-soybean-hogs, southern cotton-peanut-poultry, and coastal diversified crops-dairy. Rainfed farming systems in the USA are highly productive, economically important, ecologically diverse and technologically driven. Management approaches to achieve resource efficiency and agricultural sustainability are described, including the use of improved genetic seed sources, crop rotations, appropriate fertiliser application techniques, conservation tillage and integrated crop-livestock production systems. Issues of increasing oil and fertiliser prices, sustainability of soil and water resources, and climate change are current challenges facing agriculture in the USA.

Keywords Biofuel production • Carbon sequestration • Cattle • Conservation tillage • Corn • Cotton • Crop rotations • Dairy • Environmental quality • Forages • Hogs • Integrated crop–livestock systems • Nitrogen • Peanut • Phosphorus • Poultry • Soybean • Water quality

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_20,

20.1 Introduction

The United States of America (USA) is a large country (982 million hectares) with a diverse economic base. Agriculture currently contributes about $90 billion to the economy (USDA-ERS 2008), but this is less than 1% of the gross domestic product.

Rainfed farming systems are important throughout the USA, but are most dominant in the eastern half where precipitation is greater than 500 mm/year. Various regions of the country have unique climatic, physical, and socio-economic conditions that have contributed to the development of particular farming systems. Four major regions of the country with rainfed farming systems will be characterised and are outlined in Table 20.1.

North Dakota, Iowa, Georgia, and New York states are similar in size of land area, but different in their socio-economic and agricultural characteristics (Table 20.2).

New York and Georgia have vastly greater human population, somewhat greater per capita income and cultural diversity, and far less farmland than North Dakota and Iowa. Average farm size is largest in North Dakota, followed by Iowa, and smaller in Georgia and New York.

20.1.1 Climate of the USA

The climate of the USA is diverse. Mean annual temperature generally increases from north to south, while mean annual precipitation generally increases from west to east, except for the wetter conditions along the Pacific Coast and Rocky Mountains (Fig. 20.1).

Rainfed farming systems can be found throughout the country, even in areas with significant irrigation. Irrigation water supplies are becoming increasingly challenged by growing urban and suburban human populations in warm, arid and semi-arid regions where irrigated agriculture has traditionally been developed. Rainfed farming alternatives to irrigated agriculture are developing as a means towards maintaining agricultural sustainability in these areas.

Different regions of the country have developed specialised cropping and animal production systems under the influence of temperature and water limitations. Fig 20.2 shows examples of the differences in monthly temperature and precipitation that occur among the four major farming regions.

Table 20.1 Four major rainfed regions of USA

Region	Major enterprises	Representative state
Great Plains	Wheat–sorghum-cattle	North Dakota
Midwestern	Corn–soybean–hogs	Iowa
Southern	Cotton–peanut–poultry	Georgia
Eastern and western coastal	Diversified crops–dairy	New York

Table 20.2 Characteristics of the four representative states

Characteristic	North Dakota	Iowa	Georgia	New York
Area (Mha)[a]	17.9	14.5	15.0	12.2
Total human population (millions)[a]	0.6	2.9	8.2	19.0
Per capita income ($)[a]	17,769	19,674	21,154	23,389
Farm number[b]	30,619	90,655	49,311	37,255
Farmland (Mha)[b]	15.9	12.8	4.3	3.1
Mean farm size (ha) [b]	519.4	141.7	88.3	83.4
Value of machinery/equipment per farm ($)[b]	124,298	100,422	51,847	96,252
Total cropland (Mha)[b]	10.7	11.0	1.9	2.0
Rainfed farmland (%)[b]	99.5	99.6	91.9	99.0
Value of crop products sold ($ billion)[b]	2.5	6.1	1.6	1.1
Value of livestock products sold ($ billion)[b]	0.8	6.2	3.3	2.0
Cattle and calves sold (million head)[b]	1.1	2.9	0.6	0.6
Hogs and pigs sold (million head)[b]	0.4	41.2	1.2	0.3
Meat chickens sold (million head)[b]	0.2	9.6	1,288.5	2.8
Wheat grain harvested (Mt)[b]	5.9	<0.1	0.2	0.2
Sorghum grain harvested ('000 t)[b]	1.2	3.6	25.9	0.4
Corn grain harvested (Mt)[b]	2.8	47.0	0.7	1.1
Soybean harvested (Mt)[b]	2.4	13.3	0.1	0.1
Cotton fiber harvested ('000 t)[b]	NR	NR	351.4	NR
Peanuts harvested ('000 t)[b]	NR	NR	532.5	NR
Forage harvested (dry weight '000 t)[b]	3.2	4.7	1.3	5.2

NR, not reported
[a] Data from the 2000 US Census (http://factfinder.census.gov)
[b] Data from the 2002 Census of Agriculture (USDA-NASS 2002)

20.1.2 Soils of the USA

Soil resources are as diverse as the climate, and all 12 of the soil orders in the USDA Soil Taxonomy classification system can be found (USDA 1999). The most important soils for agriculture are Mollisols, Alfisols, Entisols, Inceptisols and Ultisols.

Mollisols are the dominant soils in rainfed farming areas, occupying 21.5% of the total land area in the USA, and are extensive in the Great Plains region. They were derived from grassland ecosystems, being characterised by a thick, dark surface horizon.

Alfisols occupy 13.9% of the land area, and occur throughout the USA. They were derived from moderately leached forests, are well developed with relatively high native fertility and contain a subsurface clayey horizon.

Entisols occupy 12.3% of the land area and are of more recent origin. They were formed from unconsolidated parent material and usually have no genetic horizons

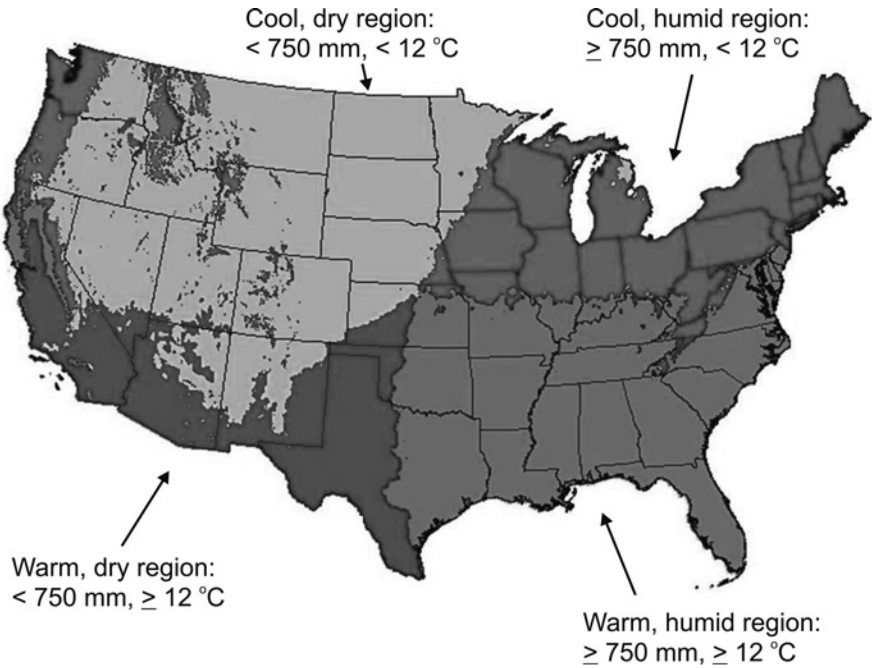

Fig. 20.1 Major climatic regions in the USA based on mean annual precipitation and mean annual temperature. Produced by H.J. Causarano using the spatial climate analysis service (www.prism.oregonstate.edu/)

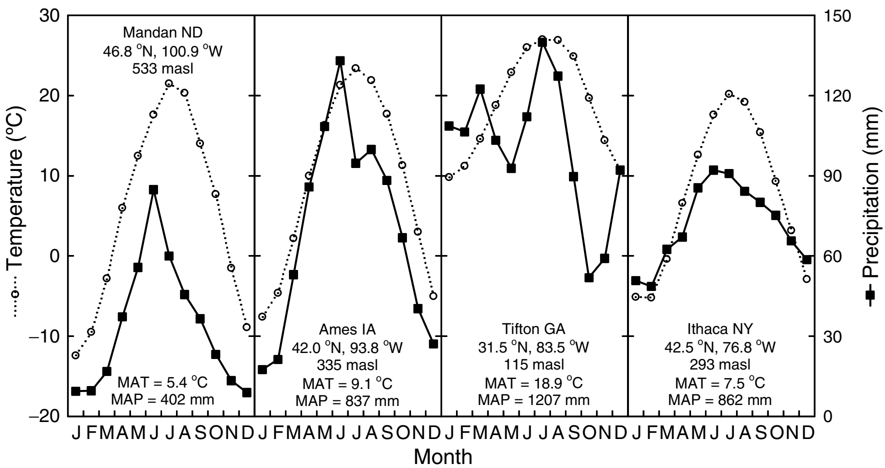

Fig. 20.2 Mean monthly temperature and precipitation at four locations representing the wheat-sorghum-cattle region (Mandan, North Dakota), corn–soybean–hogs region (Ames, Iowa), cotton–peanut–poultry region (Tifton, Georgia), and diversified crops–dairy region (Ithaca, New York). Long-term data (>30 year) from www.worldclimate.com. MAT is mean annual temperature and MAP is mean annual precipitation

except an A horizon. Soils that do not fit into one of the other 11 orders are often considered Entisols. Thus, they are very diverse, both in environmental setting and land use. Although many Entisols are found in rough terrain, they also occur in large river valleys and associated shore deposits where they provide suitable farmland.

Inceptisols occupy 9.7% of the land area. They are more developed than Entisols, but exhibit minimal horizon development and lack distinct features. Inceptisols are widely distributed and occur under a range of ecological settings, but are more typically used for forestry, recreation, and low-input grasslands than for productive farmland.

Ultisols (9.2% of the land area) are soils strongly leached, acidic, and with relatively low native fertility. Because of the favorable climate in the southeastern USA where they predominate, Ultisols often support productive forests. Being acidic with relatively low levels of plant-available Ca, Mg, and K, most Ultisols need liming and fertilising to be agriculturally sustainable. There are a number of minor soil types that are not particularly relevant to rainfed farming systems.[1]

20.1.3 Contrasting Characteristics of Agricultural Regions in the USA

Agriculture in the USA is highly and technologically advanced. It is dependent on fossil fuel for operating tractors and harvest equipment, for supplying energy to dry and process products, and for the manufacture of nitrogen fertiliser and various pesticides. There are more than two million farms in the USA, concentrated more in the east than in the west due to more favorable precipitation in the east (Fig. 20.3). Most of the cropland occurs in the eastern half of the country (Fig. 20.4a) and most of the pastureland (both native and introduced forages) in the western half (Fig. 20.4b).

Cropland constitutes 18% of the country, and pastureland 20%. Concentrated areas of animal sales are a feature of the highly industrial model of concentrated animal feeding operations (CAFOs) in the USA. This model has specialisation in each step of production with vertical integration through either contractual arrangements or ownership by large companies. In 2000, four companies slaughtered 81% of cows, 73% of sheep, 57% of pigs, and 50% of chickens (Swenson 2000).

Because of high technological and fossil-fuel inputs, many farmers in the USA are capable of utilising large land areas. In 2002, 2.1 million farms were operating on 380 Mha of farmland. In general, farm size increases with decreasing precipitation, because of lower yield potential and need for greater land area to support the investments required to farm (Table 20.2).

[1]Soil maps of the USA can be found at: http://soils.usda.gov/technical/classification/taxonomy/.

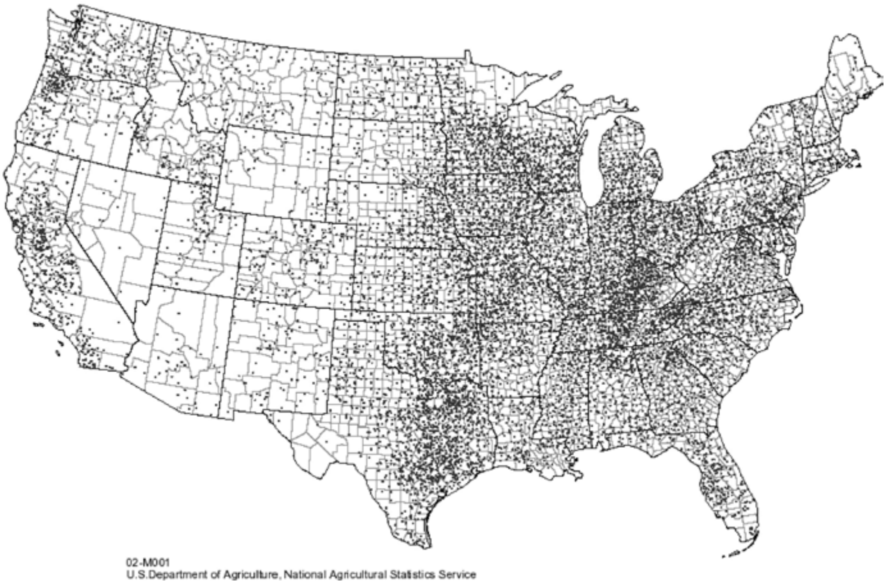

Fig. 20.3 Distribution of farms in the USA. Each dot represents 200 farms with a total of 2,128,982 (USDA-NASS (2002))

Fig. 20.4 Distribution of (**a**) cropland (total of 175.8 Mha) and (**b**) pasture land (total of 197.2 Mha) in the USA. Each dot represents 20,243 ha (USDA-NASS (2002))

20.2 Great Plains Wheat–Sorghum–Cattle Region

20.2.1 Climate and Soils

The Great Plains has a continental climate, characterised by (1) a strong precipitation gradient, decreasing from east to west by as much as 60 mm per 100 km and (2) extreme variability among seasons and years (Garbrecht and Rossel 2002).

The southern portion of the Great Plains is much ‘drier’, because the warmer temperatures in autumn, winter, and spring contribute to higher evaporative demand.

Precipitation occurs in all months, but predominantly in summer (Fig. 20.2). Evaporative demand greatly exceeds precipitation. For example in the southern portion (Bushland, Texas), evaporative demand is more than twice that of precipitation during each month of the year (Steiner et al. 1988). With year-long water deficit, crop management focuses on capturing and storing water in soil for use during the growing season and minimising evaporation from the soil (Stewart and Steiner 1990). Depending on the magnitude of the water deficit, the type and frequency of cropping is contingent upon soil water storage from previous seasons. In the northern Great Plains, a considerable portion of precipitation falls as snow, providing opportunities for snow trapping strategies to accumulate soil moisture.

Great Plains soils are predominantly Mollisols, rich in basic cations. They are capable of storing sufficient water deep in the soil profile to withstand extended dry periods characteristic of the semi-arid and arid region of the western states of the Great Plains.

20.2.2 Structure and Characteristics of Farming Systems

Wheat in the USA is grown primarily (Fig. 20.5a) in the sub-humid to semi-arid Great Plains region that lies between the Rocky Mountain foothills and roughly the 98th meridian. In the Great Plains region, wheat production was historically a monoculture, interrupted only by bare fallow in areas with unreliable and low precipitation during the growing season (Fig. 20.2). In the northern Great Plains, winter and spring wheat and other small grains (e.g. barley, oat, rye, triticale) are the main crops, as the low mean annual temperature and consequent short, summer growing season limits opportunities for alternative crops. In the central and southern Great Plains, winter wheat is grown for grain, but also as winter forage, especially in the

Fig. 20.5 Distribution of (**a**) wheat harvested for grain (total of 18.4 Mha; each dot represents 4,049 ha) and (**b**) sorghum harvested for grain (total of 2.7 Mha; each dot represents 810 ha) in the USA (USDA-NASS (2002))

southern part of the region. Evapotranspiration for wheat is high, because of a long growing season, and especially in spring and early summer, when wheat is forming and filling grain, while wind speeds, vapor pressure deficits, and solar radiation are high (Howell et al. 1997).

A large portion of sorghum in the USA is grown in the southern Great Plains, often in rotation with wheat to provide flexibility in capturing the widely varying precipitation among years (Fig. 20.5b). Grain sorghum survives extended dry periods in the summer, and therefore offers producers an alternative rotation crop to the continuous winter wheat cycle. In the central Great Plains, where evaporative demand and minimum temperature are lower than in the southern Great Plains, corn rather than sorghum is sometimes grown in rotation with wheat. Across the Great Plains, there are a number of other summer crops that have been explored for their role in wheat-based rotations.

Beef cattle production is also a key component of agriculture in the Great Plains. Some farms integrate beef production with annual and perennial crops and native rangeland, while other farms have more specialised systems (i.e., CAFOs). Cattle production in the USA has the distinct stages of (1) cow/calf production, (2) stockers (grazing after weaning), (3) feedlot, and (4) slaughter and packing. The cow/calf phase of the beef sector is dispersed on many small- to medium-sized farms across the USA (Fig. 20.6a). In the stocker phase, large numbers of weaned animals are transported to the southern and central Great Plains region where they graze for about 9 months on a combination of wheat, Bermuda grass and other warm season pastures, native range pastures, crop residues (sorghum and other warm season crops) and other forages. From the feedlot phase to the packer phase, ownership and geographic distribution of beef cattle are increasingly concentrated. Many of the largest feedlots and packer plants are located in the Great Plains states, particularly in the semi-arid regions of Texas, Oklahoma, Kansas, Colorado, and Nebraska (Fig. 20.6b). Feed grains of corn, sorghum, and wheat are readily available in these regions, from local rainfed and irrigated production, as well as from the midwestern and other regions of the USA.

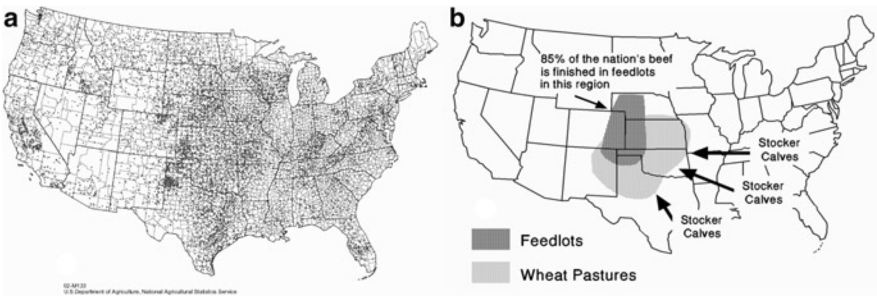

Fig. 20.6 Distribution of (**a**) cattle and calves (total of 95.5 million head; each dot represents 10,000 head) and (**b**) location of beef cattle components in the USA (USDA-NASS (2002) and Steiner et al. (2004))

20.2.3 *Efficiency, Productivity, and Sustainability*

20.2.3.1 Evolution of Cropping Systems

The Great Plains experienced one of the nation's greatest environmental disasters – the Dust Bowl – during the prolonged drought of the 1930s (Egan 2005). The Dust Bowl was associated with massive expansion of intensively tilled wheat; starting in the High Plains of Texas, Oklahoma and Colorado and extending eastward and northward to south-central Nebraska. During initial settlement, wheat was the dominant crop in the Great Plains, and plowing resulted in a large loss of soil organic C and N. Once these soils became exposed without vegetative cover, they were susceptible to erosion by water and wind. Many Great Plains soils are also subject to crusting, which impedes water infiltration and hinders seedling emergence.

To combat erosion, stubble-mulch tillage systems were developed to under-cut the soil, rather than invert it, for weed control. Over several decades, stubble-mulch tillage replaced the moldboard plow to become the 'conventional' tillage system, particularly in the drier portions of the Great Plains. However, with relatively low levels of biomass production and 14 months of bare fallow between wheat crops, residue cover was not adequate to protect the soil from wind and water erosion. As a result, soil organic C and total N declined in this type of system (Unger 2000).

In the middle of the twentieth century, researchers began developing no-tillage (NT) systems with herbicides for weed control. A number of long-term studies determined soil properties, water storage, and crop production under contrasting tillage systems and crop rotations. Reduced tillage and increased cropping intensity have had the greatest impact on increasing efficiency and sustainability of rainfed farming systems in the Great Plains (Peterson et al. 1998). Improved sustainability has been indicated by a number of experiments. For instance, soil organic C increased from 5.5 g/kg under wheat–sorghum–fallow to 5.9 g/kg under opportunity cropping (wheat, sorghum, canola, kenaf, tritacale[2]) (Unger 2001), and soil organic C and N were higher under NT than with other tillage systems and higher under continuous cropping than with fallow-based systems (Potter et al. 1997; Schomberg and Jones 1999). Greater soil organic C and N were also reported in various rotations of wheat, corn, millet, and fallow in Colorado compared with a conventional wheat–fallow system (Ortega et al. 2002), and diverse crop rotations enhanced potential soil microbial activity compared with the conventional wheat–fallow system (Ortega et al. 2005). However, the quantity of crop residue on the soil surface was more important than any other factor in affecting potential soil microbial activity. A number of other researchers have reported similar soil quality improvements with reduced tillage and greater amounts of crop residues returned to soil (Wright and Anderson 2000; Liebig et al. 2004, 2006; Cantero-Martinez et al. 2006).

[2]See glossary of plant names for scientific names

20.2.3.2 Efficiency of Water Use

Water availability is the primary limiting factor to crop production, so a great deal of research has focused on practices to increase water use efficiency (WUE). This has been approached through reduced or no tillage systems, which reduce evaporation from soils, potentially conserving water for transpiration by plants. The other primary approach to increasing WUE has been to intensify the cropping rotation to avoid fallow periods.

In a study of crop rotations and tillage practices in Kansas over 24 years (Thompson 2001), continuous sorghum with reduced tillage gave the highest economic return compared with continuous wheat, wheat–sorghum–fallow, wheat–fallow, and sorghum–fallow under reduced and no tillage. Using NT, it was possible to intensify cropping and enhance precipitation-use efficiency (PUE[3]) by 30% compared to conventionally tilled wheat–fallow systems across a range of soils in the central Great Plains (Peterson and Westfall 2004). Water was conserved in soil using NT and maintaining surface residues rather than being evaporated from bare soil under conventional tillage. Productivity was enhanced with increasing quantity of crop residue returned to the soil.

Examples of improving WUE include the following. Water-use efficiency with long-term sorghum cropping in Kansas was 22.1 kg of grain/ha/mm for stored soil water and 16.4 kg/ha/mm for in-season precipitation (Stone and Schlegel 2006). With wheat, WUE was 9.8 kg/ha/mm for stored soil water and 8.3 kg/ha/mm for in-season precipitation. Sorghum WUE increased from 12.9 kg/ha/mm under conventional tillage to 18.4 kg/ha/mm under NT, while wheat WUE increased from 8.6 kg/ha/mm under conventional tillage to 13.8 kg/ha/mm under NT.

Precipitation-use efficiency (PUE) for a range of crops potentially suited to the central Great Plains was highest (on a mass produced basis) for systems producing forage (14.5 kg/ha/mm) and lowest for rotations with a high frequency of oilseed crops (4.2 kg/ha/mm) or continuous small grains (2.8 kg/ha/mm) (Nielsen et al. 2005). Value of production ranged from $1.20/ha/mm for opportunity cropping to $0.30/ha/mm for wheat–sorghum–fallow. Soil water content at wheat planting in Kansas was lower after sunflower and soybean than after corn and sorghum (Norwood 2000). Sorghum grain yield and WUE increased with NT compared with conventional tillage in a wheat–sorghum–fallow rotation, but no differences in these parameters were found between tillage systems in wheat cropping systems (Schlegel et al. 1999). Production costs were greater with NT than with conventional tillage (CT) for wheat (due to costs of weed control), but similar for sorghum.

While cropping options remain limited for the hot and dry Great Plains environment, several water-efficient crops and management practices have shown potential for use in the region.

[3] PUE and WUE are defined and discussed in Chap. 1

20.2.3.3 System Improvements Through Diversification and No-Till

Research across the Great Plains has demonstrated the potential to increase PUE, generally through reduced tillage and diversification. Such practices have not always been economically feasible in the past, but are now being adopted across the region.

A sorghum–wheat rotation with NT generally increased economic return compared to continuous wheat and wheat–fallow, whenever sorghum grain yield was greater than 3.5 t/ha. Sorghum and sunflower were found to extract water from lower soil depths than wheat (Norwood 1999).

Long-term NT (1962–1989), despite increasing grain yield of wheat and sorghum, resulted in acidification of soil compared with conventional tillage (Tarkalson et al. 2006b). Nitrate leaching was a primary cause of the acidification under NT (Tarkalson et al. 2006a). Crop residue addition appeared to neutralise the acidity. However, this study indicates the need to improve nutrient-use efficiency under NT to mitigate soil acidification.

Diversification may include incorporation of livestock. Grazing of wheat is a common practice in the southern Great Plains; however, research has been much less focused on wheat as forage than on wheat for grain production. Often, protein supplements are required for portions of the wheat grazing period. Redmon et al. (1998) reported that annual legumes inter-sown with wheat could provide forage that met or exceeded cattle dietary quality recommendations from March through May, whereas this was possible with a pure wheat stand only in March. Soil fertility and economic aspects of including a legume in the system were not addressed in their study, but need to be investigated.

20.2.4 Economic Sustainability Through System Design and Management

Wheat has remained a dominant crop in the Great Plains for many decades, despite frequent periods of low market price. Cost pressures, economies of scale, and the need to manage risk have resulted in farm enterprises becoming larger. However, this has resulted in de-population and consequent loss of community infrastructure in some rural areas of the Great Plains. This has placed further pressures on the management of farms.

Traditional agricultural systems in the Great Plains were developed under conditions of cheap fuel, relatively low cost of N fertilisers, low commodity prices, and relatively few incentives to address negative environmental impacts of production systems. These conditions do not exist today. Diversified farms that include wheat, sorghum, and cattle enterprises often realise opportunities to offset risks in one enterprise with a benefit to another. For example, low sorghum prices may be offset by lower cost of feed for cattle.

The recent rapid interest in biofuel production, triggered by record high petroleum prices, government incentives and concerns about global climate change associated with rising CO_2 in the atmosphere, has resulted in a period of great opportunity to redesign agricultural systems to achieve greater sustainability. This new era has also brought uncertainty and risks to traditional agricultural systems in the region. Cellulosic biofuel production, particularly from forages, could bring new opportunities and challenges, especially regarding the balance between food production and energy needs.

There has been considerable change to farming systems in the Great Plains over the last 25 years. The area devoted to wheat production decreased by about 30% (Vocke et al. 2005) due to economic pressures and technical developments. These include changes in consumer preference (i.e. low carbohydrate diets), diversification of cropping systems, expansion of summer crops westward into the drier portions of the Great Plains, and land retirement under government conservation programs. The Conservation Reserve Program, one of USDA's largest conservation programs, was implemented primarily in the Great Plains (85% of enrollment area) (Vocke et al. 2005). Other changes are that some farmers are planting corn and soybean on land previously devoted to wheat, because of irrigation development, the need to diversify cropping systems, and a period of warmer and wetter climate in the region (Garbrecht and Rossel 2002).

While the Great Plains gained 4.3 million people from 1950 to 2000, 67% of the counties lost population. In particular, young adults have been leaving farm-dependent counties (Johnson and Rathge 2006). Off-farm income has become increasingly important for the majority of farms, as have government payments. Without government payments, only 18% of farms specialising in wheat production (i.e. obtaining greater than 50% of farm revenue from wheat) would have net income adequate to meet the full cost of production[4] (Vocke et al. 2005). While government program farm payments provide a short-term cash flow, there are additional effects that may exacerbate some of the challenges facing farming systems and rural communities in the Great Plains. Thus farm subsidies in the USA have resulted in increased land values and rental rates, making it more difficult for beginning farmers to compete for land. In regions of the USA where government payments are highest, cropland is most concentrated, suggesting that government payments are a major incentive to continue current production systems (Key and Roberts 2007). (Chapter 12 discusses social and political influences on the farm system).

Peterson et al. (1996) stated that wheat–fallow cropping was not economically sustainable without government payments. Experimental results have shown alternative rotations may be profitable. For example wheat grain yield was greater following sorghum than following wheat, and sorghum grain yield was greater following wheat than following sorghum (Schlegel et al. 2002).

[4]Full costs of production include: variable costs (inputs consumed in one production season), cash costs (variable cost plus rent, taxes, insurance, interest), and total economic costs (cash cost plus depreciation, returns to management and land, and family labour).

A wheat–wheat–sorghum–fallow rotation requires a yield of 3.5–4.0 t/ha for sorghum and 2.5–3.0 t/ha for wheat to be more profitable than a wheat–sorghum–fallow rotation. Economic incentive levels for adoption of NT may not have to be as high if yield enhancement with NT is substantial, such as with a significant yield increase under NT in a wheat–sorghum–fallow system (De La Torre Ugarte et al. 2004). The design of cropping systems on the Great Plains needs to take into account environmental costs and benefits and the distortions caused by government payments.

Wheat producers in the Great Plains are facing challenges from all types of risk – production, price or market, financial, institutional and human or personal (see Chap. 12). Recently, higher grain price has offered some economic gain, but rapidly rising input and transportation costs have continued the economic challenge to Great Plains farmers.

20.2.5 Integration of Enterprises

Livestock play a viable and sustainable role in agricultural production in the Great Plains, where about 17% of the agricultural land is used for pasture and grazing (USDA-NASS 2002). The estimated land area in integrated crop–livestock production is less than 10%, although this does not account for substantial grazing of winter wheat in Kansas, Oklahoma, Texas and a few other states (Wight et al. 1983). During the last quarter of the twentieth century, grain and livestock production were gradually separated as farmers tended to specialise in one or the other. This resulted in a decoupling of crop and livestock enterprises for short-term economic gain at the expense of long-term sustainability (McRae et al. 1989; Brummer 1998; Hesterman and Thorburn 1994; Krall and Schuman 1996).

Renewed interest in integrated crop–livestock systems has developed, because of increasing cost of fossil-fuel energy and natural resource degradation. Examples are rising fertiliser and chemical costs, increasing environmental concerns with CAFOs (waste disposal and pollution), and increasing awareness of the environmental effects from over-application of fertilisers and pesticides (Brummer 1998; Russelle et al. 2007).

Agricultural sustainability derived from system diversity can be attained by including multiple annual and perennial crops, such as wheat, barley, pea, sunflower, alfalfa, clovers, and meadows, and most importantly, integrating crops and livestock into a system. A key principle of sustainable agricultural systems should be that waste derived from one part of the system can be returned as food for another part of the system (Kirschenmann 2002). Using this principle, agricultural systems can be designed to take advantage of synergies such as crops providing feed for livestock and livestock helping with the recycling of nutrients and management of weeds.

In the Great Plains, extending the grazing season is crucial to reducing input costs for livestock systems. Literature on integrated crop–livestock systems is meager since this whole-farm system is one of the most difficult for researchers, who are often specialised (Luna et al. 1994). Whole-farm systems in the southern Great Plains use the traditional winter wheat cropping system to extend the cattle-grazing season by grazing winter wheat during the winter months until mid-March. Growing short-duration legume pigeonpea (*Cajanus cajan*) as a forage crop (and winter wheat in the same year) can supply forage during the summer when native perennial grass lacks sufficient quality and quantity for cattle. Pigeonpea uses water and nutrients below the effective rooting depth of winter wheat. This legume provides N for its own growth and for the following winter wheat crop (Rao et al. 2002a, b).

Livestock provide producers with an opportunity to add diversity to cropping systems, which can create additional opportunities to control weeds, explore synergies among crops, and diversify cash flow. In the central Great Plains, grazing may be as productive as feedlotting. For example, cow performance was similar whether they were grazing annual foxtail millet (*Setaria italica*) (November to December) that was swathed in late July or were fed millet in a feedlot (Munson et al. 1998). Swath-grazing cows during this fall period can also reduce environmental problems associated with cows in confined feedlots. Cropland used for swath grazing provides a means of cycling carbon produced by crops into the soil through manure, while decomposing crop residues also improve soil C sequestration (Singh et al. 1998; Soussana et al. 2004).

In the northern Great Plains, cows are typically wintered in a feedlot and fed hay baled the previous summer. These cows are, therefore, fed the most expensive forage during a period of time when their nutrient requirements are the lowest. Tanaka et al. (2005) demonstrated the feasibility of a 3-year integrated crop–livestock system. In this system, grain could be marketed directly or fed to livestock and marketed indirectly, while minimising purchased inputs, such as fertiliser (due to legume in the rotation) and pesticides, and providing swathed forage for winter cows. The 3-year cropping system provided crop diversity, as well as crop residues and forage with sufficient quality to meet the nutrient requirement of dry-bred cows. Wintering dry-bred beef cows on swathed forages and crop residues reduced winter feeding costs (November to February) by about 33% when compared to cows fed baled native hay in a feedlot (Karn et al. 2005). Crop production and livestock performance were not jeopardised by integrating crops and livestock; long-term impacts may be synergistic for both enterprises.

Just as agriculture has specialised in crops and livestock, so has the scientific community. Future agricultural systems will need to focus on the potential synergies and synchronies of multi-species systems, such as integrated crop–livestock systems, and how we can use them to develop agricultural systems that are more resilient. At present, many of our agricultural systems lack sufficient crop and animal diversity to be resilient, and so cannot be considered sustainable. A goal of integrated crop–livestock systems, from a livestock manager's point of view, is to develop crop and perennial forage systems that can supply year-round nutritional needs of livestock at a reasonable cost.

20.2.6 Natural Resource Issues

Wetland and grassland habitats in the northern Great Plains are important breeding ground for water birds. Higgins et al. (2002) indicated that these habitats are at risk from expanded cultivation in the region.

Future cropping systems based on perennial crops, such as switchgrass, alfalfa, perennial grains, to reduce fuel, labour, traction and other production costs and enhance the natural resource base are being explored (Cox et al. 2006).

20.2.7 Summary of Issues

The Great Plains is a semi-arid region that must necessarily focus on water limitations to production. Agriculture must compete for ground water with municipal and industrial sectors. Stopping both wind and water erosion are goals of sustainable agricultural systems. Conservation tillage systems are being deployed in the region to conserve soil water and to avoid soil erosion. Social issues of importance are loss of population and infrastructure in rural areas, over-reliance on farm subsidies to remain profitable, and uncertainties related to bioenergy policy. The high cost of energy and fertilisers is a concern across the country, as is the threat of climate change. Because the region has become highly specialised in crop and animal production systems, diversification of farm operations is needed to stabilise farm income against the vagaries of market forces and to hedge against future cutbacks in government support payments. Some solutions to these issues are to: (1) increase the use of legumes in cropping systems; (2) develop integrated crop–livestock systems; and (3) diversify cropping systems. Value-added processes should also be enhanced at the farm and rural community level, perhaps including identity-retained marketing (e.g. meeting locally grown, naturally produced, organic, or certified standards).

20.3 Midwestern Corn–Soybean–Hog Region

20.3.1 Structure and Characteristics of System

The midwestern states produce most of the corn (Fig. 20.7a) and soybean (Fig. 20.7b) in the USA, and are often referred to as the Corn/Soybean Belt. The area includes all of Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio, and Wisconsin and portions of the Dakotas, Kansas, Kentucky, and Nebraska. The region was settled between 1800 and 1875, so agriculture has been practiced for 150–200 years.

Fig. 20.7 Distribution of A corn harvested for grain (total of 27.6 Mha) and B soybean harvested for beans (total of 29.3 Mha) in the USA. Each dot represents 4,049 ha (USDA-NASS (2002))

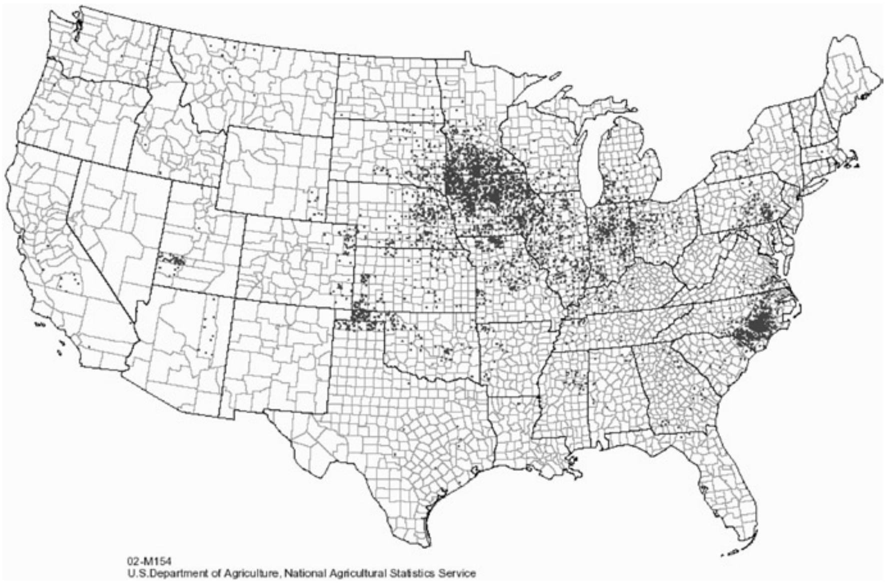

Fig. 20.8 Distribution of swine in the USA. Each dot represents 15,000 head with a total of 60.4 million head (USDA-NASS (2002))

20.3.1.1 Climate and Soils

Cold winters and hot summers are characteristic of the region, generally with sufficient precipitation during the summer to accommodate these warm-season, annual crops (Fig. 20.2). As in the Great Plains, wheat–sorghum–cattle region, the best soils for corn and soybean production are Mollisols, which originally supported grassland vegetation. There is also a significant area of Alfisols, derived from forest vegetation, in the eastern portion of this region. A majority of the hogs and pigs are housed here (Fig. 20.8).

Soils throughout the midwestern USA are characterised by a relatively high soil organic matter. To achieve maximum productivity under conditions of high precipitation and limited internal drainage, many soils have been engineered with subsurface (tile) drainage lines. Farmers in the region recognised early that "on land which is too wet, our cereals will not grow, not so much on account of the water as for the want of air which the water prevents from reaching their roots" (Hoyt 1866). To remedy this situation, county-level drainage projects commenced in the early twentieth century. By 1987, 20.8 Mha in the region had been artificially drained (Zucker and Brown 1998), and drainage systems are still being installed on many farms. This practice helps ensure high productivity, but it also increases the 'leakiness' of agrichemicals, resulting in substantial loss of nitrate to drainage waters, streams, rivers, and ultimately to the Gulf of Mexico. Loss of N, P, sediment, and pesticides, together with the presence of pathogens, has accentuated water quality concerns throughout the region in recent years (Dinnes et al. 2002; Dinnes 2004).

20.3.1.2 Historical Conditions

Up to the mid-twentieth century, farms in the midwestern USA were typically diverse operations, producing a variety of crops (including corn, wheat, oat, rye, clover, alfalfa (lucerne), grasses, garden vegetables, sorghum and tobacco) and raising a variety of livestock (including swine, dairy, beef, sheep, poultry and horses). This region is also where, at age 15, Henry A. Wallace scoffed at tradition and developed hybrid corn, which led to an increase in average grain yield in Iowa from 1.6 to 10.7 t/ha between 1931 and 2007. Following World War II, soybean was also converted from a forage crop to the second largest grain crop grown throughout the region (Karlen 2004). These changes were accompanied by a major decrease in on-farm crop diversity, primarily at the expense of small grains (Fig. 20.9). Another major shift in the midwestern USA has been the manner in which pigs and cattle are raised. Previously dispersed among many small farms, most animals are now being raised in CAFOs.

We have begun to experience the negative economic and environmental impacts brought about by this change from farm diversification to specialisation. Promoted on the basis of efficiencies of economy of scale and local consumption of corn grain, CAFOs are now being scrutinised because of concerns about odours and water quality degradation from manure spills. CAFOs and the grain marketing infrastructure associated with decreased crop diversity have also locked land owners and operators into a greater dependence on commodity-specific, government-support payments. Collectively these forces have reduced the number of farms and farm-families, and their spatial and temporal diversity. This specialisation has also made it increasingly impractical, under current market conditions, to move away from corn and soybean production, despite the recognised benefits of diversity on economic stability, labour distribution, ecological and environmental outcomes, and the need to respond rapidly to changing climatic and economic conditions.

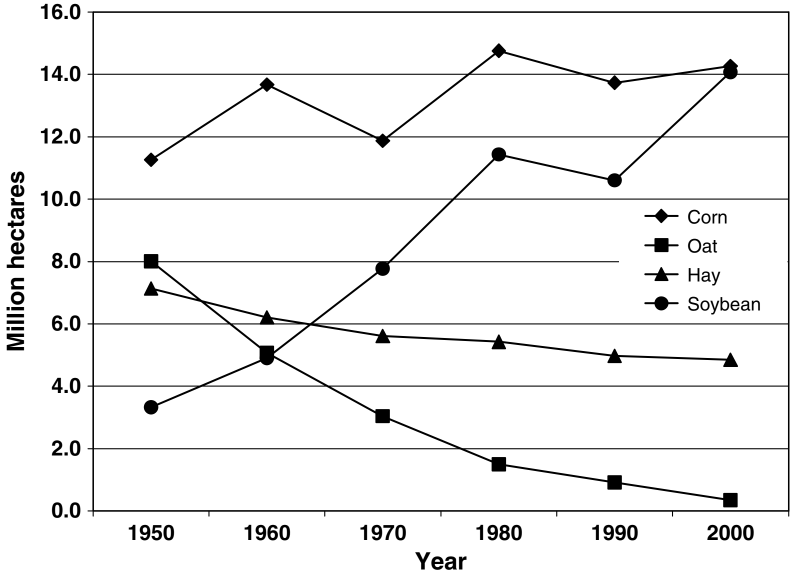

Fig. 20.9 Farmland in the midwestern USA devoted to corn, soybean, hay, and oat during the latter half of the twentieth century (USDA-NASS (2008))

20.3.2 Efficiency, Productivity, and Sustainability

Post World War II increases in efficiency and productivity throughout the midwestern USA have been associated primarily with the specialisation and separation of animal- and crop-production enterprises. Increasing farm size has also occurred, simultaneously with decreasing farm numbers (Fig. 20.10). Separating crop and animal enterprises has reduced the use of animal manure and meadow legumes as N sources, while the application rate of inorganic N fertiliser was increased by an average of 2.4 kg/ha/year from the mid-1960s to the late 1990s (Dinnes et al. 2002).

Adoption of specialised farming system practices has affected the sustainability of soil and water resources throughout the region. Reduced use of perennial legume rotations (alfalfa and clovers) and animal manure has negatively affected many soil physical, chemical, and biological properties and processes (Klapwyk et al. 2006). Specialised cropping systems may also affect water quality because annual cropping systems are inherently ‘leaky’ in spring and early winter. Thus nitrate that accumulates in the soil before and after annual crop growth is vulnerable to leaching below the crop root zone. It is then lost to groundwater through percolation or into streams and lakes via subsurface drainage lines (Rabalais et al. 1996). Economically-viable cover crop systems need to be explored further in this region to help avoid loss of nutrients during these vulnerable periods (Singer et al. 2007).

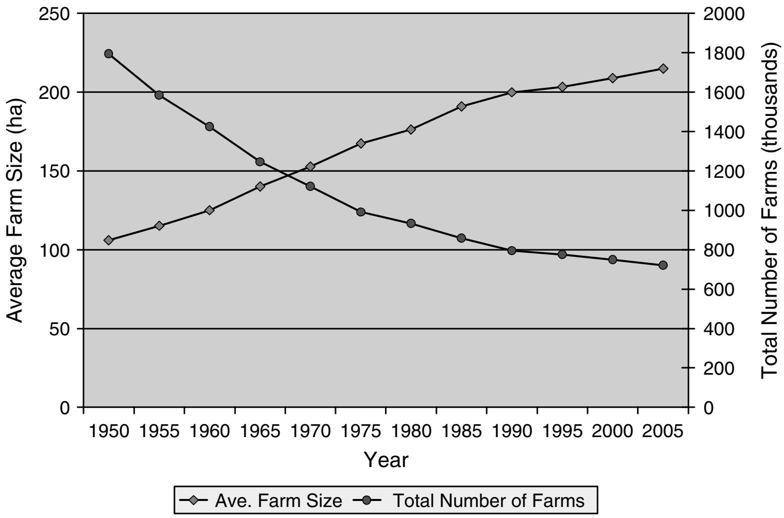

Fig. 20.10 Changes in number of farms and average farm size in the midwestern USA during the latter half of the twentieth century (USDA-NASS (2008))

A positive result of farm specialisation in the region has been a steady increase in the productivity of corn, with mean yield increases of approximately 110 kg/ha/year. The increase has been achieved through improved genetics (~70%) and better management of plant populations, row spacing, weeds, fertility, disease and insects (~30%). Average soybean yield has also improved, for example in Iowa from 1.3 t/ha in 1940, to 1.7 t/ha in 1960, 2.6 t/ha in 1980, and 2.9 t/ha in 2000 (USDA-NASS 2002). During 2006 and 2007, maximum soybean yield of 10.4 t/ha was achieved with intensive management in on-farm yield contests (Pioneer 2008). The difference between contest and regional yields suggests there is great potential to further increase soybean productivity throughout the region (if it is economically feasible).

Conservation of soil resources throughout the midwestern USA was enhanced during the 1990s with the adoption of conservation tillage practices (Fig. 20.11). This change was driven by the development of herbicide (glyphosate)-resistant soybean varieties to control weeds and ensure stability of yield.

The efficiency of use of fertiliser N applied to corn has been estimated at 40–60% (Varvel and Peterson 1990). An additional 16–80 kg/ha/year of fertiliser N is recycled into soil organic N pools when crop residues are returned to the soil (Yamoah et al. 1998). Because no N fertiliser is applied to soybean, it can help reduce the amount of N leached (Varvel and Peterson 1992).

Precipitation use efficiency for continuous corn has ranged from 3.6 to 13.7 kg/ha/mm, and for rotated corn, from 5.7 to 16.5 kg/ha/mm. For soybean, PUE averaged 3.0 kg/ha/mm (2.5–3.3) over an 8-year period (Varvel 1994, 1995).

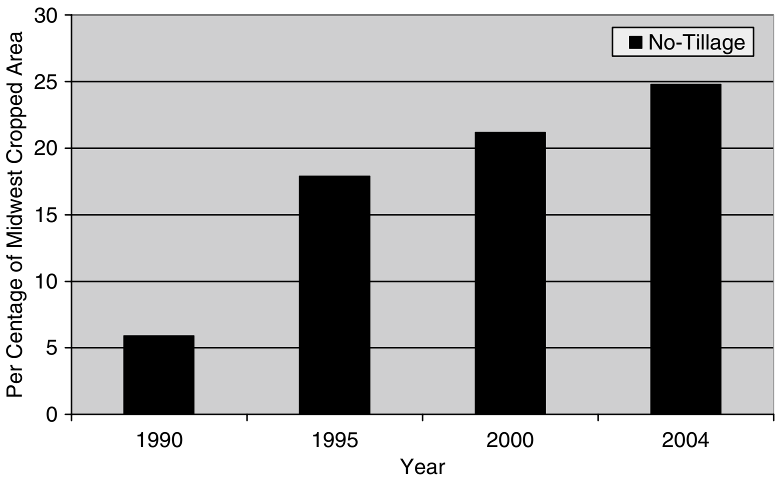

Fig. 20.11 Adoption rate of no-tillage cropping in the midwestern USA (Data from Conservation Technology Information Center)

20.3.3 Economic Sustainability Through System Design and Management

Corn and soybean farmers in the midwestern USA have, until recently, maintained their viability by collecting government farm subsidy payments. In 2002, the federal government paid $1.98 billion to corn producers and $0.67 billion to soybean producers as direct payments. Total farm subsidies peaked in 2005 at approximately $25 billion; they dropped to $16 billion in 2006 and are projected to drop further and remain around $12 billion for the next 10 years (USDA-ERS 2007a). Declining farm subsidies can be attributed to an increase in cash receipts from the expansion of the corn-based ethanol industry. However, greater input costs (such as fuel and chemicals) are projected to erode net farm income during the 10-year expansion period for ethanol production. Farmers will need to lower risk and increase profitability by diversifying their operations, to grow more crops. For example, a 5-year rotation of corn–soybean–alfalfa–alfalfa–alfalfa returned 100% and 158% more income than a corn–soybean rotation using NT and chisel tillage, respectively (Singer et al. 2003). In a tillage experiment, the use of swine- or beef-manure compost reduced the need for commercial N fertiliser by about 35%. This had little effect on economic return for a moldboard-plow system, but a large beneficial effect on economic return for a NT system (Singer et al., unpublished data). Greater returns in the future could likely be obtained by growing crops that would require lower N input than corn, and by using production systems that require less overall energy, because of the high cost of energy-intensive inputs. Lower temporal risk should also be possible through diversification, using crops of different life cycles, thus spreading the risk of unfavorable environmental conditions across the growing season.

20.3.4 Soil Fertility Management

Soils in the midwestern USA were among the most fertile in the world, requiring little supplemental fertilisation for half a century after initial cultivation. The need for lime was recognised in the eastern portion of the region and in areas where forage legumes were grown to support dairy operations. Yield responses to N and P eventually became apparent and, during the 1950s, a typical fertiliser recommendation in Iowa was 44-9-0 kg/ha N-P-K. Since the 1960s, fertiliser N and P rates have increased steadily with increasing corn yield and decreasing animal manure inputs until the farm financial crisis of the 1980s caused many producers to re-examine their fertilisation practices. This trend was evident even on research farms such as the Deep Loess Research Station near Treynor, Iowa. Here, P fertiliser rates, which had averaged 40 kg/ha/year (1964–1982), were reduced to 9 kg/ha/year from 1983 to 1995 (Karlen et al. 1999).

Reduction in fertiliser application was also a response to recognised groundwater and stream quality problems associated with midwestern cropping systems (Dinnes et al. 2002), and also to improved management assessments, such as the late-spring soil nitrate test (Blackmer et al. 1989). Widespread adoption of practices addressing water quality at the watershed scale resulted in a 30% reduction in stream water NO_3-N concentration (Jaynes et al. 2004). Increased awareness of unintended water-quality effects from excessive N and P fertiliser use was good. However, this may have resulted in a reduced effort to manage other essential plant nutrients efficiently. For example, K has been found to be a limiting factor under NT and ridge-till corn production in several locations (Rehm 1992; Borges and Mallarino 2001; Karlen and Kovar 2006). Multiple factors, including depth stratification of K, low soil temperature, and limited plant root exploration, have been postulated as contributing to development of K deficiency.

Sulfur is another essential plant nutrient not commonly recommended as fertiliser in Iowa (Sawyer and Barker 2002) and other parts of the midwestern USA, despite the occurrence of significant corn yield response to S application (O'Leary and Rehm 1990; Stecker et al. 1995; Rehm 2005; Lang et al. 2006). While yield responses to S fertiliser have been inconsistent (Hoeft et al. 1985), the need to apply S is increasing following both government regulation to reduce industrial air emissions of S and rising crop yield potential. The most responsive soils to S have been those with coarse-texture and low organic matter. Responses to S are most likely to occur in eroded areas and where crop residues have been removed for bio-fuel production. Site-specific soil fertility assessments have also revealed increasing surface soil acidification, often due to long-term use of ammonia-based fertiliser N. Site-specific assessments have led to increased use of differential liming by many fertiliser and lime distributors. Soil redistribution by tillage is a significant factor in creating within-field soil variation (Schumacher et al. 2005). Wind and water erosion maps could help target the type of conservation practices, such as cover crops, organic matter additions and NT suitable to address specific erosion processes. Projects focused on soil quality assessment have also successfully addressed soil fertility, organic matter, structure, and erosion issues, essential for sustainable soil resource management (Karlen et al. 2003).

20.3.5 Pest and Disease Management

Reliance on the two dominant crops of the region increases the likelihood of localised and widespread pest outbreaks. Major insect pests of corn in the midwestern USA include the European corn borer (*Ostrinia nubilalis*) and corn rootworm (*Diabrotica* spp.). Since 1997, *Bt* corn[5] has been commercially available to provide transgenic control of the European corn borer and, in 2003, transgenic corn hybrids were released that provided resistance to corn rootworm. Both of these technological advances have contributed to an immediate reduction in insecticide use for field corn. In 2000, insect-resistant (*Bt* only) hybrids occupied 18% of land in corn nationally, compared to 21% in 2007. Stacked hybrids[6] with multiple insect resistances occupied 1% of the land in corn nationally in 2000, but rose to 28% in 2007 (USDA-ERS 2007b).

Disease management of corn is primarily through hybrids with resistance to periodic foliar diseases such as stalk rots (*Gibberella zeae*; *Stenocarpella maydis*; *Colletotrichum graminicola*; *Macrophomina phaseolina*; *Fusarium moniliforme*), common rust (*Puccinia sorghi*), and gray leaf spot (*Cercospora zeae-maydis*), although selection for resistance to ear rots is also currently available. Corn in the northern part of the region is unlikely to respond economically to in-season fungicide applications. It is generally not recommended to spray fungicide on resistant or moderately resistant hybrids. As seen in the large increase (19%) in land planted to corn from 2006 to 2007 and the demand for corn that the corn-based ethanol industry has created, greater occurrence of continuous corn is expected to increase disease severity. Some farmers growing continuous corn have responded by once again burying stubble with inversion tillage to lower the likelihood of disease outbreaks.

Soybean is susceptible to many foliar, stem and root, seed and seedling diseases, as well as attack by viruses, nematodes, and insect pests. Major insect pests of soybean include the bean leaf beetle (*Cerotoma trifurcata*) and the soybean aphid (*Aphis glycines*). Bean leaf beetle can cause economic damage in soybean by foliar feeding and transmitting the bean pod mottle virus, which affects seed quality. Recent discoveries have identified tolerance in soybean varieties to this virus, use of which will probably become the best management tactic in the future. Soybean aphid has also periodically caused economic injury. Since its arrival in 2000, populations of soybean aphid have exceeded economic thresholds in 2001, 2003, and 2005 (Rice et al. 2007). Soybean cyst nematode is another major pest estimated to infest 70% of the production fields in Iowa. Soybean cyst nematode has been managed through a combination of crop rotation and variety selection (Iowa State University 2008).

[5] See Glossary.

[6] See Glossary for definition.

20.3.6 Weed Management

Weed management during the past decade in soybean, and more recently in corn, has relied on herbicide-tolerant crop technology to lower risk and reduce cost. Initial success of glyphosate-tolerant soybean resulted in the repeated use of glyphosate, which contributed to the emergence of glyphosate-resistant biotypes of certain weeds within 3 years after release of glyphosate–tolerant soybean (necessitating the use of alternative, more costly herbicides). The adoption of this technology accompanied a rapid increase in the use of NT for soybean production. Planting of herbicide-tolerant soybean varieties in the USA increased from 54% in 2000 to 91% in 2007. In Iowa, the percentages were 59% in 2000 and 94% in 2007. Only 6% of the corn planted in 2000 was herbicide-tolerant, but this increased to 24% in 2007 (USDA-ERS 2007b). Advantages of using glyphosate-tolerant crops compared to conventional varieties for weed management include broad spectrum weed control, greater flexibility in timing of application, and a large margin of crop safety. Hartzler et al. (2006) compared five weed management systems ranging from total reliance on glyphosate to no glyphosate (but using conventional herbicides) over a 4-year period in a soybean–corn rotation, for both chisel-plow and NT systems. Giant foxtail (*Setaria faberi*), velvetleaf (*Abutilon theophrasti*) and *Amaranthus* spp. were more prevalent in the chisel-plow system than in NT at the conclusion of the experiment, whereas dandelion (*Taraxacum officinale*) was present at higher density in the NT system. While all of these systems provided high levels of weed control, herbicide use was 66% lower in the glyphosate-only treatment compared with the system relying on conventional, pre-emergence and post-emergence herbicides.

Kegode et al. (1999) evaluated the interaction of tillage, rotation, and management on weed seed production. Increasing crop diversity in 5-year rotations that began and ended with corn and that simultaneously reduced tillage intensity resulted in lower grass and broadleaf weed seed production. However, cropping systems in the midwestern USA are currently dominated by the corn–soybean rotation and use high levels of inputs rather than relying on ecosystem or biological functioning. In Iowa in 2007, 95% of the harvested cropland was in corn and soybean, with corn occupying 63% of the harvested cropland (USDA-NASS 2002), suggesting a large potential for diversification in the future.

20.3.7 Integration of Enterprises and Land Management

During the latter half of the twentieth century, animal and crop production enterprises in the midwestern USA were separated to achieve efficiency – despite unknown environmental and social outcomes. The resulting use of feedlots (CAFOs) has concentrated animal wastes, often creating odor, water-quality problems, and excessive nutrient load on the limited land available for manure application.

Although many of these issues are being addressed on a case-by-case basis, this often does not occur without the threat of legal or regulatory action. Further, it is of concern that crop production fields are often managed uniformly without regard to their soil variability, resulting in acidification, erosion, and decreased organic matter content.

Although it is unlikely that wholesale cropping system changes will occur in the midwestern USA or that animal and crop management operations will be re-integrated into small diversified farms, there are opportunities for change if public opinion and government policies change. One vision is to shift our guidelines for natural resource and land management from the individual farm to the community or watershed, where all members would be rewarded for achieving a common good. By requiring watershed management plans to address all production, environmental and social concerns, it would be possible to address bioenergy, quality of air, water and soil, global warming, rural economic development and many other issues simultaneously. Coordinated efforts could also quickly alleviate potential conflicts, such as when the positive response to one issue (e.g. biofuels) might aggravate another issue (e.g. water quality). The key to solving complex problems in the region will be to implement agricultural practices and policies as an entire system, rather than as a collection of individual enterprises.

20.3.8 Biofuels

Resolving the negative external impacts associated with agricultural specialisation will not be easy, but it also will not be insurmountable. There has been increased public awareness that America's energy appetite cannot be ignored in an ever-increasing global community. Initial efforts to address the need for renewable biofuels were based almost exclusively on ethanol and biodiesel production from corn grain and soybean, but the Billion Ton Report (Perlack et al. 2005) stimulated efforts to identify a much broader range of cellulosic inputs that could be used for biofuel production through either biochemical or thermo-chemical pathways.

Cellulosic approaches to biofuel production are projected to be more sustainable and environmentally benign than grain-based scenarios because perennial biomass crops (for example switchgrass (*Panicum virgatum*), Miscanthus (*Miscanthus x giganteus*), and alfalfa (*Medicago sativa*)) can improve soil and water quality in several ways. Perennial biomass crops: (1) provide year-round ground cover that intercepts rain and reduces erosion; (2) develop plant root systems at greater soil depths and more extensively than annual crops – thus stabilising the soil; (3) capture a greater quantity of nutrients, improve water infiltration, but reduce leaching, reduce water runoff, and increase soil organic matter (Mann and Tolbert 2000; Dinnes 2004). They might also require less fertiliser nutrient and pesticide inputs than current row crops (Perlack et al. 2005).

In a comparison of energy budgets, McLaughlin and Walsh (1998) calculated that ethanol cropping systems derived from switchgrass could be 15 times more energy efficient than those derived from corn grain. Others have argued that, if continuous corn grain production were increased by 7.3 Mha, N loss from leaching could increase by 33% or 7.5 kg/ha (Elobeid et al. 2006; Wisner 2007) and, depending upon site-specific conditions and weather patterns, P loss could increase by 9,000 t/year.

20.3.9 Conservation Practices

Consolidation and specialisation of agriculture in the midwestern USA has drastically changed the landscape from one of diversification to near uniformity of corn, soybean and CAFOs. Water erosion potential is serious throughout the midwestern USA (USDA-NRCS 2008a). In the upper Mississippi River Watershed, where soil conservation practices such as contour strip cropping, buffer strips, farm ponds, drainage and water control structures were first installed by the Civilian Conservation Corps in the 1930s, many of the small-scale structures are being removed for the efficiency of larger equipment. Buffers and wildlife corridors, although included in many USDA-Natural Resource Conservation Service programs, are often inadequate for the interface between humans and wildlife, as evidenced by an increasing number of automobile-deer collisions and incidences of crop damage by wild turkey, deer and other animals. There are some small, localised efforts at reforestation throughout the region but, for the most part, on-farm woodlots and non-cultivated areas are rapidly disappearing – if not for agricultural crops, then for rural housing by non-farm families seeking to escape the urban and suburban environment. Such transitions affect not only land use and farming systems, but also demand for roads, bridges and better access to improved internet and telephone services.

A survey in 2005 of conservation practices in the South Fork of the Iowa River Watershed provides a snapshot of current agricultural practices (Tomer et al. 2008). The survey revealed that 85% of the total area (78,000 ha) or 95% of farmland was planted to corn and soybean. About 30% of the cropland received manure annually, before planting corn. Surface crop residues were generally inadequate (less than 30% cover) for soil erosion control. Edge-of-field erosion-control practices, such as grassed waterways and riparian buffers, were installed on 90% of those fields in which 34% of their area was classified as highly erodible. These conservation practices were generally aimed at controlling runoff, but the increased subsurface drainage exacerbated the loss of nitrate to surface waters. This example again illustrates how policies or practices intended to solve one conservation problem may inadvertently aggravate another. The long-term solution for sustainable, rainfed systems in the region should therefore be natural resource-based land management plans, policies and programs designed to ensure soil, water, and air quality, as well as social equity for all persons in the area.

20.3.10 Summary of Issues

The midwestern USA is the 'breadbasket' of North America that has highly fertile soils, relatively mild climatic conditions, and sufficient agronomic infrastructure to produce a steady supply of corn, soybean, cattle, and hogs. High fertiliser inputs in the region have caused concern for nutrient (N and P) runoff into streams, lakes, and rivers, as well as nitrate contamination of ground water supplies for the rural population. Conservation tillage systems have been adopted widely in the region in response to the availability of herbicide-resistant crop varieties, the need to control soil erosion from rainfall, and the need for savings in costly inputs of time, labour and fuel. Recent biofuel production from corn ethanol and soybean biodiesel has caused increased demand for crop commodities, which has fortunately increased gross farm returns at the same time that rising fuel and fertiliser prices have increased input costs. Sustainability of agricultural systems however will have to recognise not only key production and marketing issues at the macro-economic scale, but also key environmental and social issues at the farm and community level – such as soil erosion, nutrient runoff and dependence on government support.

20.4 Southern Cotton–Peanut–Poultry Region

20.4.1 Structure and Characteristics of System

Cotton (Fig. 20.12a) and peanut (Fig. 20.12b) are two characteristic crops of the southern region of the USA, and most of the nation's broiler chickens are also produced here (Fig. 20.13). Both crops are well suited to the sub tropical climatic conditions of the southeastern USA (Fig. 20.2). Soils of the region are dominated by Ultisols. They are generally acidic and low in native fertility and so require substantial inputs of nutrients to be productive in the long-term. Historically,

Fig. 20.12 Distribution of (**a**) cotton (total of 5.0 Mha; each dot represents 2,024 ha) and (**b**) peanuts harvested for nuts (total of 0.5 Mha; each dot represents 810 ha) in the USA (USDA-NASS (2002))

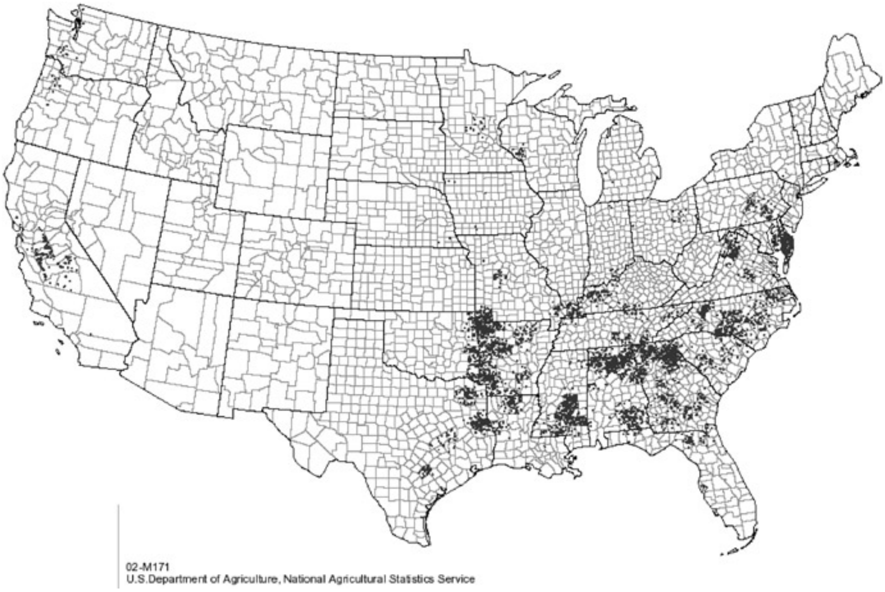

Fig. 20.13 Distribution of broiler and other meat-type chickens sold in the USA. Each dot represents two million head with a total of 8.5 billion head sold. (USDA-NASS (2002))

clearing the native vegetation and planting row crops in rotation with sod-based[7] pastures and the return of animal faeces to the land required few external inputs, but with time, soils became exhausted. Early pioneers abandoned 'worn out' soils and moved westward. Poultry CAFOs were developed in the southeastern USA in response to low heating costs in year-round production systems, and availability of cheap land and labour, and transportation infrastructure.

20.4.2 Efficiency, Productivity, and Sustainability

In the southern region, efficient use of rainfall and applied nutrients have been shown to enhance productivity and reduce environmental threats from agriculture. Adoption of improved cultivars, conservation tillage, appropriate fertiliser use, improved weed/disease/insect control, timely planting, and conservation-oriented crop rotations are management options found to mitigate water and nutrient limitations in the region.

Using conservation tillage[8] has improved crop yields. Across 95 pairs of data reported in the literature from across the southeastern USA, crop yield was an average

[7] See Glossary.

[8] Refer to Glossary for definition.

of 6% greater under conservation tillage than under conventional tillage (Franzluebbers 2005). Despite abundant precipitation in the summer, high accompanying evapotranspiration makes preservation of soil water vitally important for increasing productivity. Higher yields with conservation tillage can be attributed to the conservation of water in the soil profile under surface residue cover, especially during a critical growth period for cotton from mid-July to mid-August (Endale et al. 2002).

The effect of conservation tillage on soil quality is also generally positive. It often increases surface-soil organic matter, aggregate stability, microbial biomass, and potential N mineralisation compared with conventional, inversion tillage systems in the region (Staley and Boyer 1997; Franzluebbers et al. 1998; Nyakatawa et al. 2001; Franzluebbers and Brock 2007). Increased soil compaction with conservation tillage does not appear to be a problem if sufficient residue cover is maintained. For example, soil bulk density increased with time under conservation tillage at a greater rate when fewer crop residues were returned to the soil (Franzluebbers and Brock 2007). Under conservation tillage, soil organic C sequestration in the southeastern USA was 0.53 t/ha/year with a cover crop and 0.28 t/ha/year without one (Franzluebbers 2005).

Improved soil quality with adoption of conservation tillage can also be expected to improve crop productivity and nutrient cycling in the long-term. From a group of 11 tillage studies in the region, using various crops, the ratio of crop yield under conservation tillage to crop yield under conventional tillage, increased logarithmically with time (Fig. 20.14a). This increase has been attributed to factors that include higher soil organic matter leading to greater water storage efficiency and greater difference in surface soil quality (aggregation, water-holding capacity, and

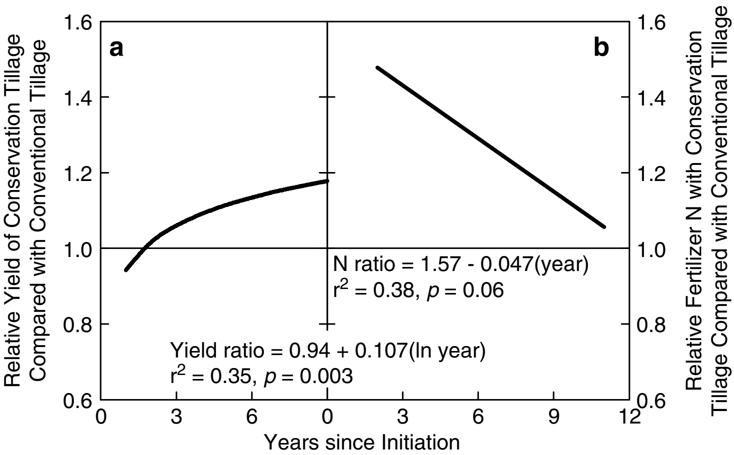

Fig. 20.14 Changes with time in (**a**) relative yield and (**b**) relative N fertiliser requirement to achieve 95% of maximum yield with conservation tillage compared with conventional tillage (Franzluebbers (2005))

nutrient cycling) due to reduced soil erosion (Triplett et al. 1996). However, early in the adoption phase of conservation tillage, nitrogen and other nutrients can be immobilised in the accumulating soil microbial biomass (Franzluebbers et al. 1999). Thus, more N is needed for optimum yield during early years of conservation tillage than later (Fig. 20.14b). In the long-term, accumulation of N and other nutrients and improvement in surface-soil hydraulic characteristics can lead to a greatly improved soil environment for sustainable crop production.

20.4.3 Soil Fertility Management

Fertiliser application programs in the southeastern USA have to consider several factors, including: (1) high precipitation that can cause extensive leaching of NO_3, Ca, and other elements; (2) high temperature that can cause rapid decomposition of organic matter and mineralisation of organically-bound nutrients; (3) kaolinitic mineralogy that can bind P and micronutrients; and (4) low pH that can reduce availability of P, Ca, Mg, S, and Mo and elevate concentrations of Al, Fe, Mn, and Zn (Brady and Weil 1999). Although soils can be sufficiently enriched in nutrients with the application of broiler manure, distributing this manure onto available crop and pasture land has been problematic. There is concern for over-fertilisation of farmland nearest broiler production facilities and its detrimental effect, through nutrient leaching and surface runoff, on water quality in the region (Sharpley et al. 2007).

For cotton production, soils should be limed to a target pH of 6.0–6.3. Application of N is based on soil type, previous crop, growth history, and yield potential. The N application may be split with about 25% at planting to ensure good seedling development and 75% as a side-dressing (first-square to first-bloom).

Low mobility of P allows it to be applied at or before planting. Potassium can be applied pre-plant or with mid-season foliar applications, while S may be applied pre-plant or as a side-dressing of ammonium sulfate (Univ. Georgia 2007a). Boron is recommended for successful flowering, pollination, and fruiting of cotton as a split foliar application applied twice for a total of 0.6 kg/ha. Manganese and Zn may sometimes be needed, especially when soil pH increases above 6.0.

Poultry litter (manure mixed with bedding) is a valuable and locally available source of plant nutrients for many crops in the southeastern USA. Nutrient concentration of litter varies depending upon moisture, season, feed ration, the number of poultry batches prior to clean-out, storage conditions, and handling. Typically, poultry litter contains the equivalent of 3.1-1.2-1.9% of N-P-K (Gaskin et al. 2007). Nitrogen availability from poultry litter applied to a crop generally ranges from 50% to 80%, because a large fraction of N in the manure must decompose and be subsequently released from soil microbial activity. Ammonia-N is often a significant (about 10%) fraction of the total N, and therefore can be easily lost by volatilisation. To avoid volatilisation of N and runoff of nutrients, poultry litter is not recommended for application before significant rainfall events, after liming, or during periods of drought and high temperature.

Due to the discrepancy between the ratio of nutrients required by most non-leguminous crops (7-1-6; N-P-K) and those supplied by poultry litter (3-1-2), poultry litter application rates should be based on the requirement of the crop for P rather than on N. If litter application rates were applied to meet the N requirement, excessive application of P would occur with time. Sharpley et al. (2007) described several management practices that can be employed to minimise P loss from poultry farming systems including: (1) enhancing P utilisation in feed; (2) manure amendment and composting; (3) appropriate method and timing of litter application to fields; (4) soil and litter testing; (5) subsurface application of litter to decrease P runoff; (6) conservation tillage to decrease P runoff; (7) pasture regeneration to enhance infiltration; (8) riparian buffers to trap particulate P; and (9) stream bank fencing to exclude grazing animals from streams.

Application of poultry litter to crop and pasture lands would be expected to increase soil organic matter. Across several field studies, soil organic C was 11% greater with than without poultry litter application (Franzluebbers 2005). Soil organic C sequestration was equivalent to 0.72 ± 0.67 t/ha/year. Poultry litter application combined with conservation tillage and winter cover cropping can greatly reduce soil erosion in cropping systems of the southeastern USA (Nyakatawa et al. 2007).

20.4.4 Pest and Disease Management

The warm and humid conditions of the southeastern USA are conducive to the development of crop pests and diseases; thus their management is more intensive than in other regions. Historically, the focus of cotton insect management has been on boll weevils. The Boll Weevil Eradication Program was initiated in 1978 by the USDA in North Carolina and Virginia (USDA-APHIS 2002), and so far Virginia, North Carolina, South Carolina, Georgia, Florida, Alabama, Kansas, New Mexico, Arizona, and California have effectively eliminated the weevil problem. Three main techniques are used during a 3- to 5-year eradication period: pheromone traps for detection; cultural practices to reduce the weevil's food supply; and malathion treatments to kill. During the first year, malathion is applied every 5–7 days starting in late summer, then every 10 days during the later part of the growing season until the first frost. Cotton stalks are shredded and plowed to eliminate a source of winter shelter. During Years 2–5, the automatic spraying is supplemented with traps (1–2 traps/ha), and malathion is applied only in those fields where weevils are detected. Finally, traps are set for every 4 ha and areas spot-sprayed when detected. Upon elimination of the boll weevil in Georgia, insecticide applications had been reduced from 15/year to only 4–5/year by 1995 (Univ. Georgia 2007a).

For successful control of pests, integrated pest management (IPM) relies on multiple approaches, such as cultural practices, variety selection, biological control, and insecticides as needed. A successful IPM program lowers production costs, delays resistance problems, and improves profitability. Specific strategies include insect scouting (every 5 days), promotion of beneficial insects (e.g. big-eyed bugs (*Geocoris* spp.), minute pirate bugs (*Orius* spp.), fire ants (*Solenopsis invicta*) and *Cotesia* wasps) (Univ. Florida 2007; OISAT 2007), spraying only when insect populations exceed a threshold, alternating insecticides to avoid resistance, and planting varieties containing Bt genes (Univ. Georgia 2007a).

Other pests and diseases of economic concern in cotton are nematodes and seedling diseases. When environmental conditions are cool and wet, seedling diseases can develop from *Rhizoctonia solani, Pythium* spp., and *Fusarium* spp. (Univ. Georgia 2007a). Seedling diseases can be controlled with a range of chemicals and agronomic management practices. Various nematodes can infect cotton and cause economic damage. As symptoms are ambiguous (Univ. Florida 2007), control of nematodes has not been adequately addressed. Crop rotation of cotton with non-host crops is a key strategy to control nematode damage. Some non-host crops to rotate with cotton are peanut, corn, various summer forage crops, and many different grass and leguminous winter cover crops. A variety of rotations is needed because crops may be non-hosts for some nematode species, but not others.

Peanut diseases (e.g. cylindrocladium black rot, sclerotinia blight, early leaf spot, web blotch, and tomato spotted-wilt virus) are most effectively and economically controlled using a combination of strategies, including sanitation, crop rotation, resistant varieties, scouting, and judicious use of pesticides (Virginia Cooperative Extension 2007). Equipment should be cleaned to avoid transport of inoculum across fields. Although moldboard plowing to bury crop residues is still recommended, harvest or burning of vines is not, since much of the potential disease inoculum remains in the field, and soil fertility declines. In Virginia, a 4-year rotation of peanut–corn–sorghum–grass is recommended for control of diseases. Since soybean and other leguminous crops share many of the same diseases with peanut, they should be avoided in the rotation or used sparingly with grass cover crops and separated by a summer cereal or grass phase. Resistant varieties are available for some of the common diseases found in peanut. Life cycles of peanut diseases and strategies for control have been developed (Univ. Georgia 2007b).

Non-chemical alternatives to conventional pest control are becoming more widely discussed, researched, and promoted in different parts of the USA (SARE 2007). These approaches rely on greater understanding of the life cycle of pests and management decisions to avoid outbreaks, such as through crop rotation, variety selection, residue management, timing of field operations, and promotion of beneficial organisms. Other sources of information for non-chemical alternatives to pest control include ATTRA (2007) and Rodale Institute (2007).

20.4.5 Weed Management

Weeds are a serious concern in cotton and peanut production because of the long growing season and their potential to severely reduce yield and distribute seeds to infest cropland for years to come. Many chemical control strategies are available to help control weeds but, when used alone, in conventional, monoculture cropping systems, they are costly and can contribute to environmental degradation. Moreover, they are often only marginally effective in controlling weeds in the long term unless diverse cropping systems are developed to limit the weed competitiveness that thrives under monoculture.

Several technologies have been developed that allow greatly reduced chemical inputs for weed control. These include herbicide-resistant crop varieties, conservation tillage, and more diverse crop rotations with winter cover crops. Together, these can create a dynamic, biologically-intensive agro-ecosystem with a smothering mat of surface residues that discourages weed growth and seed dispersal. Transgenic cotton varieties allow glufosinate and glyphosate to be sprayed directly to the crop to kill emerging and established weeds during a critical period prior to crop canopy closure. Winter cover cropping and high-residue-producing crop rotations offer significant physical impediments to the establishment of weeds under a thick coating of surface residues. A wide variety of chemical and non-chemical weed control strategies can be found on state extension service websites in the southeastern USA (Alabama Cooperative Extension System 2007; Clemson Univ. 2007; Louisiana State Univ. 2007; Mississippi State Univ. 2007; North Carolina State Univ. 2007; Texas A&M Univ. System 2007; Univ. Georgia 2007a; Virginia Extension Service 2007).

Conservation tillage avoids soil mixing, thus inhibiting weed-seed germination. In Georgia, conservation tillage is implemented primarily using strip tillage, which provides a narrow zone of tillage in the crop row. Strip-tillage implements remove weed or cover crop debris, typically loosen soil under the row, and provide a suitable seedbed for planting (Univ. Georgia 2007a). This operation allows for optimum seedbed preparation while maintaining inter-row residue cover.

20.4.6 Integration of Enterprises

The cotton–peanut–poultry region of the southeastern USA contains nearly equal quantities of crop (20%) and pasture (15%) land areas, along with the dominant land use of forest (USDA-NASS 2008). Integration of crops and livestock (e.g. poultry, swine, and cattle) is currently limited compared to its historical predominance in the region. Manure and feed grains provide significant transfer of matter and energy between crop and livestock operations, although within-farm integration of these components is not generally practiced.

Integrated crop–livestock systems have potential to impart major benefits to the environment and help to develop sustainable agricultural production systems for the region by: (1) more efficiently utilising natural resources; (2) exploiting natural pest control processes; (3) reducing nutrient concentration and consequent environmental risk; and (4) improving soil structure and productivity (Franzluebbers 2007). Sustainable agricultural systems should consider profitability but also maximising investment in natural capital and reducing environmental impacts, and consider social values of animal treatment and human exposure to synthetic chemicals.

Some reasons to shift from a specialised production system to an integrated crop–livestock production system are: (1) specialised farms operating on marginal profit; (2) economic vulnerability with specialised production; (3) high cost of fuel and nutrients; (4) pests becoming more damaging with monocultures; (5) yield decline due to long-term management-induced constraints on soil quality and biological diversity; (6) spatially and temporally improved nutrient cycling on a field and landscape level with integration of enterprises; and (7) conservation of soil and water resources with greater adoption of sod-based management approaches (Franzluebbers 2007). With the accumulation of soil organic C and N during a perennial pasture phase, long-term data have shown that crop requirements for external N inputs can be greatly reduced and yield potential can increase. These responses may be due to a number of causes, including better soil physical condition, disease suppression, increased diversity of soil biological communities and enhanced fertility. Information on enhanced yield responses to pasture–crop rotations (e.g. peanut, cotton, and corn) was synthesised in Franzluebbers (2007).

Different forms of integrated rainfed farming systems are possible, including: (1) the growing of grain as a home-grown source of high-energy feedstock to supplement a primarily livestock-based production system; (2) rotating cropland with pasture to alleviate pest and disease problems in a predominantly cash-crop production system; (3) introducing stocker cattle onto winter cover crops to diversify farm operations; and (4) spatially and temporally diversifying farm operations with crops, forage, and woodland plantations.

Integrated crop–livestock systems are being investigated again at several research locations throughout the southeastern USA. Near Tifton Georgia and Headland Alabama, research and extension projects were developed to evaluate the impacts of stocker cattle grazing winter cover crops following cotton and peanut (Hill et al. 2004; Siri-Prieto et al. 2007a, b). Crop yield and soil properties have been variable in response to winter grazing; being both unaffected and negatively affected in different evaluations. The additional cattle gain of 178–561 kg/ha in these studies has increased income and justified diversification. Pasture–crop rotations are being investigated near Quincy Florida to improve production potential (Katsvairo et al. 2006, 2007a, b). Peanut following bahiagrass yielded greater than following cotton, due probably to reduced nematode and disease pressures after bahiagrass (Katsvairo et al. 2007b).

Marois et al. (2002) used an economic model to compare a conventional system (53 ha cotton, 27 ha peanut) with a sod-based rotation system (20 ha cotton, 20 ha peanut, 40 ha bahiagrass). Net profit was estimated to be $15,689/year on the conventional farm, $35,552/year on the pasture-based farm with hay harvest only, and $44,840/year on the pasture-based farm with cattle grazing second-year bahiagrass.

Near Watkinsville Georgia, the impact of stocker cattle and cow-calf herds is being investigated in cotton and diversified grain production systems; these impacts include their effect on soil and water quality, crop and animal production, and economic return (Franzluebbers 2007; Franzluebbers and Stuedemann 2007; Schomberg et al. 2007). Livestock grazing of cover crops has had variable effects on subsequent crop production, but has almost always increased economic return and diversity of income. Cattle gain on cover crops has been excellent with 200–350 kg/ha/season and greater gain on cover crops managed with NT than with conventional tillage (330 vs. 240 kg/ha) (Franzluebbers and Stuedemann 2007). Cover crop production has been consistently greater with NT than with conventional tillage – probably due to more efficient utilisation of precipitation and conservation of nutrients in surface soil organic matter. The impact of cattle trampling on soil compaction has been minimal. With conventional tillage, the frequent cultivation can alleviate surface compaction. With NT, the high surface soil organic matter following perennial pasture resists the compactive force of cattle traffic (Franzluebbers and Stuedemann 2008a, b). Using conservation tillage with cover crop grazing by cattle has helped to avoid the negative effects of sod-busting on soil organic matter decline and nutrient cycling deterioration.

The effects of tall fescue and orchardgrass pastures on cotton and peanut production characteristics and soil quality responses are being investigated near Suffolk Virginia (Faircloth et al. 2007; Weeks et al. 2007).

Within-farm integration of crops and livestock can provide stability to a farm operation – as well as complementary nutrient cycling, biological pest control, and economic diversity. Among-farm integration has also been proposed to avoid imbalances in regional nutrient transfers, better utilise regional resources, and allow more participants to share in responsibilities and outcomes (Russelle et al. 2007). The complexity and potential for public benefit of within-farm and among-farm integrated systems should justify the establishment of regional, national, or even international research initiatives. These could overcome constraints in current (i.e. conventional) agriculture and move rainfed farming systems towards greater sustainability through better integration of crops and livestock (Russelle et al. 2007).

20.4.7 Summary of Issues

The southeastern USA is a warm, humid region that has a variety of options available to produce a diversity of crops and animals for local, regional, and international markets. Although precipitation is generally abundant, periods of inadequate water availability occur due to high evaporation, especially in summer. Therefore, conservation tillage systems are needed to improve water-use and nutrient-use efficiencies. Cropping-system diversification, for example peanut–cotton–corn–wheat–pasture rotations with winter cover crops, along with conservation tillage, can help to control weeds, diseases, and insects with reduced inputs of synthetic chemicals. High-intensity storms in the summer can cause enormous soil losses and can make fertiliser applications from both inorganic and manure sources ineffective. The development of a sustainable agricultural system has to take into account the interests of the growing human population in the region. Abundant surface water resources, appreciated by year-round recreational enthusiasts, need to be protected from contamination by nutrients, pesticides, and faecal-borne pathogens. Runoff from animal manure applications is of increasing concern in the area. Integration of crop and livestock systems in the region will help improve productivity of soils, increase the utilisation and distribution of nutrients, increase the economic stability and diversity of farming systems, and reduce environmental pollution from agriculture.

20.5 Coastal Diversified Crops–Dairy Region

20.5.1 Structure and Characteristics of System

Although not designated as a single region, the west coast and east coast regions have significant rainfed agricultural production. Tree-fruit production occurs in California, Washington, and Oregon on the west coast and in Florida, New Jersey, and New York on the east coast. Harvested forage and pasture are also significant components of the agricultural landscape in the northeastern USA (Fig. 20.15a), making perennial pasture the single largest agricultural land use system in every state in the region. Dairy production is one of the largest animal enterprises on both coasts (Fig. 20.15b). The following discussion on rainfed diversified agricultural systems will focus mostly on the humid, temperate region of the northeastern USA.

Precipitation in the region is generally 1,000–1,200 mm/year, distributed relatively uniformly throughout the year (Fig. 20.2). However, precipitation may be as low as 750 mm (western New York) and as high as 1,800 mm at the coast. Growing-season drought is more common and more severe in the southern third of the region. Temperature follows a distinct north–south gradient, with mean annual temperature of 3–4°C in northern Maine and 13–16°C in Delaware and Maryland. Soil resources and properties vary widely and, in many instances, the combination of soil type and topography constrain the type of cropping system (USDA-NRCS 2008b). The northern half of the region (New York and all of New England) is a glaciated landscape, resulting in soils formed from both glacial till and glacial outwash.

Fig. 20.15 Distribution of (**a**) hay including haylage grass silage and greenchop (total of 25.9 Mha; each dot represents 4,049 ha) and (**b**) dairy cows (total of 9.1 million head; each dot represents 2,000 head) in the USA (USDA-NASS (2002))

Soils formed from marine sediments and coastal plains are common in the southern half of the region. Soils formed from sedimentary bedrock are common throughout southern Appalachia (e.g. Pennsylvania and West Virginia).

Agriculture in the northeastern USA is characterised by its diversity – in resource base and climate, in the crops grown, and in markets. Parts of this region, which stretches for nearly 1,500 km along the Atlantic coast, from northern Virginia through Pennsylvania and New York to New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont), have been actively farmed for more than 350 years. During that time, there have been cycles of afforestation and deforestation; for example, much of New England was deforested and farmed by the mid-nineteenth century but is more than 80% forested now. Throughout much of the northeastern USA, diversity of production has been a characteristic at the farm level for centuries, lacking the profound shift to specialisation that has occurred in the last half century in the Corn/Soybean Belt and the Wheat Belt.

Distinct, diversified cropping systems in the northeastern USA can be categorised as: (1) arable agronomic crops (e.g. corn, soybean, small grains, oilseeds), (2) forage and pasture crops (e.g. alfalfa, clovers, timothy, orchardgrass), and (3) intensive horticultural crops (vegetable, fruit, and ornamentals). Agronomic and forage production is almost exclusively rainfed, while horticultural crops rely to varying degrees on supplemental irrigation, (e.g. Maine potato production is less than 15% irrigated whereas New Jersey horticultural crops are greater than 90% irrigated (USDA-NASS 2008)).

Maryland and Delaware are dominated by grain and poultry production. Pennsylvania, New York, and New England have systems that are integrated at the farm level, primarily as small- to medium-scale dairy farms, which will be the primary focus of following sections. Small-scale beef production is prevalent throughout the region. Although there are striking examples of concentrated, vertically integrated animal production systems in the region (e.g. poultry on the eastern shore of Maryland, some dairy systems in western New York), agriculture still exists primarily on moderately sized family farms.

One notable difference in the production of corn and soybean in this region is the prevalence of more diverse rotational cropping systems; for example, dairy farms may have four to five different crops present on a field during a 10-year period. An alfalfa–grass mixture with a projected stand life of 5–6 years may be planted in the first year with a nurse crop of wheat or oat. Two or three successive corn crops may be followed by soybean or a return to perennial pasture.

20.5.2 Efficiency, Productivity, and Sustainability

Although farmers in the northeastern USA have not specialised to the extent of other parts of the USA, they have adopted similar technological and management tools, and hence productivity and efficiency have increased. Changes in dairy production components are illustrated in Fig. 20.16 for New York, with similar

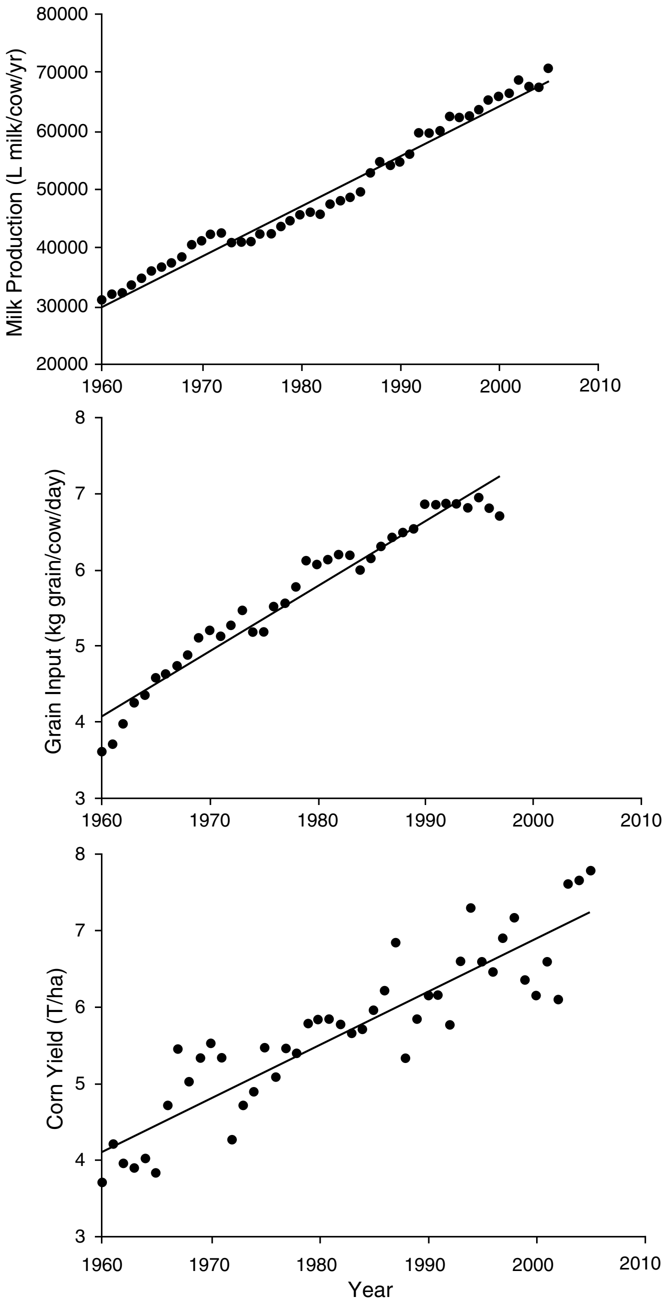

Fig. 20.16 Historical trends in milk production (*top*), grain input in dairy rations (*center*), and corn yield (*bottom*) for the state of New York from 1960 to 2005 (USDA-NASS (2008))

changes having occurred in other states of the region. Milk production per cow has more than doubled since 1960, which is attributable to a combination of factors, including animal genetics, breeding, health, and feeding strategies. The quantity of supplemental grain fed to dairy cattle has doubled, as has corn grain yield. Increasing corn grain yield can be attributed to improvements in hybrid variety yields, soil fertility and chemical weed control.

Increased efficiency of the dairy production system in the northeastern USA has resulted in stable to increased milk production in different states, despite dramatic reductions in the number of farm operations and dairy cows. New York and Pennsylvania had a total of about 80,000 dairy operations in 1965, but only about 15,000 operations in 2005 (USDA-NASS 2008). Compared to large dairy operations in the southwestern USA, dairy farms in the northeastern USA have higher costs of production, partly due to a difference in economy of scale, but also due to higher costs for energy and other inputs (Short 2004).

Although farm size and productivity have increased since 1965, agriculture in the northeastern USA has shrunk considerably; for example, cropland in Maryland declined from 1.5 to 0.8 Mha, and in Maine from 1.4 to 0.6 Mha. This contraction has had severe effects on the agricultural infrastructure, such as input suppliers and marketing services, making continuation of existing operations more difficult.

20.5.3 Soil Fertility Management

Inherent fertility of soils in this region varies widely. The Connecticut River Valley of Connecticut, Massachusetts, New Hampshire, and Vermont is characterised by highly productive alluvial soils. In contrast, the mountainous soils are highly weathered and the coarse-textured soils of the coastal plains are relatively infertile, requiring significant nutrient inputs.

The use of commercial, inorganic fertilisers, especially N and P since the mid-twentieth century, has increased in the coastal areas, although there has also been significant recycling of nutrients from animal agriculture. The environmental outcome of this recycling has depended to some extent on location; long-term application of poultry litter in Maryland and Delaware has resulted in accumulation of P in soil (Sharpley et al. 1996) and similar results would be expected in areas with high concentration of dairy operations. The primary source of P accumulation at the landscape scale has been animal manure via imported feed grains (Bacon et al. 1990), and subsequent crops in many fields no longer respond to further P application (Heckman et al. 2006).

Several approaches have been made to mitigate the negative effects on water quality of increasing P from agriculture. A national network was established to develop a P Index that could rank sites on their vulnerability to P loss, including effects of P source, transport mechanisms (e.g. runoff and leaching), and other factors (Lemunyon and Gilbert 1993; Sharpley et al. 1993, 2001; Sims 1993). Refinement and validation of the P Index have continued over the past 15 years

(Gburek et al. 2002; Kleinman et al. 2006; Kogelmann et al. 2006), as have developments of soil and manure analyses and management practices to help reduce the potential for P movement into streams and lakes (Magdoff et al. 1999; Van Kessel et al. 1999; He and Honeycutt 2001; Dou et al. 2003; He et al. 2004; Kleinman et al. 2006, 2007). Although positive P balances – related to high animal density – still exist for many dairy regions in New York, the difference between P input and output (in products) at the county level has declined significantly and steadily since 1992 (Mekken et al. 2006).

For both economic and environmental reasons, there has been a significant effort to refine estimates of N availability from soil, crop residue, and animal manures. Accounting for residual soil N from current and past manure applications, and from incorporated legumes such as alfalfa, was the primary rationale for the development and use of the pre-sidedress soil N test (PSNT) in Vermont (Magdoff et al. 1984). By analysing soil nitrate-N when corn is 30–45 cm tall, the need for additional N fertiliser can be decided at the latest possible time, thus accounting for N from mineralisation of organic N from animal and green manures (Magdoff 1991). The PSNT has been widely tested throughout the Corn Belt and eastern USA (e.g. Guillard et al. 1999; Balkcom et al. 2003). On-going evaluation of other management tools such as post-harvest stalk nitrate concentration (Balkcom et al. 2003) and soil amino sugar content (Mulvaney et al. 2001; Klapwyk and Ketterings 2006; Klapwyk et al. 2006) may also provide valuable tools to quantify the contribution of N from soil and manure. These tests should help minimise the negative environmental impacts and waste from leaching and denitrification of N.

20.5.4 Pest and Disease Management

Although there are numerous insect pests and diseases of the major agronomic crops in the northeastern USA, damage severe enough to reduce yield or cause crop failure is sporadic. University recommendations vary within the region, but are based on IPM principles. These require monitoring and establishment of threshold populations before implementing control strategies. Recommendations for pest control are available for different states in the region (Cornell University 2008; Penn State University 2008).

Corn plant population can be significantly reduced by seed rot and larval insects feeding on seed (e.g. seedcorn maggot, grubs, and wireworm). Some of these problems can be exacerbated when rotating corn with perennial forages – a common rotational strategy in dairy cropping systems. Because of the increasing use of NT in corn production and low soil temperature early in the season, more corn is now being treated with fungicide, insecticide, or both. Other in-season insect pests, such as earworm, armyworm and European corn borer, are a more serious problem for sweet corn production because of market appearance, than for corn grain crops. As described in Sect. 20.3.5, the use of genetically-engineered *Bt* corn has increased rapidly since 2000, and damage from many foliar and stalk diseases of corn has been minimised with the development and selection of resistance in hybrids.

Soybean pests in the region are less problematic than in the midwestern USA because soybean is less common and is often grown in more diverse rotations. Some of the same pests that have reduced corn populations by predation of seed have also impacted soybean populations (e.g. seedcorn maggot). Similar strategies have been employed to minimise these problems. The recent occurrence of Asian Soybean Rust in the southern USA has not yet impacted this region, but several states (e.g. New York) have developed management guidelines for this emerging pest.

Soil-borne diseases that can shorten stand life of alfalfa in the region include bacterial, *Verticillium*, and *Fusarium* wilts, *Phytophthera* root rot, and anthracnose. Most of these organisms are ubiquitous in the region and chemical control is not effective, except for seed treatment to establish a good stand. Primary management strategies are identification of locally-important disease problems, including those specific to soil type, and the use of improved, disease-resistant varieties.

Established alfalfa stands can be affected by three main insect pests – potato leafhopper (which also affects alfalfa seedlings), alfalfa weevil, and alfalfa snout beetle (which is especially problematic in some parts of New York). IPM guidelines and chemical and cultural control strategies are available for all three of these pests.

20.5.5 Weed Management

The important aspects of managing weeds in corn and soybean have been covered in earlier sections of this chapter, and similar management strategies are being increasingly adopted in the northeastern USA. In the diverse rotational dairy farm cropping system mentioned in Sect. 5.1 an alfalfa–grass mixture with a projected stand life of 5–6 years may be planted in the first year with a nurse crop of wheat or oat. Weed management during this stand establishment phase may rely only on competition from the cereal crop. During the pasture phase of the rotation, annual weeds are generally not problematic although perennial weeds such as quackgrass (*Agropyron repens*) may encroach. Perennial pastures may be chemically killed (e.g. with glyphosate) before planting corn.

Long rotations create fluctuations in resource availability (i.e., light, nutrients, and water) that negatively and differentially affect weed emergence and growth. Liebman and Dyck (1993) found that a reduction in weed emergence was a prominent feature of rotations compared to monoculture production systems in a number of studies that were reviewed. Westerman et al. (2005) noted that the survival of weed seeds of *Abutilon theophrasti* was substantially lower in 4-year rotations than in 2-year rotations. In reduced tillage systems that include long rotations of corn, soybean, and winter wheat, increased weed diversity has been observed, but the increased crop diversity generally prevents the dominance of a single weed species (Murphy et al. 2006).

20.5.6 Integration of Enterprises

Many farms in the northeastern USA can be characterised as integrated crop–livestock production systems. Many dairy farms in the region are self-sufficient in terms of forage production, and may be partially self-sufficient in grain production. Even so, substantial feed grain may be imported at the farm, watershed, and county levels, which effectively concentrates nutrients at these scales.

In areas where crop and livestock farms are spatially intermixed, or that have some diversity in the types of farming operations present between farms, efforts have been made to increase integration between pairs of farms, or among groups of farms. For example in Maine, over a 10–15 year period, some potato and dairy farms have developed business and social relationships (Hoshide et al. 2006), in which dairy manure is transported to potato fields and feed from potato farms transported to dairy farms.

The demand for forage by dairy farmers has encouraged some potato farmers to establish longer crop rotations with forage crops to harvest and sell, as well as to increase the ecological stability of their own potato production system. Beneficial outcomes of this among-farm integration include: (1) distribution of manure nutrients over a larger area (in many cases, allowing the dairy partner to increase farm size knowing that manure can be spread onto neighboring fields); (2) local marketing of grain and forage resources; and (3) importation of organic matter onto potato fields, which were previously characterised by short rotations, limited crop residue, and intensive tillage. This example of among-farm integration has been successful because of the local availability of diversified operations. Transfer of this model to other parts of the USA may not be as successful, because of the loss of local agricultural diversity resulting from regional specialisation.

20.5.7 Summary of Issues

The northeastern USA is a cool, humid region with an assemblage of relatively small farms, many of which can be characterised as integrated crop–livestock systems. Dairy production in the region requires sufficient forage and energy resources. Thus, high-quality pastures for grazing and conserved forage for feeding in the winter are a significant part of the landscape. In addition, production of commodity grain crops (e.g. corn and soybean) are an important source of feed for these integrated systems and they occupy a significant area of crop-only farms in parts of the eastern USA. The importation of feed grains from other regions may further add to the concentration of nutrients at the farm and watershed level. Recycling of manure onto nearby land is common and reduces the need for inorganic fertilisers. Nutrient management strategies are a key focus to minimise nutrient losses to runoff and leaching and reduce fertiliser input costs. Diversification of agricultural operations in the region has allowed both within-farm and among-farm integration of resources and outputs from crop and livestock operations.

20.6 Conclusions

Rainfed farming systems in the USA are defined by unique soil and climate conditions found in different parts of the country. The Great Plains region (or Wheat Belt) is characterised by limited precipitation resulting in the predominance of wheat and sorghum production, along with a significant number of cattle brought to the region for finishing in feedlots. Wheat–fallow has been the traditional cropping system but, with the adoption of conservation tillage that conserves soil moisture and protects soil from erosion, more intensive cropping systems are being adopted to make the most efficient use of available water.

The midwestern region (or Corn/Soybean Belt) has highly fertile soils and relatively mild climatic conditions that allow excellent production of corn and soybean. The region also has large numbers of hogs and cattle. A major resource issue in the region is excess N and P that can cause deterioration of surface and ground water resources in the region, as well as downstream into the Gulf of Mexico. Conservation management systems are being developed to limit nutrient losses.

The southeastern region (or Cotton Belt) has generally adequate precipitation, although summer water deficits are common due to high evaporative demand during the long-hot summer. Conservation tillage systems are needed to reduce evaporation from soil and protect the soil surface from the common threat of high-intensity storms that can cause serious erosion. Soils are relatively infertile, with subsoil acidity, but can be improved with permanent vegetative cover and application of animal manures. Management approaches are needed to avoid over-application of animal manures that can threaten surface water quality.

The northern coastal regions represent a diversity of farming operations that have little specialisation. Resource issues are related to high-density animal operations and the need to balance nutrient inputs and outputs to avoid water quality concerns.

In all regions, farming is pressured by economic concerns with rising costs of production, because of the reliance on fossil-fuel based energy, fertiliser, and synthetic chemical weed and pest control. Government support payments are an integral component to maintain profitability of many current agricultural systems. Agricultural biofuel production (based on corn ethanol) is increasing dramatically and is creating a renewed interest in agriculture by the government, following a century in which the contribution of agriculture to the gross domestic product has gradually declined from nearly 10% at the beginning of the twentieth century to less than 1% at the beginning of the twenty-first century. The opportunities for USA agriculture to supply corn-based ethanol, soybean-based diesel, and eventually cellulose-based ethanol are expanding, yet the challenges that this new era brings will be certainly as daunting as ever before. Can farmers in the USA and the world expect to supply the ever-increasing demand for staple grains, high-protein diets, and diversity of safe and affordable food products without harming the environment? Can both food and bio-based energy demands be met without further tapping into dwindling ground water resources and threatening the quality of fresh-water supplies with the by-products of agricultural production (e.g. nutrients, pesticides, and pathogens)? Adoption of conservation-tillage systems in the USA has helped to conserve water, preserve soil, and even increase production, but further advances (e.g. increasing crop diversity, integration of crops and livestock, and balancing nutrients within watersheds) will likely be needed to make rainfed farming systems more water- and nutrient-efficient and ecologically sustainable in the future.

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Chapter 21
Rainfed Agroecosystems in South America

Evaluation of Performance and Environmental Sustainability

Gloria Rótolo, Charles Francis, and Sergio Ulgiati

Abstract Farming and grazing in South America are essentially rainfed activities, with over 98% of the agricultural lands and systems depending on natural rainfall. There is great diversity in latitude, elevation, climate, topography, and soil types across the continent, supporting a wide range of crops, animals and farming systems. This chapter is focused on four important ecoregions that represent the rainfed systems of South America: *Pampas* of Argentina, *Cerrado* of Brazil, *Llanos* of Colombia and Venezuela and Savanna Guyana, and the *Andean Puna* region in the highlands. Regions vary greatly in their lengths of growing season, complexity of farming systems, and potential productivity. New technologies have reached farmers in the more accessible areas with better soils and conditions for crop and pasture growth, yet many farm families in remote areas still practice traditional subsistence systems. There is still much to be learned about the diverse array of crops and indigenous systems across South America, and research in agroecology is exploring farmers' current systems and how they can inform the choice of appropriate technologies. Various agro-ecosystems are compared using the emergy concept and method, also described in the Supplement of Chap. 1, which account for the energy, matter, information and labour flows that directly and indirectly contribute to generate the products and services yielded by the system, expressed in a common unit (joule of solar energy).

Keywords Farming systems • Crop–animal systems • Indigenous technologies • Sustainable agriculture • Adaptation • Resilience • Biodiversity • Energy • Emergy

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_21,

21.1 Introduction

Agroecosystems in South America occupy most of the potentially arable land, and modern industrial technologies have replaced or influenced many indigenous (pre-Colombian) and introduced agricultural systems. More than 98% of agricultural land is rainfed (World Resources Institute 2007) with water a common limiting factor. 'Agriculture' in this chapter includes both rainfed farming and grazing systems, and we identify and evaluate four important ecoregions. We discuss the potentials and challenges of their production systems, and suggest methods to assess their performance in terms of energy and other resource use, as well as other dimensions of sustainability.

For over 10,000 years, food production depended on organic sources of plant nutrients, on biodiversity to control pests, and on rainfall. However, population has increased exponentially over the last two centuries, and agricultural technologies such as new varieties, fertilisers, pesticides, and irrigation have been introduced in order to increase food production and support more people.

With increasing population, wealth, development, and extraction of natural resources in a country come negative impacts on the environment, including its capacity to absorb and neutralise pollution of soil, air and water (Ohl et al. 2007). Part of the problem with the application of classical science is a focus on finding linear causality, and most investigation has been limited to the study of systems only through their component parts (Brunckhorst 2005). Nature is often exploited and is not recognised nor valued for its ecosystem services. Natural, non-renewable resources are being used at an increasing rate each year (Gutman 2007; Ohl et al. 2007). Humans with their increasingly intensive technology became an integral part of virtually all ecosystems (Vitousek et al. 1997; Redman et al 2004). We are facing the challenge of protecting our environment, while obtaining economic profits and promoting sustainable development. However, in the words of Albert Einstein: "*We cannot solve problems with the same kind of thinking that was used to create them*" (Harris 1995). Alternatives are needed for both the evaluation and the management of natural resources; these would embrace nature–society interactions in all their complexity (Crutzen and Stoermer 2000).

This chapter on South America examines four of the major representative rainfed farming regions: the temperate *Pampas* Region of Argentina; the extensive *Cerrado* plains of Brazil; the *Llanos* or plains of Colombia; Venezuela, and Guyana; and the *Andean Puna* of the Andean Zone including the intermountain valleys (Fig. 21.1). Farming systems are described as managed human activity systems. To evaluate the efficiency of these systems only in conventional terms of biological productivity and economic return stops short of using more comprehensive analyses in terms of energy and resource use that provide a better measure of their long-term durability. Thus we achieve a broader understanding in this chapter through emergy analysis and life cycle analysis (Chap. 1) applied to the grazing system of the Argentine Pampas as a case study. Results are then compared to other mainly South American systems investigated by different authors.

Fig. 21.1 Locations of four ecoregions in South America

21.2 An Overview of South American Rainfed Agriculture

South American agroecosystems are many and varied, over latitudes from 10° north to 50° south, including tropical, subtropical and temperate ecoregions. Elevations where agriculture is important extend from areas near sea level along the coasts and in the major river basins of rivers such as the Amazon and Orinoco, to 4,000 m above sea level in the farming areas around Lake Titicaca in the Andes. The widely-varied agricultural systems depend on unique local resources and are characterised by differences in economic, political, social structures and environmental fragility. Those concerned with agricultural and rural development need to consider this wide range of factors before making recommendations to improve productivity.

Much agricultural development has occurred in a framework of 'transfer of technology', including plant varieties and hybrids, fertiliser recommendations, and weed management strategies, especially technologies from temperate regions in North America. The introduction of climatically-adapted practices such as extensive monocultures of cereals and soybeans in Argentina and Brazil has resulted in dramatically increased productivity – at least in the short term. In many other regions, the success has been marginal. When systems are detrimental to the soil or other features of the environment or seriously disrupt social structures that have been sustainable for decades, the lasting results can be negative in spite of apparent profits measured by neoclassical economic parameters. Understanding the complexity of climates, soils, farming systems, socioeconomic conditions, and environments in South America can lead to more productive, economically viable and sustainable rainfed agricultural systems.

21.2.1 Four Rainfed Agricultural Regions

Complexity of the South American landscape is such that diversity could only be fully explained by identifying and describing all of the existing ecoregions, an impossible task. Thus we have chosen four areas of major importance that can be defined by their location, soils, climate and the predominant crops and systems. We recognise that this process over-simplifies the agriculture and underlying environment of the continent. In the case of the pampas ecoregion, although the bioma is also found in neighbors countries, our discussion concentrates on the large area in Argentina as shown in Fig. 21.1.

21.2.1.1 Pampas Region of Argentina

The vast grassland area of Río de la Plata basin occupies nearly 800,000 km^2 and comprises two ecoregions: *Pampas* in Argentina and *Campos* in Uruguay, part of Brazil and north-east portions of Argentina (Dinerstein et al. 1995; Soriano et al. 1992). The Argentine Pampas region, located in the Central-East, occupies around 550,000 km^2 (Viglizzo et al. 2006) and represents 30% of the total agricultural area of the nation (Fig. 21.1). Precipitation decreases gradually from 1,000 mm in the northeast to 400 mm in the west. Even though it rains throughout the year in the eastern, wettest areas, most rain falls in spring and summer, both there and in the west (Garbulsky and Deregibus 2004). Mean daily temperatures are 6–10°C in winter and 21–26°C in summer (Castaño 2003).

The soils are composed of wind-blown *loess* derived from volcanic eruptions and deep accumulation of loose materials from dry river beds. They rest upon granite and other ancient crystalline rock to the north and east (Clapperton 1993). They are mainly Mollisols, usually free of stones, associated with Alfisols and Vertisols towards the east and with Entisols towards the west (Soriano et al. 1992).[1]

The land is generally flat but with some undulations in the north-east, some hills in the south-east and a large depression in the Salado river basin (Soriano et al. 1992). It is characterised by its lack of native trees, mostly flat terrain and fertile soils.

The natural habitat characteristics and soil quality have provided good conditions in the east for tall-grass prairie including native temperate legumes that are highly valued for cattle grazing (Garbulsky and Deregibus 2004). However, most of the native species have been replaced by 'improved' pastures and crops.

Except for small and large rodents such as Viscacha (*Lagostomus maximus*), the few native fauna can still be found in reserves but populations of Ñandú (*Rhea americana*), for example, are decreasing because of modification and fragmentation of the open grasslands (Bazzano et al. 2002).

European colonisation of the pampas was a gradual process. It started in the south-western and central part as rough frontier cattle operations to raise 'criollo' or native cattle on the open range, and evolved into mixed cropping–cattle operations (Solbrig and Viglizzo 1999) on individual farms of about 1,000 ha. The north-eastern part was peopled by colonial peasants on farms averaging 100–150 ha.

By the end of the 1800s and through the first third of the 1900s, (the golden years of Argentinean development) the main crops were wheat,[2] maize, and linseed, grown on a rotation of 5–7 years of grazing with 3–5 years of cropping under a variety of sharecropping arrangements (Solbrig and Viglizzo 1999), and grazing of fallow land between crops. These enterprises resulted in relatively low productivity, but also low environmental impact (Viglizzo et al. 2006). Annual grain crops and pastures for dairy and beef production were based on the high natural soil fertility and stored soil moisture as a result of rain distribution through the year, yet concentrated from October to March. This allowed Argentina to produce and export large amounts of meat, wheat and maize (Soriano et al. 1992).

Through the middle of the twentieth century, many of those crops were grown in long-term rotations with grazed pasture lands (Viglizzo et al. 2006) and using a high number of cultivations that made it possible in many cases for wheat to follow maize. This production pattern was intensified in the 1970s by the introduction of machinery for conventional tillage and herbicides for weed management – together with introduction, then widespread adoption, of the soybean crop. Soybean was well adapted to the region, used much of the same equipment as other crops, and found a ready world market.

With increasing technology in the 1980s, traditional systems gave way to an integrated and mixed crop–livestock model, with greater emphasis on cropping in

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[1] This chapter uses the US system of soil classification.

[2] See Glossary for botanical names of plants.

rotation with semi-intensive livestock production (Garbulsky and Deregibus 2004; Viglizzo et al. 2006). Soybean culture was expanded and adopted by more farmers, with the help of a new generation of herbicides and by the use of No-till planting, which also started to spread. By this time, the sharecropping and tenancy contracts were replaced by the *contratista de labores* and by the *pool de siembra* (Solbrig and Viglizzo 1999). The first consists of farmers, with good knowledge and experience, who are owners of small farms and have excess farm machinery capacity. This situation allows them to lease other land to operate farming as a service. The second is a group of investors with capital, who wish to cultivate large areas of leased farms. Because of the large size of their farming operations, these groups can obtain low prices for their purchased inputs and can market collectively to access good international commodity prices. These successful arrangements are still operating, although they are subject to political interruption by the export tax structure.

Up through the 1980s, the main problems were soil erosion, increased use of pesticides (Solbrig and Viglizzo 1999), and the shift of systems from traditional livestock for beef or milking enterprises to an annual row-crop. Crop productivity increased markedly, but profitability was erratic because of fluctuating world prices and export taxes; at the same time, the living standards and working conditions for farm labourers improved (Solbrig and Viglizzo 1999).

With the tremendous growth in world demand for cereals and oilseed crops since the 1980s, there has been a shift in land use toward more land for crops and less for pasture. This increase in crop production for food and, currently, for biofuels has been highly dependent on an increase in additional inputs and technologies, and it also coincided with soybean crop expansion. The area of cropland increased from six million hectares at the beginning of the 1900s to 20 million hectares during the period of 1935–1944; then reached 26 million ha in 1984 (Soriano et al. 1992) and 27 million in 2002 (INDEC http://www.indec.gov.ar or www.indec.mecon.ar). In the period of 1993–2004, the total production of maize, soy and wheat have increased by 22%, 173% and 50% respectively, while yields per hectare have increased 43%, 12% and 26% respectively (SAGPyA http://www.minagri.gob.ar/SAGPyA/agricultura/index.php). Even though there are still intensive grazing cattle operations throughout the Pampas region, much of this traditional practice has been displaced and is now concentrated in marginal areas.

A common rotation today in areas with potential for livestock grazing is still around 6 years cropping, followed by 3–4 years of pasture (Garbulsky and Deregibus 2004). However, with the introduction of GMOs,[3] fertilisers, new chemical pesticides and no-till practices, double cropping (two crops in 1 year) and continuous cropping have become more popular in areas with the best conditions for agriculture – and even in some areas that are marginal for continuous annual crops. A common cropping rotation in the northern part of the Pampas region is soybean–wheat/soybean, or soybean–wheat/soybean–maize. Soybean is the main crop that is expanding due to new technology and favourable market prices. It is replacing mainly forest and grasslands where rain is not usually a limiting factor. It now covers

[3] See Glossary for abbreviations and acronyms.

around 57% of the planted area (SAGPyA http://www.minagri.gob.ar/SAGPyA/agricultura/index.php), especially in the north-eastern pampas sub-region. Soybean, a legume, fixes nitrogen; however, nitrogen fertiliser consumption for cereals has not diminished. One reason is that the biological fixation by soybean is mainly used for its own growth and reproduction, with the small amount of nitrogen left in soil by soybean; coming from roots and stubble.

Agriculture is less coupled to livestock, even if the farmer is running both activities, with areas on the farm now specialised. Highly intensified cow-calf operations are found mainly in the northern and eastern part of the Pampas where the conditions for pastures and crops are suitable. The number of feedlots for fattening has been increasing slowly. No-till practices are becoming more common for crops. Derpsch (2008) quotes a figure of greater than 18 million hectares under no-till in Argentina in 2003.

Of the national production, the Pampas region contributes 90% of the maize, 82% of the wheat, 90% of the soybean and 67% of the meat produced in Argentina; this makes it the centre of major agricultural activity and a primary contributor to Argentina's economic growth (World Bank 2006). Argentina also occupies a prominent global position in the production of these commodities due to both expansion in crop area and per hectare productivity (SAGPyA http://www.minagri.gob.ar/SAGPyA/agricultura/index.php).

In spite of this agricultural success, due to the natural potential of the region, technological advances and market conditions, living standards in general have not changed appreciably, and wealth is not equitably distributed. In addition, the increased load on the environment has resulted in many problems including soil compaction (Soza et al. 2003; Ferreras et al. 2007) aggravated by a negative balance of nutrients (Cruzate and Casas 2003), low use of drainage terraces, increased weed resistence/tolerance to herbicides (Papa et al. 2008), as well as inappropriate input use that endangers human health and wildlife (Altieri 2000). At different universities, research centers and technological institutions such as INTA (*Instituto Nacional de Tecnología Agropecuaria*), researchers are working to address these different problems. However, the successful adoption of new management strategies also requires participation by all the stakeholders involved in the agricultural production system, as well as new attitudes, long-term integrated agricultural programs, and continued development of new technologies with incentives to embrace them.

In summary, although the output of this area has been the backbone for national and international trade for more than two centuries, the underlying contributions of its ecosystems have been most often ignored. Throughout Argentina's history, changes in agricultural land uses and practices have been mostly determined by the international prices of commodities and by the policies followed by the government in order to offset high budget deficits. These fluctuations were recently illustrated when the imposition of higher export taxes was rescinded after a few months due to widespread protest. Agricultural decisions on land use and management are closely linked to political actions (which are usually for short-term gains), market prices, higher profits and technological advantage. These may or may not promote sustainability.

The current situation is further complicated by the expansion of agriculture to more marginal lands, threatening the natural and potential productivity of the area, and endangering the future of sustainable development of the entire region. In response, universities and other institutions are now focusing on these critical topics, mainly those promoting the importance of the functions and services provided by ecosystems and on evaluating them through methods that use both qualitative and quantitative tools.

21.2.1.2 *Cerrado* Region of Brazil

The *cerrado* region of Brazil (Fig. 21.1) occupies over two million km^2, or about 21% of the total area of the country. This woodland and savanna area is located in the south-central part of Brazil, from near the borders of Bolivia and Paraguay toward the eastern coast. Rainfall ranges between 800 and 1,600 mm per year, concentrated in a 6-month rainy season from October to March (summer). Temperatures are high, and the region would be classified as semi-humid. These are typical savanna grasslands, with patches of distinct trees and shrubs, and gallery forests[4] along the rivers that dissect the region. Some areas are almost completely grass-covered, and the vegetation has been shaped by periodic natural fires started by lightning.

The soils in this region of Brazil are old and highly weathered; they are characterised by low pH causing high exchangeable aluminium that results in Al toxicity and high phosphorus fixation (Oliveira and Marquis 2002). One characteristic soil, a red Oxisol, is high in clay, deep, well-structured for water holding but with low exchange capacity. There is frequent and aggressive activity of ants and termites, the latter being especially important for vertical mixing of the soil profile as described in an example from the Colombian llanos (Sect. 21.2.1.3). Termites and leaf-cutter ants are also important in consuming and decomposing organic matter from foliage.

The *cerrado* region is highly biodiverse with more than 6,000 species of plants (Mendonça et al. 1998) and 1,600 species of mammals, birds and reptiles (Oliviera and Marquis 2002), but this biodiversity is being challenged by the expansion of monoculture cropping of a few favoured export crops.

The predominant grazing enterprises have been displaced in much of the Brazilian savanna over the past two decades by annual food and fuel crop production, especially sugar cane, maize, rice and, most recently, soybean. In most years, rainfall is not adequate for double cropping; which is fortunate because such intensity of cultivation would more rapidly exhaust available soil resources. The use of GM crops was not allowed in Brazil until 2005 when the president signed a bill authorising their planting.

High world commodity prices for grain and oilseed crops have caused a rapid shift toward monoculture plantings and high inputs of fertiliser and pesticide,

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[4] See Glossary.

although areas planted to export crops fluctuate in response to world markets. These crops, with sugar cane for ethanol production, have pushed out grazing livestock. There is also planting of fast-growing trees, mostly eucalypts and pine species, for cellulose or paper production. In a domino pattern, the ranchers have moved into higher rainfall areas of Amazonia to cut the rainforest and plant pastures, which is displacing indigenous peoples and creating erosion and reduced biodiversity.

There is concern that the wide-scale continuous cropping of the same species will quickly reduce soil carbon and diminish the native fertility of the soils of the *cerrado* region, despite the heavy application of chemical fertilisers. This pattern of exploitation can be equated to that in the U.S. Midwest where over half of the top-soil has been lost in just over a century of farming. According to the FAO (2005) maps, there is light, moderate, and severe soil degradation across most of the *cerrado* region. One must question the long-term ecological viability of such a change to continuous cropping, and hope that, in the future, there will be greater focus on crop–livestock systems that are more sustainable.

21.2.1.3 *Llanos* or Plains of Colombia, Venezuela, and Guyana

The large grassland areas of Colombia, Venezuela and Guyana (Fig. 21.1) (*Rupununi* Savanna) occupy around two million km^2, and are characterised by shrubby perennials across grassland where these areas are not farmed. There are more trees in the gallery forests along the narrow rivers that transect the region. These tropical grasslands are found near the equator at the edge of the tropical rainforests. The climate is hot and semi-humid, with annual rainfall from 600 to 1,600 mm, and distinct wet and dry seasons. In Colombia and Venezuela, the *llanos* or grassland region is primarily alluvial soil from the Andes that is much younger than the cerrado Brazilian shield described in the previous section. Soils are also very acidic, making it difficult to sustain crop growth without additions of lime and phosphorus. Most of the area drains into the large Orinoco River basin (Sarmiento 1983).

The savanna or *llanos* areas of all three countries have been occupied by indigenous peoples for centuries. These hunters and gatherers were marginalised by immigrants from Europe who began to raise cattle that were introduced to South America. Much of the agricultural exploitation of the savanna since arrival of Europeans has been by grazing of livestock, with beef cattle predominating because of their ability to graze extensively and seek out forage during the changing seasons. The intensity of livestock production has been much lower in these savannas than in the savannas in Brazil, and there has been far less conversion to cropping (Rivas et al. 2004).

The *Rupununi* Savanna area of Guyana lies between the border with Brazil and the Rupununi River, and is characterised by overlays of sandstone and shale that are indications of a prehistoric sea bottom. The savanna is similar to areas of Kenya, with abundant wildlife and an emerging tourist industry. Cattle ranches were established by mostly Scottish immigrants who brought beef cattle to the area.

Given the highly weathered condition of the llanos soils, it is remarkable that native and some introduced pasture plants grow so well. Among the native species that are common in the area are crinkleawn grasses (*Trachypogon* spp.), carpetgrass (*Axonopus* spp.), bluestem (*Andropogon* spp.), threeawn grass (*Aristida* spp.), bahiagrass (*Paspalum* spp.), and dropseed (*Sporobolus* spp.). Two native species that have undergone extensive selection and are now used as improved pasture are tick trefoil (*Desmodium* spp.) and stylosanthes (*Stylosanthes guianensis*).

The question has been asked, "Where does the phosphorus come from, when it is so tightly bound in these acid soils?" One answer came from a personal experience (C. Francis) in the Colombian *llanos* during the 1970s. A study by the *Instituto Colombiano Agropecuario* (ICA) showed that individual termite mounds covered a wide and deep area of excavation by termites, 2–4 m in diameter, and often extending 6 m or more into the soil profile. It was found that termites brought up soil richer in phosphorus from lower strata and deposited it on or near the surface where it was available to plants. From their calculations, it appears that the llanos soil profile across the entire area is stirred to this depth every 80 years, and thus termite action explains the successful growth of pasture during the rainy season each year.

Cropping systems with annual plants have been slow to adapt to the llanos. There have been plantings of the improved pasture species mentioned above, mainly by ICA in Colombia and the *Centro Internacional de Agricultura Tropical* (CIAT), which has specialised in increasing the productivity of acid soils in the region. Crops such as maize[5], cassava, rice, and grain sorghum have been tested by CIAT with limited success in the region, although small areas of these crops are planted for subsistence in the more fertile alluvial soils along rivers.

21.2.1.4 *Andean Puna* and Intermountain Valleys of the Andean Zone

Although highland rainfed farming systems do not occupy a large land area in South America, they are historically and culturally important. Found on the sloping lands along the Andes Mountains and in the intermountain valleys, these systems occupy important areas in Colombia, Ecuador, Bolivia, and Peru, and, to some extent, in Chile and Argentina (Fig. 21.1). They comprise about 800,000 km^2 at elevations of 2,000–4,000 m, with mean daily temperatures from 0°C to 20°C, and rainfall of 250–700 mm per year. The lands continue to provide a substantial diet for subsistence farmers who have traditionally lived in these areas or who were forced there by the European conquerors and have been unable to secure better land in the valleys at lower elevations.

Multiple cropping systems have been common to the region for at least 1,000 years. The soils in these sloping lands are typically shallow and of volcanic origin. Farmers interplant a variety of common crops by hand, including maize,

[5] See Glossary for botanical names.

squash, tomatoes, peanuts, potatoes, and chili peppers, along with some that are unique to the region such as amaranth (*Amaranthus* spp.) and quinoa (*Chenopodium quinoa*) for grain, and root crops such as *oca* (*Oxalis tuberos*a) and *ulluca* (*Ullucas tuberoses*) (Popenoe et al. 1989). These crops have their centres of origin in the Andean Zone, and some have spread to other continents to become staples and a part of the local culture.

Most cultivation on the hillsides even today is by hand or with animal-drawn implements, as mechanised equipment is neither available nor adapted to the small and sloping fields. Subsistence agriculture is the primary activity, although some intensification of crops and addition of value-added industries with products for export have been developed, especially in the intermountain valleys. These sloping lands of South America have been least affected by new technologies; high technology agriculture exists only in the most fertile, flat valleys with irrigation.

The intermountain valleys of the Andes are not extensive in area but are important historically for the indigenous groups that settled in these prime lands as well as the colonial settlers who took over many of them. Originally home to hunter-gatherers, the fertile soils supported sedentary agriculture as long ago as 7,000 years BP. This evolved into a pottery-based culture where people raised maize, beans, banana, plantain, yuca (cassava), and another root crop called *arracacha* (*Arracacia xanthorriza*) (Popenoe et al. 1989). This endured up to the time of conquest by the Spanish.

The colonisers pushed the indigenous people out of the highly fertile valley lands into the surrounding hills where they continued cultivating these same primary food crops. Large tracts of the valley lands were ceded in grants to officers and soldiers from Spain, as well as to administrative clerks and others who served in the colonial regime. The flat valley lands were used for extensive grazing while the food crops were grown on the more marginal surrounding land – a reverse of what makes ecological sense. The patterns of land ownership and land use today still reflect these colonial decisions; for example in the Cauca and Magdalena Valleys of Colombia, there has been no effective land reform for nearly 500 years. Although maize, soybean, cotton, and sugar cane have replaced grazing in most of the valleys, the larger farms still represent the ownership patterns of the colonial times.

Because of the fertile soils and relatively level topography, these valleys were among the lands that were first to be mechanised. Also, their intermediate elevations from 500 to 1,500 m and the adaptation of a number of commodity food crops to this climate meant that technologies from other prime agricultural areas could be quickly adapted. For example, the Central Valley of Chile, south of Santiago, is so closely similar to the Central Valley of California that there is regular exchange of crop and fruit cultivars, and adoption of similar chemicals, fertilisers, and even of whole systems. Unlike the Cauca Valley (Colombia), land holdings are relatively small.

The land tenure situation in Chile, similar to some other areas of South America, is due in part to a land reform program under President Frei in the 1960s (Strasma 1969). Many of the less productive large farms were distributed to labourers, the land became more productive, and the pattern has persisted through several changes of government. While the historical situation in each country is unique, it is noteworthy that current patterns of ownership and management often reflect political decisions that stretch back to colonial times, as well as to policy changes of the past century.

21.2.1.5 Other Rainfed Farming Regions

Although these four regions include many of the most important food crops and large populations throughout the continent, there are other tropical, subtropical, and temperate areas that provide significant food and raw material production in South America. In the lowland, high-rainfall areas, there is extensive banana and plantain (*Musa* spp.) production for national consumption and for export. There is a substantial and growing export potential for tropical fruits such as pineapple, mango, papaya, and other perishable fruits that are gaining favour in markets of North America.

Rubber (*Hevea brasiliensis*) is native to Brazil, as the species name implies, and is widely grown in the tropical lowlands where it produces a sustainable yield and provides employment for many people. Tropical oil palm is native to the humid tropics of West Africa, but has become an important plantation crop in South America. The area planted is growing rapidly due to its potential for biofuel production, and plant breeders have been highly successful in selecting for increased oil content of the fruits.

There are also subtropical and temperate fruit crops that are grown for local use and for export; although many of these are found in the highly fertile valleys and they are often irrigated when rainfall is insufficient for adequate production. Crops include grapes, peaches, nectarines, oranges and other citrus fruits, apples and kiwi fruit. Brazil is one of the major exporters of frozen citrus juice. Argentina and Chile are known for production of good-quality wines as well as export of grape juice concentrate.

This overview provides only a glimpse of the wide biodiversity and agricultural potential of South America. There are many more crops, both indigenous and introduced, that contribute vital nutrition to local diets and value from export. New crops to the continent, such as rice, now occupy a major part of the diet, although this cereal is almost entirely produced under irrigation. There are some areas of rainfed rice in the higher rainfall and flooded areas along the Pacific Coast and in the lower elevation inland valleys. Overall, the crops and cropping systems of the continent reflect a long history of cultivating species that evolved here, and these have been supplemented by a number of important crops from North and Central America (maize, beans, squash), Europe, Africa, and Asia. Most of the continent depends on rainfed agriculture, with irrigation in only a few of the most favoured and fertile areas. Agriculture is a mainstay of the economies of every South American country, and there is still a substantial percentage of the population that is involved in farming.

21.3 Quantitative Analysis of Complex Systems: The Pampas Region

Farming systems in the Pampas Region are strongly driven to meet national and export demand for food, fibre and, increasingly, raw materials for conversion to fuel. Crop production using new technologies such as improved varieties, chemical pesticides, and fossil fuel-based fertilisers is increasing because of its higher economic profit compared to extensive livestock grazing. The regional and national economy also benefits from the shift to intensive cropping, although a recent increase in export tax on commodities has raised concerns about the distribution of benefits between farmers and the federal government. When the focus shifts to short-term monetary benefit, there is likely to be less attention to the environment or to preserving the natural resources on which long-term wealth depends.

Rural economic development and farmer profits are essential for societies, but these cannot be sustained without conservation of natural resources (Campbell 2000). Thus there must be a balance between economic benefits and sustainable management of the resources. Although there are many economic pressures on farmers to produce maximum yield per hectare and output per farm (and some of these arise from government policies), at least as much emphasis should be placed on producing *ecosystem services* (Rótolo and Francis 2008). Although these services are not normally recognised nor rewarded by neoclassical economics, they are essential to long-term agricultural performance. To ensure long-term sustainability, it is usually better to aim for optimum rather than maximum production and efficiency.

Such a requirement for system management requires methods of system evaluation that combine the value of local natural resources, input flows from outside the farm and output flows to society in a single unit of measurement. A large number of qualitative and quantitative tools are available for assessing the performance and health of farming systems. Authors have reviewed (Payraudeau and van der Werf 2005), compiled (Jorgensen et al. 2005), and compared or summarised methods and indicators (van der Werf and Petit 2002; Halberg et al. 2005; Munasinghe 2007) in order to better understand which ones are more suitable for their evaluation. Broadly speaking, quantitative or analytical tools are those that are focused on technical aspects of the analysis; an example is Life Cycle Analysis (LCA). Qualitative tools are those focused on the procedures and their connections, such as Environmental Impact Assessment (EIA) or *Marco de Evaluación de sistemas de Manejo incorporando Indicadores de Sustenatabilidad* (MESMIS) (Masera et al. 1999). Quantitative tools can range from those that consider a few indicators of the natural or the socio-economic context of the system, such as the "presence or absence of a particular species" to those that try to embrace the context of the system such as SFA (Substance flow analysis), as well as LCA and EMA (Emergy Analysis). These different tools can also be located and described in relation to a number of different characteristics such as its scope (local, regional and global), the objective for which the analysis is done (policies/programs, regions, products/services) and whether the methods are descriptive or change-oriented.

A quantitative and integrated evaluation recognises that all flows and components of the biosphere are interconnected and driven by similar systems principles (Odum 1996). Systems are characterised by the circulation of energy, materials and information; among these, energy is the fundamental driver of all processes in an ecosystem (Brown and Ulgiati 2005). In order to evaluate farming systems to cover all the above processes, we have chosen to use thermodynamics tools which, according to Jorgensen et al. (2005), are the most holistic tools available to quantitatively evaluate farming systems health. Whether a system is healthy depends on its integrity, which refers to an ecosystem whose structure contributes to meeting the goals of a system's manager and to its long-term sustainability (Brown and Ulgiati 2005; Campbell 2000).

Emergy analysis was suggested as an appropriate tool for such an evaluation. *Emergy is defined as the whole available energy (based on a common unit, usually solar energy) that is used directly and indirectly to obtain a product or service (Odum 1996). It is the energy 'memory' of the product, and accounts for all the available energy supplied by nature and society that is invested into attaining a certain output.* It therefore provides an ecological-economic evaluation (See Supplement to Chap. 1).

In this chapter, we present a Case Study of emergy analysis of grazing cattle from Argentina's Pampas region (Rótolo et al. 2007b) to provide an example of comprehensive system measurement which includes the hidden value of ecosystem services (Rótolo et al. 2007a). This study serves to illustrate quantitative systemic analysis, and its scope, which embraces dimensions across-scales and over time within the framework of a farm system. The analyses provide donor values[6] for the synthesis of process components and products and gives insight into long-term behaviour (health and functioning) of the system. A brief comparison with other studies provides a standard for benchmarking. An overview of the parameters and objectives of these selected systems is shown in Table 21.1. Later in this chapter,

Table 21.1 Examples of emergy-based studies of agroecosystems in Argentina, Brazil, U.S.A., and Mexico, with descriptions of objectives and purposes

Country	Description	Source
Argentina	*System studied*: complete cycle of grazing cattle, low-input, system in Argentina Pampas Region; sub-systems involved, such as natural and sown pasture, hay, forage crops, maize, horse, cow-calf operation and steers, were also studied. *Objective*: to evaluate the complete cycle of grazing cattle in an environmental and economic context, in order to assess long-term sustainability of cattle production, indicators of performance and environmental sustainability.	Rótolo et al. (2007b)

(continued)

[6] Donor value is derived from the value of all inputs to create a product compared with 'receiver value' favoured by economists – what the purchaser is willing to pay.

Table 21.1 (continued)

Country	Description	Source
	Purpose: goal is to improve or maintain management and reach decisions for strategies to ensure the future economic welfare and environmental integrity of the region. *Commentary*: the renewability percentage[7] of most of the items has been accounted for; the coupled systems were analysed as well as the sub-systems and total system behaviour.	
Argentina	*System studied*: complete cycle of grazing cattle, low input system in Argentina Pampas Region, with focus on steers for internal trade. *Objective*: to quantify the environmental contribution embedded in the product that is not measured in the current marketplace and to discuss the need for different actions by policy makers to recognise the true value of this product. *Purpose*: to provide insights about how certain policies could be established to promote a more sustainable agriculture and rural landscape. *Commentary*: focus on the environmental services hidden in the market prices of steers and how an Emergy Exchange Ratio could be useful to show their relevance and value.	Rótolo et al. (2007a)
Argentina	*Systems studied*: emergy flows supporting the Argentine economy during twentieth century and an overall study of five different farming alternatives of Rolling Pampas. *Objective*: to measure Argentine economy variations and ecological sustainability of agricultural production in the Rolling Pampas during the twentieth century. *Purpose*: to attempt an ecological interpretation of the Argentine economy and to contribute to the evaluation of national and regional policies and resulting management practices. *Commentary*: the strength of the work was in analysing the economy of the country during the last century and producing a general analysis of farming activities.	Ferreyra (2001)
Brazil	*Systems studied*: production systems of grain (corn, soybean and wheat), pigs and fish in small farms in the south region of Brazil. *Objective*: to improve emergy accounting by considering the renewable part for each item that has contributed to the system. *Purpose*: to assess public policies as tools to help avoid the pollution problems occurring in other regions of Brazil with similar production systems. To suggest some better management practices useful for farmers. *Commentary*: each item that has contributed to produce maize, fish or pigs has been considered for its potential contribution and renewability.	Cavalett et al. (2006)

(continued)

[7] Renewability percentage is: Renewable emergy divided by total emergy used expressed as a percentage.

Table 21.1 (continued)

Country	Description	Source
Brazil	*System studied*: the soybean chain *Objective*: to evaluate soybean production and the subsequent industrialisation processes. *Purpose*: To estimate the proportion of the emergy involved in each stage of the process evaluated, in order to identify specific stresses on the environment. *Commentary*: the soybean production stage included both a family farm model and an industrial farm model.	Cavalett and Ortega (2006)
USA & Mexico	*Systems studied*: three agricultural systems: conventional maize with irrigation in Kansas, U.S.A.; blackberry with irrigation in Ohio, USA; and Lacandon polycultural rotation and rainfed system in Chiapas, Mexico. *Objective*: to compare and contrast resource use, productivity, environmental impact and overall sustainability of three systems contrasting in biodiversity and location. *Purpose*: to assess sustainability using emergy analysis and to compare systems that differ in number of enterprises and intensity of input use. *Commentary*: the emergy methodology allowed comparisons across agricultural systems and helped identify a management strategy to achieve greater sustainability, which relies more on renewable resources while obtaining high yields.	Martin et al. (2006)

we also make reference to Embodied Energy and Exergy, as well as to Life Cycle Analysis (LCA) as complementary evaluation tools.

21.4 Case Study: Emergy Analysis of a Farming System

Building on concepts introduced in Chap. 1, we performed a quantitative emergy analysis to evaluate the resource use, environmental sustainability, environmental load[8] and output of a complete-cycle cattle grazing system in the *Pampas,* integrating its natural and socio-economic aspects. In addition to presenting our methods and results, we have demonstrated the interactions among its components. The analysis provides information and insights for long-term management decisions and public policies.

Grazing cattle is clearly an important traditional activity of Argentina's society and economy. However, the enterprise is subject to policy changes and also closely interacts with the natural resources and the ecosystem services on which it relies.

[8] Environmental load is the disturbance in ecological systems caused by humans, resulting in deviations from normal behaviour.

In recent years in Argentina, periodic policy changes have not benefited the grazing enterprise. Sometimes expansion is supported because of the increasing opportunity of external markets. Alternatively, trade may be restricted because of the need to preserve quantity and price for internal consumption.

21.4.1 Methodology

Within such a context in Argentina, the emergy evaluation of grazing cattle published in Rótolo et al. (2007a, b) and explained here, allows the investigator to:

- analyse the matter and energy flow to each component and product or service, and to make comparisons among flows and sub-systems facilitated by the use of solar energy as a common unit.
- study the performance of each sub-system embedded in the overall window (area) of study.
- analyse the behaviour of the coupled sub-systems involved and, at the same time, understand how the whole system is performing.
- identify the position of this activity in the country's economy
- calculate the value of the product from a donor point of view. This is done by considering the environmental support to all inputs flows that create a product, instead of their market value based on scarcity or willingness to pay.
- investigate the system under focus along with the larger environmental and economic ones. This provides a tool to study each component without losing a view of the whole.

Emergy accounting is organised as a top-down and systemic approach where all input and output flows of the system are considered and accounted. First, with a wider view, the whole study system is characterised, then narrowing the focus, the sub-systems are analysed and tables are constructed. Finally, the view is widened again with the analysis of indices obtained.

21.4.1.1 The Cattle Grazing System

Understanding the nature–society interface in a system involves providing information on components, processes and connections leading to system definition and characterisation, as already described in Chap. 1. However, we recall from that chapter (in the words of Ulgiati and Brown 2009) that "*ecosystems circulate materials, transform energy, support populations, join components in network interactions, organise hierarchies and spatial centres, evolve and replicate information, and maintain structure in pulsing oscillations.*" Thus for example, the cattle grazing system structure consists of different organisation levels (e.g. pastures and steers) which influence different spatial areas, are organised in energy hierarchies, and are coupled and evolve according to the dynamics of their contexts.

The clearly-defined system of interest to the researcher or manager, in this case the complete cycle of a cattle grazing system, is depicted in Fig. 21.2. An initial diagram is then drawn in Fig. 21.3 using symbols defined in Chap. 1, showing flows and relationships. In an emergy analysis, it is important to identify which

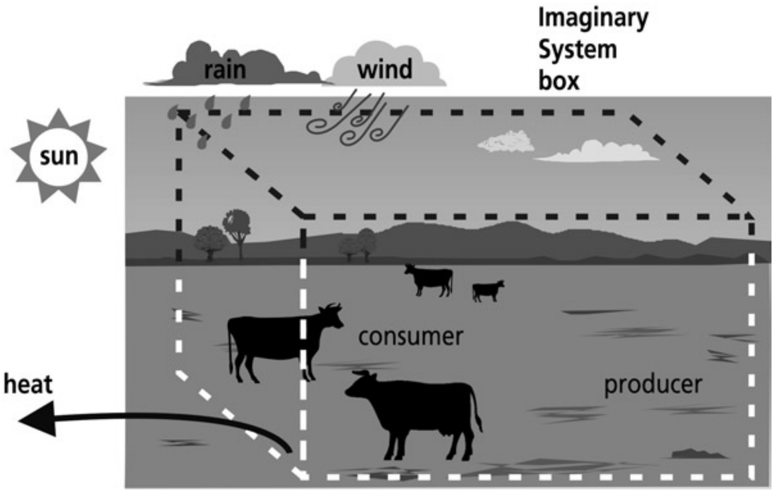

Fig. 21.2 Defining the study system ('producer' is the photosynthetic process yielding grass; 'consumer' is the herbivore system converting grass into meat and concentrating solar energy)

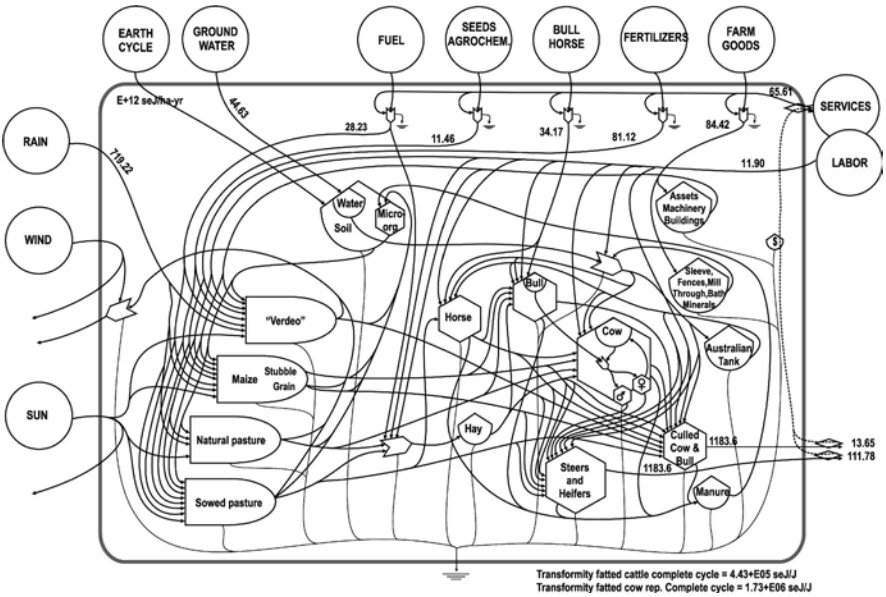

Fig. 21.3 Detailed system diagram of grazing cattle in energy language

elements and processes are outside of our window of concern (assumed as the boundary of the system) and which are inside, as well as the interactions among them. The picture of networks that shows components and relationships (Fig. 21.3) is helpful for visualising the processes, storages and flows that are considered important in the system, as well as those that are interacting from outside of our window (Brown et al. 2000). Moreover, the diagram is a guide to thinking about the relationships between components and pathways of exchange and resource flows (Sciubba and Ulgiati 2005).

21.4.1.2 Using the Diagrams

Diagrams are designed using a language of universal energy symbols. A rectangle always represents the window of attention (the system on which the researcher is focused); the energy, material and information (as labour) sources that drive the system are represented by circles; the consumers by hexagons; the primary photosynthetic producers by a bullet; the storages by tanks and so on. The broad arrows usually mean flows of energy, as shown in Fig. 21.3. A complete description and discussion of the symbols can be found in Emergy Accounting (Odum 1996) and in Systems Ecology (Odum 1983).

In diagrams such as Fig. 21.3, energy circulates in a left-to-right direction. Natural sources are placed on the left and top-left side of the diagram and socio-economic sources are placed on the top-right and right side. The components of the system are organised or placed in the diagram according to their hierarchical organisation (i.e. production, consumption). In an hierarchical organisation, each higher level (e.g. cattle) is fed by those that are below it (Ulgiati and Brown 2009). In the meantime the driving energy (i.e. solar radiation, rain, fuel, labour) flows within and across the components of the system. It may be transformed to energy of the same or a different form in order to be part of or provide support to a new component of the system. It increases in quality and decreases in quantity, while material circulates and information is sustained and/or renewed. In this process, energy builds or updates the structures needed for system operation. It provides feedback to lower units to self-organise in time, space and connectivity and to optimise the system efficiency, thus ensuring its survival.

For the sake of clarity this is explained as follows: the huge amount of available energy supplied by the sun decreases all along the metabolic chain in its way through pasture to steers. This is because part of it is used in building and maintaining structures such as cells and organisms, and some is degraded as heat. Analysing this process in 1 ha, the available energy received from the sun is 4. 4E+13 J/ha/year,[9] that stored within the pasture is 1.2E+11 J/ha/year and that stored within the steers is 2.5E+09. On the other hand, the solar radiation is transformed from a

[9] The so-called 'scientific' notation 4.4E+13 means 4.4×10^{13}. It is used above and hereafter in the text as well as in the tables and figures.

dispersed energy form to a more concentrated one (from radiation to sugars in the grass, to proteins, fats, etc. in the meat). Therefore the energy stored in the steers has undergone many transformations and is characterised by a higher 'supply-side' quality (concentration) than the energy supplied by the sun or stored in the grass. Pastures transform solar radiation into chemical energy, while losing heat. Moreover, pasture is not totally grazed or cut; around 35% of its biomass is left in the field, and this is utilised for the regrowth or formation of new plant structures and for soil micro-organisms. Thus part of the solar energy required to produce grass goes back into the system, in a feedback process, which allows the system to self-organise.

If we focus on the whole system (Fig. 21.3), we can first identify the energy entries and interactions necessary to produce, for instance, sown pasture, and 'Verdeo', which is an annual, usually winter grass (e.g. oats). In the diagram, *transformity* is the emergy input per unit of available energy of output (seJ/J). The numbers on pathways – multiplied by the number indicated in the top left corner – represent the emergy contribution of each component to the output; for instance 103 E + 12 seJ/ha/year is the emergy of net soil loss (erosion); 11.46 E + 12 seJ/ha/year is the emergy from agrochemicals and seed. The natural resources contribution is represented only by the largest environmental flow which, in this case, is the rain. Smaller environmental flows (direct radiation, wind, etc.) are included in the rain emergy and are not accounted for.

One of the outputs of the system is steers and heifers in a range of around 200 kg/ha/year, which has an emergy content of 111.78 E + 12 seJ/ha/year.

It is easy to visualise from the many components and interactions what is necessary to obtain the steers. A system such as feedlot production, where manure is not usually recycled back to the fields, depends exclusively on purchased inputs such as calves and feed, and has few opportunities to provide feedback to lower units. Therefore it is difficult to ensure its functioning over time unless the animals and their feed are annually guaranteed by external sources. A different situation can be found in a system such as a complete cycle of grazing cattle where, depending on the management, calves are produced and raised in order to be fattened and sold, while some heifers are raised to replace the old cows. This brief example shows certain feedbacks, such as the cycling of nutrients from animals' faeces that allow a longer survival of the system, depending on the other necessary components for this complete cycle of grazing cattle production. This permanent cycling makes useful material and information reusable by the system. In contrast, when they are sequestered in unreachable or unusable storages, such as when nutrients in animal manure are not recycled, they are of no value and soon lose their relevance (Brown and Ulgiati 1999).

In summary, "understanding the relationship between energy and cycles of materials and information provides insight into the complex interrelationships between society and the biosphere" (Ulgiati et al. 2007).

Once we have drawn a detailed diagram, it is possible to group the components of the system to produce simpler diagrams. This is done by aggregation, without losing the system's integrity and without changing the meaning of its functioning (Odum 1996). By aggregation of the components, we can much more easily understand

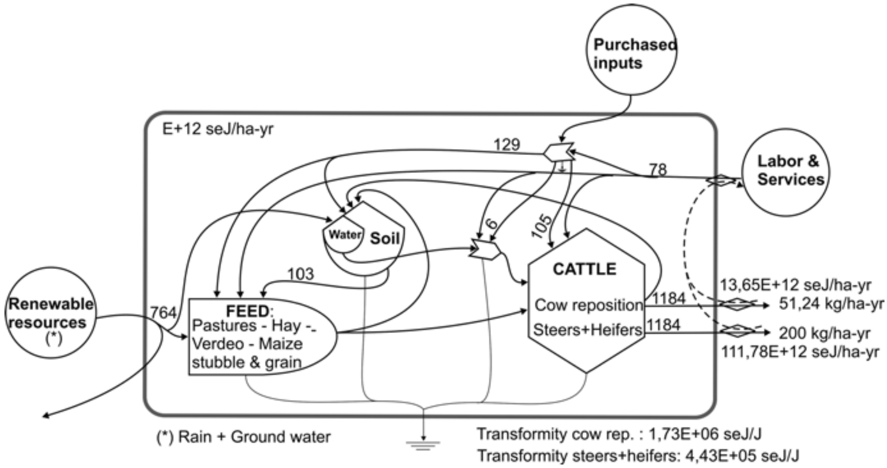

Fig. 21.4 Aggregated diagram in energy language of 'complete cycle of grazing cattle' system. The numbers on pathways – multiplied by the number indicated in the top left corner – represent the emergy contribution of each component to the output. For example, the amounts of emergy required from purchased inputs for primary (feed) production (129 E + 12 seJ/ha/year), water for cattle (6 E + 12 seJ/ha/year) and for secondary (livestock) production (105 E + 12 seJ/ha/year) that together are required to obtain the output with the management utilised. Both outputs (cows and steers + heifers) need the same amount of emergy per unit of product

diagrams such as Fig. 21.4. Conversely, it is also possible to ungroup units of the system in order to study each of its sub-systems, e.g. the maize sub-system, sown pasture sub-system (Fig. 21.5) or steers sub-system, which can also be aggregated. Therefore, each sub-system that can be identified in Fig. 21.3 can also be analysed. The more the number of component parts and their connections within a system or sub-system, the greater its complexity. Thus complexity is a property of systems (Odum 1983) and increases according to the increase of interactions within and among hierarchical levels. It is possible to visualise complexity even in the aggregated diagrams.

The flows coming into the system from nature are as important as the ones coming from society and need to be properly accounted for. The diagram helps us to be aware of the relevance and importance of the contributions of the various elements, mainly the ones coming from nature, such as solar radiation, rain, ground water, earth cycle (the last refers to the processes driven by geothermal heat, which contributes to soil formation and deep soil temperature). In addition, by means of a system diagram, it is possible to visualise the changes or trade-offs needed in case one of the system components is eliminated or modified.

21.4.1.3 Using the Tables

After the diagrams are drawn, tables need to be constructed in order to list all input flows, convert them into emergy units and calculate performance indices. In order to

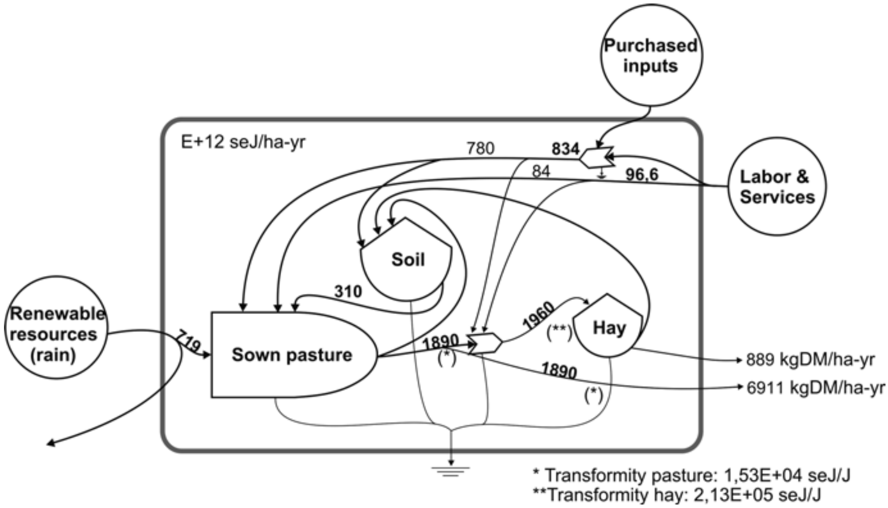

Fig. 21.5 Aggregated diagram in energy language of complete cycle of sown pasture sub-system. The numbers on pathways – multiplied by the number indicated in the top left corner – give the emergy contribution of each component to the output. For example, 1,960 E+12 seJ/ha/year is the emergy required to obtain the grass plus the emergy required to make the hay

obtain the table of the whole system, it is first necessary to develop and to analyse the tables of each sub-system. Table 21.2 details, as an example, the flows supporting the pasture sub-system, while Table 21.3 shows the main aggregated flows to each sub-system as well as to the whole system. In Table 21.2, data for column (a) are taken from statistics, literature, specialists in the field or own data; data for column (b) are taken from literature and personal evaluations; and data for column (c) are calculated by multiplying the entries of the two previous columns. It is possible to see that the total of renewable inputs is not, in fact, a sum; it was put equal to the largest flow coming from the same source, i.e. the rain, in order to avoid double counting. Looking at the system from the larger biosphere point of view, the energy coming from the sun directly reaches the land, the ocean and the atmosphere. It adds up to the other driving sources that also support the earth crust and oceans, i.e. the gravitational energy of the system earth-moon (that drives tides) and geothermal deep heat. Within the ocean and atmosphere, the energy from these sources (sun, tide and deep heat) interact and contribute to develop rain, wind and land cycles that in turn affect the local land area of analysis (1 ha). The transformities of global flows (wind, rain, minerals, etc.) are calculated by considering them as co-products of these three main driving forces acting together. When two of these co-product flows are applied simultaneously to a system (1 ha of land) and generate a product (forage or corn), their emergies cannot be summed, because this would mean double counting their 'production cost'. Only the largest flow (i.e. the largest production cost) is added to the total, because the production cost of the smaller flows is already accounted for in the largest one (e.g. in the rain, as shown in Table 21.2).

Table 21.2 Emergy table of sown pasture sub-system from complete cycle of grazing cattle

Note	Items and units	Data (unit/ha/year) (a)	Emergy per unit (seJ/unit) (b)[a]	Emergy (E+12 seJ/ha/year) Pasture (c)	Emergy (E+12 seJ/ha/year) Hay	% of total Emergy allocated to pasture
Renewable resources (R)						
1	Sun radiation, J	4.67E+13	1.00E+00	46.72		2.47
2	Rain chemical energy, J	3.95E+10	1.82E+04	719.22		37.98
3	Wind kinetic energy, J	2.46E+07	1.50E+03	0.04		0.00
4	Earth cycle, J	1.00E+10	3.44E+04	343.77		18.16
	Largest renewable input			**719.22**		**37.98**
Non-renewable Resources (NR)						
5	Net top soil loss, J	4.19E+09	7.40E+04	310.21		16.38
	Sum of free inputs (R+NR)			**1029.40**		
Purchased Resources (PR)						
6	Gas-oil-lubricants past.& hay, J	1.40E+09	6.60E+04	45.63	46.46	2.41
7	Seeds, J	7.56E+07	2.27E+05	251.14		13.26
8	Nitrate fertiliser, g	3.94E+04	9.54E+09	375.99		19.86
9	Phosphate fertiliser, g	1.08E+04	8.70E+09	94.17		4.97
10	Agrochemicals, J	1.43E+06	6.60E+04	0.07		0.00
11	Machinery to pasture, & hay, g	1.56E+03	1.13E+10	11.81	5.79	0.62
12	Buildings to pasture & hay, Tn	1.49E−03	1.78E+15	1.32	1.32	0.07
	Sum of purchased inputs allocated to past (PR)			**780.11**		**41.20**
	Sum of purchased inputs allocated to hay(PR1)				**833.70**	

(continued)

Table 21.2 (continued)

Note	Items and units	Data (unit/ha/year) (a)	Emergy per unit (seJ/unit) (b)[a]	Emergy (E+12 seJ/ha/year) Pasture (c)	Emergy (E+12 seJ/ha/year) Hay	% of total Emergy allocated to pasture
Labour and Services (*S*)						
13	Direct labour pasture and hay, h	5.25E+00	1.68E+12	6.72	2.10	0.35
14	For goods, fuel, infrastruc. and labour: pasture **(L&S)**, dol	39.82	1.94E+12	77.25		4.08
15	For goods, fuel, infrastruc. and labour: Hay **(L&S1)**, dol	5.43	1.94E+12		10.53	
	Sum (P+S)			**864.10**		
	Sum to hay (PR+L&S+PR1+L&S1)				**930.30**	
Output (*Y*)						
16	Grass above ground prod., J	1.24E+11	1.53E+04	1893.50		100.00
17	Production for making hay, J	9.20E+09	2.13E+05	1959.70		

[a] Total emergy flows supporting the geobiosphere are about 15.83E+24 seJ/year, based on a re-evaluation and subsequent recalculation of global emergy flows made by Odum (2000). Prior to that date, the total emergy contribution to the geobiosphere that was used in calculating unit emergy values was 9.44E+24 seJ/year. Such an increase of the global emergy baseline affects all the unit emergy values that directly and indirectly are derived from the value of global annual empower. Thus, unit emergy values calculated prior to that year should be updated by multiplying by 1.68 (the ratio 15.83/9.44). In the present paper we use the old baseline, 9.44E+24 seJ/year, for easier comparison with studies published before 2000

Table 21.3 Environmental and economic forces driving the selected sub-systems and system of complete cycle of grazing cattle, expressed in emergy terms (seJ/ha/year)

Driving forces (E+14 seJ/ha/year)

System/subsyst	Outputs	Local renewable (R)	Local non-renewable (NR)	Purchased inputs (PR)[a]	Labor and services (L&S)[a]	Emergy yield (U)
Sown pasture subsyst.	Pasture	7.19	3.10	7.80	0.84	18.94
	Hay	7.19	3.10	8.34	0.97	19.60
Natural pasture subsyst.	Nat.past.	7.19	1.14	0.00	0.10	8.43
	Hay	7.19	1.14	0.33	0.20	8.86
Verdeo subsist.	*Verdeo*/forage	7.19	5.69	6.88	1.28	21.04
Maize subsist.	Grain	7.19	4.55	8.55	3.94	24.23
	Stubble	7.19	4.55	8.55	3.94	24.23
Cow-calf operation sub-system	Calves and cows	8.56	2.09	1.24	0.65	12.54
Complete cycle system	Steers and cows	7.64	1.03	2.39	0.78	11.84

[a] PR+L&S=F (total outside resources)

When we add the complexity of consumers into the system, i.e. cattle, the emergy of renewable resources (8.56 E+14 seJ/ha/year) is slightly different from that of primary production (7.19 E+14 seJ/ha/year) (Table 21.3). This is because of the influence of new renewable flows that enter the system, such as the renewable fraction of feed (pastures, maize, etc.) and groundwater used by the animals. However, the renewable emergy of the feed, which is a product of the same energy source, the sun, is not added to the emergy of the rain, since the latter is still the largest locally renewable flow. A different situation occurs with groundwater which should be added to rain since it comes from the larger watershed (with energy influences from outside the studied area). Therefore the renewable emergy flow increases in the cow-calf operation sub-system to 8.56 E+14 seJ/ha/year (Table 21.3). Even though groundwater is not a fully renewable resource due to its slow recharge, it was assumed that the amount used by animals is annually recharged across the watershed.

Once all the sub-systems were analysed, their data were integrated into the whole system evaluation. Each sub-system was analysed according to a standardised area of one hectare. However, when we broaden the scope to analyse the whole system, integrated calculations are necessary because all the sub-systems are functioning together and interacting within the hectare. Therefore, the input data to the complete cycle of grazing cattle of Table 21.3 are not the sum of input data to the different sub-systems. For instance, as shown in Table 21.3, the value of the emergy flow of renewable resources of the complete cycle (7.64 E+14 seJ/ha/year) is not the sum of the renewable resources of the different sub-systems such as sown pasture, natural pasture, and *verdeo* that contribute to it. The same occurs with the other driving forces of the complete cycle, such as local non-renewable, purchased input and labour and services; they are not the sum of the corresponding emergy value obtained in each sub-system.

Next, by relating the data of the main flows shown in Table 21.3 we can obtain *performance indices* or *ratios*. These indices and ratios allow us to understand the system performance and behaviour, as well as to infer its optimum efficiency in comparison with other systems and how it may adjust to changes in context. These indices and ratios (obtained by relating local and purchased input flows and/or renewable or non-renewable flows) allow us to emphasise the environmental load over a system, or the efficiency of a process in comparison with other systems under different management.

21.4.2 Emergy Environmental Value

The emergy value of a product is not the actual energy that is left in the product. It takes emergy to drive a process and to make the product. An emergy evaluation is a top-down and systems-context approach. As a top-down process accounting for larger processes of the biosphere, the emergy value of a product is the amount of available energy that was used up to obtain that product. It reflects the total emergy needed to run a certain process and its transformity relates the total emergy needed for a process to the unit of product obtained. Once all input flows are evaluated in emergy terms (i.e. the same unit), it is also possible to calculate the fraction (or percent) of each flow's contribution to the output. This way of accounting for inputs through a hierarchy of levels within and across systems and time, using solar energy as the common unit, builds the *donor value* of the product. Moreover, it analyses the process integrally and specifically, because it allows valuing the whole system – the complete cycle of grazing cattle – as well as its parts or its sub-systems.

Consequently, the emergy value of a product or service is an objective value independent of the oscillations of market prices and preferences, that embodies all the driving forces from nature and society. Since it also provides a thermodynamic and environmental basis to flows that are not always properly accounted for by neoclassical economy and market dynamics (such as labour, information, fairness of trade, as well as environmental flows and services), the emergy valuation method provides researchers and policy makers with relevant and impartial information to devise strategies for the sustainable development and welfare of their region or country.

Not only are the local socio-economic and environmental contributions to a process embodied within the emergy value of a product, but also the contributions coming from the larger surrounding area and broader time scale, that influence the interactions among components of the process.

Emergy analysis appears to be a suitable methodology to integrate nature and society and to offer an objective value of a process, from a donor (or supply side) point of view. By definition, it does not address the direct effect of emissions and waste usually defined as 'pollution'. Some emergy analysts have therefore integrated emergy (an upstream evaluation method) and Life Cycle Assessment[10] (a downstream evaluation method more concerned with the direct impacts of economic activities), in order to exploit in a complementary and synergistic way the potentiality of both approaches (Ulgiati et al. 2006). Through combined analyses, Haw and Bakshi (2004) lead up to the concept of Ecological Cumulative Exergy Consumption (ECEC). Ulgiati et al. (2006) arrive at a Sustainability Multicriteria Multiscale Assessment (SUMMA), and Ulgiati et al. (2007) provide an even more comprehensive Emergy Life Cycle Assessment.

Comparisons between emergy analysis and other energy methodologies have emphasised the strengths and weakness of each method, as provided in detail by Brown and Herendeen (1996), Bakshi (2000) and Sciubba and Ulgiati (2005), among others.

21.4.3 Cross-Scale[11] and Complexity Accounting

The emergy per unit of product is usually named '*transformity*' when it refers to one unit of energy output (seJ/J), as defined in Chap. 1. Sometimes, it is also named *emergy intensity* (e.g. emergy per unit mass, emergy per unit time). Since its value depends on the metabolic pathway over different hierarchical levels, it is easily related to system complexity (numbers of connections at the same and/or different scales).

On the one hand, transformity is a cross-scale 'cost' evaluation since it includes all the energy and matter flows (renewable and non-renewable) that have converged over time and spatial scales to produce a component (steers, pasture, etc.). As a top-down cascade of material and energy flows from nature and society, it accounts for all input flows (from solar radiation to the information included in the technology) applied to generate the product (e.g. a steer). On the other hand, transformity is also a supply-side quality measure since the higher the transformity of a component the higher the number of transformations that it has faced over the production chain.

Thus, products that have different transformities could share the same hierarchical level (e.g. primary products such as pasture and maize) or they could occupy different hierarchical levels (e.g. primary products and consumers). In the first case, differences between transformities can point to differences in the emergy efficiency of processes used to produce a particular product, or differences between situations. In the second, situation differences are related to the position of the process or component within the system, i.e. its role within the system itself (Brown and Ulgiati 2005). In the latter case, the higher the emergy flow necessary to sustain a system or a process (complete cycle of grazing steers), the higher are the hierarchical level (one steer has more complexity than 1 ha of pasture), domain (one steer

[10] See Glossary.

[11] Across the scales of space and time.

needs more than 1 ha of pasture and other components to survive), turn-over time (higher life time), and contribution to the system that can be expected from it. Broadly, pasture contributes feed for animals, while animals contribute dung for nutrient cycling, seed dispersion, food, clothing, leather goods, cultural activities. Therefore, transformities could be either efficiency or hierarchical position indicators, aspects that are strongly related to the complexity of a system (Ulgiati and Brown 2009).

Since most farming systems are heavily stressed, by over-utilisation or exploitation of the resource base (e.g. soil), increasing pressure from the larger economic system over years (e.g. using more fertilisers or agrochemicals) is likely to change the relationships among components, provoking the farming system to re-adjust to a new pattern in order to recover. Examples of this include the emergence of species herbicide tolerance/resistance, or the appearance of pest species that used to be below the threshold for damage. Therefore, the efficiency of a given process as well as the hierarchical positions that current or new structures occupy in the system could increase, decrease or otherwise change in response to the new conditions or simplified structure of the system (Brown and Ulgiati 2005). Consequently, transformities referring to different periods or to alternative development stages of the same system could reflect the variations in the system performance and we can infer changes in its health. For instance, the emergy analysis of maize in USA during two different periods showed transformities of 0.5 E+05 seJ/J (Ulgiati and Brown 1998) and 0.9 E+05 seJ/J (Martin et al. 2006) – which implies an increase of intensification.

However, in order to have a complete picture of the performance of a certain activity or process we must not only account for the cross-scale contributions – for all the past and present renewable and non-renewable energies contributing to generate a product – it is also necessary to look at other relations among the different input sources (renewable, non-renewable, and purchased) listed in Table 21.3 and the yield. This is done by means of the different emergy-based indices (indicators) listed in Table 21.4. The next sections provide an explanation of how the different indicators can be interpreted.

21.4.3.1 The Importance of an Emergy National Analysis

At the beginning of this chapter, we established the importance of defining the system boundaries before performing an emergy analysis. However, systems in the biosphere are complex and open systems, and we cannot avoid the influence of the larger system in which the investigated process is embedded – for example the national system. Performing a national analysis provides a larger perspective, a frame and a foundation for analysing the smaller scales. If such an evaluation is done periodically, it allows tracing and visualising the trend of the natural capital of the country, as well as its economic development and performance. In our case study, we utilised the emergy evaluation of Argentina's economy from Ferreyra (2001).

Table 21.4 Description and definitions of indicators. For more details see Brown and Ulgiati 2004. Abbreviations are explained throughout this table

Acronym, name and formula of the indicator	Description of the indicator	Meaning
Total emergy (U) U = R+NR+F	The sum of all emergy inputs (independent of each other) that have contributed to the system. For example grain and stubble, are dependent on each other and should be counted once.	The total investment that nature and society have made in order to produce a product or service. R and NR are renewable and non-renewable resources respectively. F is imported flows of emergy
Emergy to money ratio (U/GDP) U/GDP	The total emergy of a country divided by its Gross Domestic Product. It is a characteristic value for each country's economy in a given year.	A measure of the donor value, which is the account of all energy contributions, delivered from nature and society to the national economy per unit of currency.
Transformity T = Emergy/available energy of a component or product	Emergy invested per unit product or flow.	An efficiency and/or a hierarchical position indicator. See previous explanation in this chapter
Emergy Yield Ratio (EYR), or Emergy Appropriation Ratio (EAR) (Raugei et al. 2005) EYR = (R + NR + F)/F or EYR = U/F	Relates local renewable (R) and non-renewable resources (NR) to imported flows (F). It is a measure of the ability of a process to exploit and make available local resources by investing outside resources (F) (Ulgiati et al. 2005).	A high EYR in human dominated systems could indicate a process relying on local resources. Low EYR (minimum possible value = 1) indicates a conversion process: outside resources are converted into a new product without much local emergy added.
Environmental Investment Ratio (EIR) EIR = F/(R + NR) or EIR = 1/(EYR-1)	Relates imported (F) to local flows of renewable (R) and non-renewable (NR) resources.	A low EIR, corresponding to a high EYR, could be attractive for external investors. Such investors obtain a good return in terms of local emergy resources from their outside resource investment.

(continued)

Table 21.4 (continued)

Acronym, name and formula of the indicator	Description of the indicator	Meaning
Environmental Loading Ratio (ELR) ELR = (NR + F)/R	Relates local non-renewable (NR) and imported (F) to renewable (R) flows. It reflects the direct and indirect load of the process on the local system.	A high ELR implies a high contribution from non-renewable resources (NR) and/or high investments from external non-renewable resources (F). In agricultural systems such as the one we are dealing with, (NR) is usually related to soil erosion or other degradation or excess ground water withdrawal. A high (F), in contrast , implies pressure on other systems far from the investigated area, in order to supply resources to the process. A high ELR indicates that the local process is likely to have a high indirect impact on far away areas.
Renewability (Ren) Ren = [R/(R + NR + F)]*100 or Ren = 1/(1 + ELR)	The percentage of renewable emergy used. This index provides a different way to express ELR. It gives us an idea of how much the system is supported by renewable resources.	Ren focuses on the contribution of local renewable resources, whereas ELR measures the contribution of non-renewable resources compared to local renewable resources.
Emergy Sustainability Index (ESI) ESI = EYR/ELR	Provides an aggregated measure of profitability (EYR) and environmental pressure (ELR). It can be very useful to monitor the global economic and environmental sustainability of a process over time.	Its value depends on many factors (relations and trade-offs among local resources exploited, imported resources, and renewability of resources used), and therefore it provides a complete picture of the system's performance[12].
Emergy Exchange Ratio (EER) EER = emergy in exported resources/emergy in imported resources (or in money paid for)	The ratio of the emergy exported with the product or service to the emergy of the money or the product received for it.	Product trade based on emergy calculation allows us to infer the equity of the transaction. Usually one part sends more emergy than it receives endangering its further competitiveness and environmental sustainability.

[12] See Brown and Ulgiati 2004 and Franzese et al. 2009, for use of this index.

Once the total annual emergy (U) that contributes to the economic functioning of a country is calculated, it is possible to relate its different flows and obtain different performance indicators. One of these indicators is the emergy to money ratio [U(seJ)/GDP($)] (Table 21.4). This ratio is the emergy that generates and supports each unit of currency of the local economy. It could be seen as the true environmental support to the money that circulates in the country's economy. Inputs such as seeds, machinery, and fertilisers have two aspects to be analysed. These aspects are the energy and/or material (J or g) flows and the economic flow ($). Seeds for example have their energy content (J) as well as a monetary cost ($); i.e. seeds have both a nature and a society value. The economic aspect of each input is related to the society labour and services that were necessary in order to produce and deliver it. Labour refers to the activities directly applied to the process while services refer to the activities indirectly applied to the process (Franzese et al. 2009). When all the system entries are converted to the same unit (solar emergy) using their corresponding emergy intensities (seJ/J,seJ/g or seJ/$), all the components of the system can finally be compared to each other and/or added, and therefore analysed.

Usually, the total annual Emergy to money ratio (U/GDP) is also an indicator of the development of the country. The higher the ratio the less 'developed' the country in conventional terms. This is the case of countries that utilise high 'free' contribution levels from the environment for their economy, such as food and wood from the forest, represented by a high Ren (renewability) (Tables 21.4 and 21.5). This wealth is mainly obtained from the environment. When a nation becomes more technologically developed and more people needs are met by economic growth supported by technology and information, much more money circulates; the country's GDP increases and the emergy to money ratio becomes smaller (Odum 1996).

Emergy from labour and services is usually an important fraction of the total emergy driving all local processes/sub-systems. In a maize sub-system where direct sowing and contracted harvesting are used, it represents 16% of the total U used in maize production (Table 21.3). Agricultural systems cannot function without the interactive contribution of goods and services from the environment and society. Goods, labour and services provided by society are as important as the emergy provided by nature in obtaining products such as the sown pasture or the steers. Most of the services offered by nature, for example soil binding with roots to control erosion or water purification by plant cover, are usually omitted in evaluations and therefore outside of the market circuit. Information is usually the silent layer that supports any 'know-how', experience, labour, development, activity, good or tool that is generated or utilised within the nature-socio-economic system. Information is the basis of labour and services applied to any product or process. Usually, it is considered that labour (human hours) and the local currency carry the weight or representativeness of information. As with environmental services, information is usually omitted or only partially accounted, because of the difficulties in obtaining data and defining it, especially when complex systems are involved (Tribus and McIrvine 1971).

Table 21.5 Common indices used to measure efficiencies, performance and fair trade of selected countries, systems and sub-systems, in Argentina, Brazil, U.S.A. and Mexico

	Indices										
System	Tr (E+5)	Rain %	Ren %	EYR	ELR	ESI	EIR	EER	U E+14 seJ/year	U E+23 seJ/year	U/GDP E+12 seJ/$
Argentina[a]			56.0	8.2	1.0	8.4	0.2			4.9	1.9
Sown Pasture[b]	0.15	38.0	38.0	2.2	1.6	1.3	0.8		18.9		
Natural Pasture[b]	0.16	85.3	85.3	80.7	0.2	468.0	0.0		8.4		
Maize[b]	0.18	29.7	29.7	1.9	2.4	0.8	1.0		24.2		
Forages[b]	0.60	34.2	34.2	2.6	1.9	1.3	0.6		21.0		
Calf[b]	11.7	57.4	68.3	6.6	0.5	14.2	0.2		12.5		
Steer complete cycle[b]	4.40	61.0	64.5	3.7	0.6	6.8	0.4	11.0	11.8		
Brazil[d]			69.7							27.8	4.8
Soya[c]	1.6		54.0	3.5	0.9	4.2	0.4				
Pig[e]	20.9	0.4	18.0	1.2	4.7	0.3	4.6	7.9	7,680		
Fish[e]	30.4	2.1	22.0	1.3	3.6	0.4	3.2	15.0	1,470		
Grains[e]	2.8	7.4	23.0	1.4	3.4	0.4	2.7	12.7	412		
Integrated syst[e]	9.5	9.3	24.0	1.4	3.1	0.5	2.3	6.8	325		
USA[f]			9.9							80.8	1.4
Maize[g]	0.9	5.0	5.0	1.1	18.8	0.1	13.9		130		
Blackberry[g]	2.3	10.4	31,0	1.5	2.2	0.7	2.2		86		
Mexico											
Indigeneous syst[g]	13.7	62.5	91.0	12.2	0.1	116.0	0.1		36		

N.B.: Natural pasture in Argentina and indigenous systems in Mexico, with small or no human intervention, show very high values of the percent Ren, which determines high values of EYR, low values of ELR, and finally high ESI values. The difference with the other cases is due to the strong nonlinearity of the formulae used for the calculation

[a] Ferreyra (2001)
[b] Rótolo et al. (2007a, b)
[c] Cavalett and Ortega (2006)
[d] Cohelo et al. (2003)
[e] Cavalett et al. (2006)
[f] Odum (1996, page 198)
[g] Martin et al. (2006)

The different emergy indicators should be calculated using (a) biophysical factors alone, as well as (b) with inclusion of labour and services. This allows evaluation of economic factors in the global performance.

21.4.4 Comparison of Performance of Selected Systems

In order to provide a comprehensive picture of the performance of the complete cycle of grazing cattle, Table 21.5 shows results of some selected systems which are described in Table 21.1. They will be discussed using the indicators defined in Table 21.4.

Although these systems are similar or related, it is necessary to emphasise that they were operated with different agricultural practices, climate and complexity and in diverse locations. Moreover, there are emergy analysis disparities among systems at national or farming level in (a) the way to account for labour and services and (b) the country or activity evaluation that is related to its total emergy (U) and its renewable emergy portion (Ren).

Directly or indirectly, all inputs carry fractions of renewable and non-renewable resources. Specifically, the fraction of renewable and non-renewable emergy carried by labour and services depends on the country where the process takes place. In Table 21.5 the renewable emergy percentages (Ren %) of labour and services are given as 56%, 70% and 10% respectively for Argentina, Brazil and USA. These proportions make a difference in the emergy performance of the economy of each nation. In the Argentinean study (Ferreyra 2001), labour and services were considered non-renewable, whereas in USA and Brazil the renewable and non-renewable fractions were each accounted for.

Concerning the values of total emergy (U), for example at the farming level in the Argentinean case study, 2.3 times more emergy, and much less renewable emergy, is used to produce sown pasture than to produce natural grass per unit of dry matter; therefore more imported resources were needed to produce sown pasture. At a national level, Argentina and Brazil use respectively 6% and 35% of the total emergy that is necessary for running the U.S. example (Table 21.5).

Values of Table 21.5 show the limitations of comparisons across enterprises, cultures, currencies, and contexts, even though there is a common unit of measure. However, they give a general idea.

Transformities are efficiency indicators for processes that provide the same product, and hierarchy indicators for components that occupy different metabolic levels. As an efficiency indicator, the lower the transformity of a certain product, the more efficient is the process that converts primary input to the final output. Transformities of primary production are the lowest among the different systems investigated in each country (Table 21.5). Higher transformities occur in secondary production. Animals' sub-systems need the feed or pastures to function; therefore they have a higher complexity and a higher transformity than just the grass or the feed.

It seems to be much more efficient to obtain a product such as fish, pig and calves or even steers from an integrated system than in separate processes (Table 21.5).

However, in Brazil transformities of the system's product as a whole, as well as of its individual outputs, are much higher than for Argentina systems, suggesting a lower efficiency in Brazil in spite of the better integration of production. This case clearly shows that emergy indicators must be considered within the production context in which the system develops. For example, if the emergy cost of labour and services is higher in a given country, this transfers to the system the huge load of the emergy needed to drive the wider economy and is very likely to affect the evaluation and performance indicators of each sub-system.

The Emergy Yield Ratio (EYR) and Emergy Investment Ratio (EIR) (Table 21.4) indicate the intensity of the exploitation of local resources by a process in which outside resources (F) are invested. A high EYR with a low EIR in a human-dominated system could indicate a process relying on local resources but also suggests the potential risk of long-term depletion of natural resources. In the short-term, it could provide competitiveness. The processes that seem to most exploit local resources are natural pasture in Argentina and soybean in Brazil, since they have the highest EYR and lowest EIR respectively (Table 21.5). Investors could be attracted by these enterprises since, with low investment, they could obtain good profits from resources already available. However, maintaining this situation could be risky since these enterprises could over-exploit the resources. The local resources will not be able to support the process for long without mechanisms of recycling or feeding back. Decision makers should prevent depletion of resources and the large costs of restoration. The sub-systems of maize in Argentina, pigs in Brazil and maize in USA show the lowest EYR with the highest EIR within each country. This means that they may be unattractive for investors in comparison with other enterprises within the same country. The integrated system in Brazil that merges grain, fish and pig production shows a lower EYR and a higher EIR than in the complete cycle of Argentina systems. One of the reasons can be ascribed to the much lower fraction of renewable emergy supporting such a system. The relatively low EIR of steers from the complete cycle in Argentina makes this enterprise attractive when choosing among agricultural alternatives. It implies that there is room for investment that could either improve the process linearly by just adding inputs to increase the output yield, or by stimulating interactions within the system. The latter option could lead to long-term sustainability. However, compared with the country-wide EIR (0.15), steers from the complete cycle of production are less attractive than other activities that are probably different from agriculture.

The Environmental Loading Ratio (ELR) and the percent of Renewability (Ren) indicators (Tables 21.4 and 21.5) reflect the environmental pressure on the local system. However, they do not necessarily indicate a local polluting effect of the process since emergy is a donor-side accounting method (Ulgiati et al. 2005) and also includes distant flows that may pollute outside of the system investigated. Systems without human investments are fully renewable, their percent Ren is 100% and their ELR is 0. In Table 21.5, the process carried out to obtain grass from natural pasture in Argentina and many different products from the indigenous polyculture system of Mexico seems to be the nearest process to environmental equilibrium. In contrast, maize production in USA seems to be the more fragile system since it develops with the highest ELR and lowest Ren. It is necessary to recall that this production is managed with irrigation unlike the others ones.

Environmental Sustainability Index (ESI) provides an aggregated measure of profitability (EYR) and environmental pressure (ELR). The higher the ESI the better. Moreover, it expresses two aspects of environmental sustainability: (a) the dependence on local resources (renewable or not); for instance, the high numerator (EYR) of the ESI value of natural pasture in Argentina is due to the lack of purchased input as well as to the use of very little labour to produce only one output, grass; and (b) the dependence on renewable resources. For example, the numerator (EYR) of the ESI value and Ren indices of 13 products obtained from the indigenous production in Mexico could be explained by the use of much more labour (work and knowledge) for producing the outputs.

When dealing with complex and dynamic systems, we face situations with different resources and input flows used for each development as well as with different stages of a system's life (Odum and Odum 2001). Therefore, emergy efficiency and performance indicators should be analysed with each one related to the others, as a whole set, for each case and for each step of a process.

For instance, the natural pasture sub-system shows the highest EYR and Ren as well as the lowest ELR and EIR. Options to add purchased inputs and integrated management, such as inter-sowing with higher quality forage species or a different strategy for grazing or mowing should be carefully evaluated and selected. Such choices would certainly increase F (purchased inputs), which will in turn cause a decrease in EYR and an increase in ELR. The total emergy utilised by this sub-system and, very likely, the amount of grass obtained would also increase, thus making possible a decrease of the transformity (more efficient system). A better performance will depend on many factors (rate of increase of F, rate of increase of the yield, but also rate of use of recycling mechanisms within the system, capable of affecting F).

Data from soybean production in Brazil suggest that the total amount of emergy to support one energy unit of output is mainly dependent on local renewable flows, since this system shows a relatively high %Ren and EYR, and a relatively low ELR and EIR. These data imply that further improvement is possible for increased yield without risk for the local environment.

In analysing data obtained from the complete cycle of grazing cattle, we considered all the sub-systems integrated and functioning together. Thus, it is a sustainable operation with a relatively high contribution from local renewable resources, a relatively low contribution from NR and F with a low ELR, showing it to be an attractive operation for investors. However, we cannot ignore the potential problems that, for instance, could arise in the pasture sub-systems in the medium time frame if we do not adopt any kind of management.

21.4.4.1 Emergy and Fair Trade

The corollary of any production is the sale of the product obtained – steers in this Case Study. Such a final step could be evaluated by means of the emergy exchange ratio (EER) (Tables 21.4 and 21.5), which is an indicator of equity and fair trade. It is the emergy embodied in the money received.

The value of EER for steers of 11 (Table 21.5) indicates that, for each unit of emergy embodied in the money received by the farmer, he is sending 11 times more emergy away from the farm in the product. Such emergy invested by the farmer for the steer, includes the emergy contributed by the society such as the purchased inputs, as well as by the environment such as soil, rain, and water needed for animals, earth or plants to provide fuel and the work of the plant to cycle water through evapo-transpiration. It also includes the emergy of erosion control contributed by the length of the pasture during 5 years as part of the whole system. This environmental emergy may or may not be re-cycled, but in any case it is usually neither accounted for nor given any value by traditional analysis. Such an imbalance of exported and imported flows represents unfair trade that makes the farming system and its region lose its natural capacity for supporting the same level of production in the long term. Therefore it is feasible to suggest policies that regulate agricultural production in order to help farmers select attractive and profitable enterprises that can be maintained together with the care and protection of efficient internal processes and positive feedback to the system. To stimulate an equitable requirement from local renewable resources and external inputs that allows the system to work at optimum efficiency, it is essential to design for optimum internal interaction and resource use, and not just focus on maximising production.

The data obtained by the EER add information for decision makers who are seeking to design programs and strategies for the long term, in order to make the trade more equitable. This is achieved by preserving the dynamic sustainability of the natural resources and thus ensuring the long-term wealth of the region and its inhabitants.

21.4.4.2 The Role of Rain in the Investigated Systems

Rainfall in east Pampas is, in general, high compared to that in many other regions. Conversion of rainfall into emergy terms can show the effect of rainfall in producing the final product. For instance, 60% of the emergy sent with the steers coming from the complete cycle in Argentina (EER = 11) is due to rain. Rain is affected by larger, global system changes, such as deforestation and global warming. Policies should be implemented at regional and national level in order to prevent a decrease in rainfall with a consequential decrease in livestock productivity.

A reduction in rainfall or increased variability as in drought or flood markedly affects agricultural production. In order to prevent these unpredictable situations and to contribute to sustainable development of the region, medium and long-term political decisions and plans are needed. They may be oriented to protecting forested and wetlands areas and to using agricultural management and technologies already available which are environmentally friendly.

21.5 Summary and Conclusions

Rainfed systems predominate in South America, a continent where there is a minimal number of irrigated hectares and 98% of the agriculture depends on rainfall. Moreover, relatively favourable rainfall patterns provide adequate moisture for normal crop and pasture growth in most years. As described in the section on systems that are dominant in four major ecoregions, there are bimodal rainfall patterns that allow for two crops per year that are usually different and adapted to each season, as well as potential for year-long pasture and forage growth when temperatures are favourable. There is a high degree of diversity among these regions, and productive systems are found from sea level to high in the Andes Mountains.

Applications of newer technologies and mechanised production methods prevail in the vast plains of Brazil and neighbouring countries, in the Argentine Pampas, and in the favourable and level areas of the intermountain valleys and coastal lowlands. Small farm systems predominate in much of the highland region of the Andes Mountains, and where land holdings are small throughout the continent.

The most striking change in recent years has been the expansion of commodity grain production in cleared areas of the Brazilian *Cerrado* or central savanna, where soybean and maize production under rainfed conditions have caused a substantial shift in the country's export earnings and provided competition to other grain-exporting nations. Although there is concern about the long-term sustainability of production systems in this region, their productivity is a large factor in providing food in this time of global grain shortage and rising food prices. The production of sugar cane for consumption, and especially its expansion for conversion to ethanol, is another major change in the region.

There is potential for long-term sustainability in most of the systems of these diverse regions as long as care is given to conserving the resource base through use of a form of conservation agriculture adapted to the environment. For example, the present change from long-term rotations of crops and pastures in the *Pampas* Region is converting a system that was highly sustainable with minimal outside inputs into one that is highly dependent on fossil fuels. A number of evaluation methods have been applied to this specific region aimed at influencing policy to promote sustainable practices and systems, if necessary by providing appropriate incentives.

Complex farming systems should be studied as a whole rather than as individual enterprises, in order to better understand their behaviour within the context where they evolve. The neoclassical economic model of short-term input/output analysis does not take into account the numerous and increasingly limited inputs from natural resources and society. For this reason, we have provided quantitative analysis that includes consideration of all inputs to the systems.

In this chapter, emergy analysis is described as it applies to the grazing livestock system in the *Pampas* Region of Argentina as well as to diverse systems in Brazil, USA, and Mexico. This has proven to be a useful form of analysis that puts all inputs and outputs from nature and from society into common units. The case of rain is especially important. Emergy of rain accounts for a large proportion of total emergy supporting South American ecosystems and qualifies as one of the most crucial resources to be saved by maintaining the integrity of the water cycle. At present, rainfall is not receiving much attention in South America due to its being an abundant and free resource. Emergy analysis allows calculation of a number of indices such as the Emergy Yield Ratio, the Environmental Load Ratio, the Emergy Sustainability Index, the Environmental Investment Ratio, and the Emergy Exchange Ratio, all of which are useful for providing guidance to the farm managers making production decisions based on planned, long-term viability of systems. It also assists policy makers to define the impacts of alternative strategies and provide support to keep agriculture profitable and sustainable for the long term.

Even though emergy analysis gives a useful perspective on systems by analysing them in terms of all energy memory and calculating all factors on the same basis, no single methodology captures by itself the whole performance of a complex system. By combining the emergy method with additional methods such as exergy, embodied energy, and life cycle analysis, and especially by combining methodologies at different scales, we can provide greater richness to the analysis to better embrace, understand, and quantify complexity. Approaches which deal with the complexity of whole systems are becoming more accepted by farmers, researchers, and national policy decision makers. Basic data for their application are increasingly available or can be easily estimated for most systems in South America. This type of analysis will provide guidance for the design and support of future agriculture and food systems in the region, and its application will become more widely used in the decades to come.

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Chapter 22
Important Rainfed Farming Systems of South Asia

Peter R. Hobbs and Mahmood Osmanzai

Abstract Rainfed farming in South Asia uses some 60% of agricultural land. Much of this land receives no irrigation but some receives a partial or life-saving water supplement. These rainfed lands have a wide array of climates, rainfall regimes and soil types, which determine their cropping systems. The major systems in Afghanistan, Bangladesh, India, Nepal and Pakistan are described. Various common features are discussed, including use of animals, fallowing, mixed cropping, rotations, legumes, manual labour, cow dung for cooking, water harvesting and need for off-farm income. These rainfed areas have benefited from the introduction of new crop varieties and modern technology, including farm mechanization, although to a lesser extent than in the irrigated areas. Crops and livestock are both crucial to these systems with the animals often providing draught power and fiscal security. The highly variable rainfall is an important source of risk to millions of the poorest people in South Asia. However, suitable policies and greater emphasis and funding for these rainfed areas could improve livelihoods and contribute substantially to the economies of South Asian countries.

Keywords South Asia • Afghanistan • Pakistan • India • Bangladesh • Nepal • Rainfed farming • Dryland agriculture • Farming systems

22.1 Introduction

Rainfed farming in South Asia encompasses a continuum of management options – from fully rainfed through varying degrees of supplemental irrigation to full irrigation. In rainfed agriculture, supplemental irrigation and even full irrigation during dry

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_22,

Table 22.1 Area (million hectares) and percent of cultivated land under rainfed agriculture in various South Asian countries

Country	Arable area	Rainfed area[a]	Percent rainfed
Afghanistan	7.9	5.5	70
Pakistan	21.4	3.6	19
India	161.7	104.5	66
Bangladesh	8.0	3.4	45
Nepal	3.2	2.1	65
Total	202.2	119.1	59

[a] Total rainfed area was estimated as the difference from the total arable land minus the irrigated land data; this included grazing lands but not forests (World Research Institute 2002)

seasons improve yields and returns to financial and labour investments. There are thus important rainfed elements in irrigation and irrigation elements in rainfed systems.

In this chapter, rainfed agriculture is defined as where rain falling directly on a given field is the predominant source of water for growing crops, trees or pasture on that field. Irrigated agriculture, on the other hand, relies on application of water from other sources. Supplemental irrigation for rainfed agriculture (to bridge dry spells and to minimise effects of droughts) is a strategy to upgrade rainfed farming with normal technologies of irrigation management. Rainfed agriculture is a common feature of South Asian countries as shown in Table 22.1.

The climate, soils and other factors vary within and between each country in South Asia to create different farming systems based on different major crops. The rainfed systems of the more temperate northern areas of India, Pakistan and Afghanistan rely on wheat-based cropping systems whereas those in the south of India and the eastern areas of South Asia rely on tropical cereals such as rice and maize in moister areas and on sorghum and millets in more arid climates.

This chapter describes the various farming systems prevalent in Afghanistan, Pakistan, India, Bangladesh and Nepal. It discusses the structure, relationships, operation and management of important types of systems. It deals with both scientific and technical features and also describes how particular systems are responding to technological, sociological, economic and environmental challenges. Some issues that are common across all systems are described first, with specific examples of these factors examined in the country sections.

22.2 Features of South Asian Systems

22.2.1 The Role of Animals

Animals are a critical asset for all rainfed farming systems in South Asia. Traditionally, they provided draft for tillage and for cartage of goods and agricultural inputs. This has changed over the past 20 years as more land is being tilled with tractor power. Tractors are often used for the first tillage operation, with animals used to complete the task and level the land. Farmers have shifted to tractor power for tillage since caring for and feeding a pair of bullocks throughout the year has become expensive in terms of inputs and labour. Tractors can do the tillage for less cost and faster resulting in better yields because of timelier planting. Many farmers in rainfed systems with small land holdings cannot afford to own a tractor and so use tractor contractors working at an hourly rate. With the rapid increase in rural roads, transport of goods and inputs has shifted from animal-powered transport to motor vehicles.

Although animals are being replaced as a source of power for land preparation, they are still an important component of the rainfed farming system. In many cases, rainfed farmers have shifted from draft animals to types that produce milk, meat and hides. These are a critical part of the system because they provide income and by-products such as manure used for cooking. Animals can also be considered as a bank to be sold when the farmer needs cash or bought when he has surplus cash or when the climate has been favourable for cropping.

Many farmers in the rainfed areas traditionally rely on crop residues and by-products to feed their animals. The main crop residues are straw or stover remaining after harvest or threshing but may include protein-rich cake left after oil extraction from crops such as mustard, cotton, sunflower or groundnuts. Traditionally, farmers release their animals on harvested rainfed lands to graze weeds and stubbles although some cut and feed waste-land weeds and a few grow a specific fodder crop. Specialised fodder production has increased with the move towards more profitable stall-fed milking cows; this reduces animals roaming the village for grazing and protects the more intense cropping land.

22.2.2 Use of Fallowing

Fallowing is traditional in most rainfed cropping areas where rainfall is insufficient to sustain cropping every year. It is used in Afghanistan, Pakistan, N.W. India and parts of southern India but not in the higher rainfall areas of eastern India, Nepal and Bangladesh.

Fallowing is used to ensure sufficient moisture in the soil profile before sowing a crop; it also gives the soil a chance to mineralise needed nutrients. The land is usually left in fallow for 1 year, with animals allowed to graze the weeds and crop residues, and then cropped in the second year. Weeds that are not reduced by grazing are controlled by shallow tillage sometimes after rain and just after the crop harvest.

22.2.3 Use of Inter-Cropping, Mixed Cropping, and Relay Cropping

Use of crop mixtures in rainfed systems is common in South Asia.

22.2.3.1 Mixed Cropping

In this chapter, mixed cropping is defined as a crop-mixture system in which all the crops are broadcast together at the same time with no row arrangement. This is common in the wheat-based systems in Pakistan where mustard (*Brassica* sp.), chickpea (*Cicer arietinum*), lentil (*Lens esculentum*) and flax (*Linum usitatissimum*) may be grown together. Similar mixtures are also common in Bangladesh and eastern India in the rice–wheat zones where the various crops are mixed with wheat.

22.2.3.2 Intercropping

Intercropping is defined as mixed systems where the different crops are arranged in definite rows. This is more common in southern India where crops such as maize (*Zea mays*), cotton (*Gossypium* spp.), sorghum (*Sorghum bicolor*), and millet (*Pennisetum typhoides*) are planted in rows. Common crops mixed with these row crops include pigeonpea (*Cajanus cajan*), groundnut (*Arachis hypogea*) and even mixtures of the above cereals. In some of these systems, the cereal crop is harvested first and the second crop, such as pigeonpea, is left to extract any residual soil moisture before being harvested later.

22.2.3.3 Relay Cropping

Relay cropping is where the major crop is grown first and a second crop is planted before the first is harvested. This is common in the wetter, deepwater rice areas of Bangladesh and eastern India where several winter legumes such as grasspea (*Lathyrus sativus*) and lentil are broadcast before the rice is harvested.

Farmers have learned that these mixed systems help spread risk. In years with good rainfall both crops grow well whereas, in poor years, the second crop provides some compensation.

A term often used in mixed or intercropping systems to compare the mixed- or inter-crop with a pure crop is Land Equivalent Ratio (LER). This is defined as:

> "The ratio of the area needed under sole cropping to the area under inter- or mixed-cropping to give equal amounts of yield at the same management level" (Norman et al. 1995, p. 93).

It can also be calculated using the yields of each crop adjusted for the same area. For example, if a pure stand of maize gives 4 t/ha and a pure stand of beans 2 t/ha but in a mixed stand the maize gives 3 t/ha and beans 1 t/ha, the LER would be 125. Thus the mixture gives the farmer 25% more total yield than the pure stands. LER is based on yield and not value.

Land equivalent ratios are often higher than 100%; possible reasons include fewer disease or insect problems with mixed species, different rooting patterns extracting water and nutrients from different layers of the soil, more efficient light interception and inclusion of legumes, which add symbiotically fixed N.

Such traditional systems are suitable only for hand harvesting as machine harvesting cannot be used, and so they are disappearing in irrigated areas. Planting crops with seed drills instead of traditional broadcasting also reduces the opportunity for adopting these mixed systems; however, some farmers drill the main crop, say wheat, and then plant a crop such as mustard every 1–2 m by hand as an intercrop.

22.2.4 Use of Labour in Farm Operations

Labour is still a major component of all farm operations in rainfed systems in South Asia, although the introduction of tractors and powered threshers in the 1960s and 1970s has reduced the labour needed for tillage and threshing. Combined harvester-threshers have been introduced in India and Pakistan since the 1990s but mostly in irrigated areas.

All other farm operations in rainfed areas use manual labour – family and/or hired. Many farms are subsistence in nature, providing food, work and income. The important labour activities conducted by rainfed farmers include sowing (broadcasting), weeding (once or twice depending on weed problem), nitrogen fertiliser topdressing, harvesting, transportation of bundles to the threshing floor, threshing by hand, animals or stick (if thresher not available), cleaning and storage. In the last 10–15 years, service contractors have been available to plough, weed, harvest and thresh. Service providers may own equipment (tractors, threshers, combines) or consist of a group of hired labour. Payment would be in cash on an hourly rate for equipment hire and in cash and/or kind for transplanting, weeding or harvest.

Migration of labour from the rural villages to towns and cities has driven up labour rates and has resulted in more farmers considering hiring or buying machinery for ploughing, harvest, weed control (herbicides) and threshing. Many young males prefer to work in cities than obtain the small income from the drudgery of agriculture.

Farmers in the irrigated rice-wheat areas of South Asia have adopted no-tillage establishment of wheat after rice, with benefits in yield, incomes and savings in fuel and in wear and tear of equipment. Use of zero-tillage and permanent soil cover with plant residues will improve water harvesting, reduce costs, increase organic matter, and increase productivity in rainfed lands (Hobbs et al. 2006).

22.2.5 Use of Dung for Cooking and Possibilities for Other Sources of Fuel

Although animal numbers have remained constant in rainfed areas, the amount of manure returned to the field to provide much needed nutrients has remained low – most dung is burned to cook food. Deforestation of rainfed ecosystems has been dramatic over the past 40 years under high population growth, and firewood supplies have dwindled from this potentially renewable resource. Farm families are reluctant to purchase expensive fossil fuels such as kerosene or bottled gas for cooking since animal manure is free. Initiatives to harness renewable energy through solar power, methane digesters or forestry would help promote the use of animal manure to improve soil fertility. Similarly, introduction of improved fodders would allow crop residues after harvest to be returned to the soil as organic matter rather than be burnt or used to feed animals. The physical and biological health and the productivity of the soil have been deteriorating in many rainfed situations because little organic matter is being returned.

22.2.6 Crop Rotations

Crop rotations are not common in rainfed areas, mainly because farmers need to produce enough food of the local staple; for example, wheat is the major crop in rainfed areas in Pakistan and there are few substitutes. In mixed cropping systems, there is no scope for rotations as most of the crops that the farmers need are grown in the mixture. As crop diversity is introduced to improve incomes, crop rotations should help with management of diseases, pests and nutrients. Introduction of better-quality fodders to replace less nutritious crop residues and more cash crops such as vegetables, oilseeds and potatoes would improve the scope for rotation.

22.2.7 Use of Legumes

Legumes are integral to cropping in rainfed systems in South Asia but contribute little to soil fertility. With grain legumes such as pigeonpea, chickpea, mungbean, groundnut and soybean (*Glycine max*), most of the fixed nitrogen is removed in the grain. The little protein left in the crop residue is removed by animals whose dung is burned for fuel. Plant roots left in the soil are the only source of nitrogen for a subsequent crop and since grain and residues are removed the overall nitrogen balance is negative. Green manure legume cover crops have not been much used so far to improve soil fertility; farmers are only now experimenting with fodder legumes to feed their new improved cattle.

22.2.8 Water Harvesting

Efficient utilisation of rainfall water is critical in rainfed agriculture, and has resulted in the traditional systems. In these, the land is kept fallow for a year (even longer in more arid areas) to accumulate soil moisture and replenish available soil

Table 22.2 Effect of tillage treatments (mouldboard plough or cultivator) on the grain yield of wheat in barani areas of Punjab (Hobbs et al. 1986)

		Grain yield t/ha		Yield increase over cultivator	
Year	No. of experiments	Mouldboard	Cultivator	t/ha	%
1982–1983	1	4.3 a[a]	3.7 b	0.6	16
1983–1984	3	3.8 a	2.5 b	1.3	52
1984–1985	16	2.9 a	2.1 b	0.8	36
1985–1986	35	5.1 a	4.1 b	1.0	24
1986–1987	12	4.1 a	3.6 b	0.5	15
Average		4.33 a	3.46 b	0.87	25

[a] Means within a row followed by a different letter are significantly different at $P \leq 0.05$

nutrients through mineralisation. The fields are kept relatively free of weeds with an occasional tillage to reduce water loss through transpiration. However, excessive tillage and poor ground cover can result in wind and water erosion.

Plough pans that have developed at 20–25 cm after centuries of shallow tillage can restrict water infiltration. Deep tillage with a mouldboard plough can significantly increase yields (see Table 22.2) (Hobbs et al. 1986; Khan et al. 1986) on various types of soil. Straw yields were also increased with deep tillage, representing a significant economic gain from this source of fodder.

Important effects of deep tillage with a mouldboard plough include:

- Breaking compacted layers that restrict root growth at 10 cm, resulting in more profuse rooting throughout the first 30 cm of soil and increasing available nutrients and water.
- Improving water infiltration, resulting in higher soil moisture levels at depths beyond 30 cm.
- Burying weeds, thus reducing weed growth in both winter and summer.
- Burying fungal pathogens, which can significantly reduce common (dryland) foot rot (Wiese 1977) caused by *Fusarium* spp. and *Helminthosporium* spp. (common problems in *barani* wheat).

As a result of a good farmer participatory extension program and the availability of suitably priced mouldboard ploughs, deep tilling became a common practice in *barani* areas, and is now considered to be the conventional practice in these rainfed areas. However, its potentially adverse impact on soil erosion through wind or water is not understood.

Recently, zero-tillage or no-till, with residue retention for permanent soil cover (referred to by FAO as 'conservation agriculture') has been promoted to increase water infiltration and yields without causing soil erosion. This lower cost system has become popular in the rice-wheat growing areas of NW India and Pakistan (Hobbs and Gupta 2003).

Conservation agriculture has been successful in rainfed systems in Brazil, Argentina, Paraguay and other parts of the world (Derpsch 2005) and should be promoted in rainfed areas in South Asia. An important issue for extension will be to convince farmers to minimally disturb soil and leave crop residues on the surface.

22.2.9 Importance of Off-Farm Income

Agriculture in South Asia is suffering from increasing input costs (for agro-chemicals and fuel) but slow growth in output prices. Food prices for city dwellers have remained low while profits in agriculture have declined in both rainfed and irrigated systems. Farmers and their families have to look to off-farm income to survive, and remittances from family members with jobs within or outside their countries play a vital role in keeping farm families viable financially. Many younger members of the farming family migrate to cities in search of better paying jobs and living conditions, putting an economic strain on urban areas. It also creates labour shortages in rural areas, increasing the work load by the remaining womenfolk. Off-farm employment is often the only way to get rainfed farming families out of poverty and to improve their livelihoods.

22.2.10 Use of New Crop Varieties and Modern Technology

Low rainfall, compounded by high year-to-year variability makes it difficult for farmers to invest in modern technology in rainfed areas. The 'Green Revolution' of the 1960s gave farmers the option of adopting the new varieties of crops that had stiffer straw and responded better to added nutrients. Farmers in irrigated areas of South Asia quickly adopted improved wheat and rice varieties but adoption has been slower in rainfed areas, and pockets of farmers in the drier areas continue with traditional varieties. These had tall straw and long-duration, photoperiod-sensitive responses, but their high quality is preferred for making *chapatti* (flat bread).

In the wetter rainfed areas, the use of new varieties increased rapidly in the mid-1970s, to include 100% of farmers within a decade. Along with higher yield, these new varieties were more resistant to leaf and stripe rust; they were also faster maturing, allowing more time for double cropping.

Improved varieties of maize, sorghum, pearl millet, pigeonpea, groundnuts, soybean, chickpea, mungbean, lentil, mustard and cotton are being adopted by rainfed farmers because of better yield and resistance to pests and diseases, although many traditional varieties are still grown. The insect resistance of transgenic cotton has led to a rapid increase in this modern cotton variety in recent years, on both irrigated and rainfed lands in India. Farmers have been willing to pay more for seed of these transgenic varieties because they save on the application of pesticides that were often ineffective against bollworm.

Chemical fertiliser use has followed the adoption of responsive new varieties; it is higher in the wetter areas where the risk of poor rainfall is lower. Herbicides and fungicides are rarely used in rainfed areas although pesticides are used when needed. Mechanisation has increased in dryland areas although animal power is still used in more arid regions.

The next section describes the rainfed systems found in a number of countries in South Asia.

22.3 Afghanistan

Afghanistan is a land-locked country lying between 29°and 38° N and 60° and 75° E. Over most of the country, winters are cold and summers hot; the climate is arid and semi-arid, with annual rainfall ranging from 100 to 400 mm, mostly falling in the winter months of October to April. Accumulated winter snow from the high mountains sustains agriculture in the summer, with farmers using ingenious methods to lead water from springs to cropping land. The country has six distinct climatic regions with most of the arable land falling under temperate ecologies, and a few lowland areas subtropical. Most of the area is grassland steppe.

Wheat and barley are the main rainfed crops. They are planted with the onset of rain, which starts in October–November although it may be delayed until March or not occur at all. Depending on rainfall, farmers may fallow for 1–2 years to refill the soil profile with water before planting. Winter wheat varieties are planted in October-November and spring varieties in the spring. Some farmers practice mixed cropping with legumes (chickpea and lentil) and/or oilseeds (B*rassica* sp.) and mixtures with the herb cumin (*Cuminum cyminum*). As fertilisers are not used, cereal yields are very low, averaging 1 tonne/ha in the good years but with total crop failure in dry years. Table 22.3 shows yield data for 2005, a relatively good rainfall year.

Before 2003, the area of rainfed wheat was equivalent to about one-third of irrigated area, but it has since increased dramatically as grazing land has been ploughed for crop production. Animal husbandry is a significant component of agriculture with 80% of rural households raising livestock. For the nomadic *kuchis* people, animals and animal products are their main source of income. Sheep wool is the basic input of the carpet industry and *karakul* pelts (from new-born lambs of a local sheep breed) are an important export.

Animals are an important component of rainfed farming since nearly all the land is cultivated by bullock-drawn ploughs. Many years of war have meant that tractors

Table 22.3 Wheat area and production in Afghanistan in 2005

Wheat crop	Area ('000 ha)	Yield (t/ha)	Production ('000 tonnes)
Irrigated	1,094	2.47	2,704
Rainfed	1,255	1.24	1,561

Source: Food, Agriculture and Animal Husbandry Ministry, Kabul, Afghanistan are in short supply and farmers have to use bullocks, horses and even camels for ploughing. Cereal crop residues are the main sources of food for cows and bullocks with some farmers carrying the straw from the fields for feeding their domestic animals. There are some buffalo, and recent programs encourage more milk production from dairy cows, but cattle farms as such do not exist. Small ruminants (goats and sheep), including large flocks of *karakul* sheep, graze the rainfed wheat fields over the winter and grasslands in the summer. Horses used for transporting people and goods are fed barley grain, while some camels are used for hauling wheat straw or cotton bales to the gin. Degradation of land is a serious problem since little organic matter is returned to the soil.

Farmers in Afghanistan have some ingenious ways of harvesting rainwater for crop production. The most famous are the intricate '*karez*' systems, where winter snow melt is tapped by underground tunnels and led to 'oases' where crops are grown; this is essentially an irrigated system. Another system harvests rainwater by leading it through ditches to lower and bunded areas. This provides water to fill the soil profile, as well as plant nutrients carried in the water. Farmers plant melons, sesame, and wheat and sometimes cotton on this residual water. This system is called '*selab'* in Afghanistan; there is a similar system in neighbouring Pakistan.

Opium poppy (*Papaver somniferum*) is a major cash crop for Afghan farmers and is mainly grown under irrigation either in the fall months in the valleys or in the spring in the high lands. Small patches of rainfed poppy are found in good rain years. There are many programs designed to find alternatives to this crop, but so far none match the economic returns for poppy.

Many years of war in Afghanistan have left agriculture in a poor state; hopefully, a return to peace will introduce improvement and restore food security. Currently, there is little improvement in rainfed agriculture from the traditional system. Yet there is ample scope for improving water harvesting through better management of soils, by returning more organic matter, and improved watershed management. In order to return more organic matter (crop residues and manure), alternative renewable energy sources, such as solar power and agroforestry products, as well as improved fodder production will be needed to provide farmers with an alternative energy source for cooking and alternative feed for their animals. Afghanistan needs help in all aspects of agriculture, both rainfed and irrigated, from research, education and extension, to provide correct and relevant information.

22.4 Pakistan

22.4.1 Dryland Plateau

Twenty percent of arable land in Pakistan is rainfed (Table 22.1). Rainfed cropping systems are determined solely by rainfall, which ranges from 300 to more than 1,000 mm per year (Fig. 22.1). Two-thirds of the rain falls in the summer monsoon,

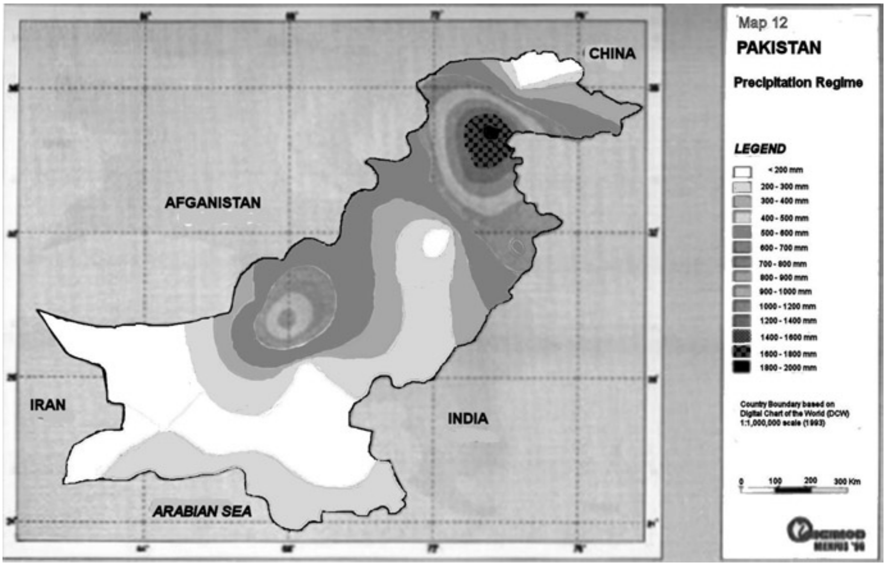

Fig. 22.1 Mean annual rainfall in Pakistan (ICIMOD, 1993)

the rest is variable during the dry winter season. Rainfall increases in a northward direction being higher in the Himalayan foothill regions. The goal of farmers is to harvest rain efficiently when it does fall. Under the lower rainfall regimes in the southern plains, crop production gives way to livestock grazing on rangeland. One traditional technology found in some areas of Baluchistan and NWFP provinces is the practice called '*Sailaba*', which (as *selab*) has been described for Afghanistan. This system harvests rainwater through channels into bunded fields. The soil profile is filled with water after a rain event, allowing farmers to grow wheat, melons and other crops on this residual water.

This section describes some of the key features of rainfed agriculture, and is based on a survey in 1985 of farmers in districts with varying rainfall in the rainfed plains – the '*barani*' lands – of the Pothwar Plateau region of Punjab (Byerlee and Husain 1992). The main crop in the *barani* land is wheat, while livestock are an integral part of the farming system and become increasingly important in the drier areas.

22.4.1.1 Rainfall Zones

The agricultural enterprises of the *barani* areas of the Pothwar Plateau are diverse and based on land type, soil type, rainfall and socio-economic factors. The Plateau can be divided into three rainfall zones: above 750, 500–750, and below 500 mm. Cropping intensity can be low and variable from year to year in drier areas. Fallowing is a common practice in dry areas, where land may be left for a year or more to fill the soil profile with water before wheat is planted in October–November. This bare fallow results in wind and water erosion.

22.4.1.2 Farm Size and Land Types

Farm size averages about 4 ha, with larger farms found in the drier areas. Owner operators are common – as are tenant farmers who give a share of the crop as rent. Tenant and owner may share costs of inputs although, in drier areas, the tenant often pays all. Many farmers own bullocks, but land may be prepared with animals and now more frequently tractors, especially in wetter areas.

Land types can be distinguished as *lepara* land and *mera* land. *Lepara* land is near the homestead and receives regular additions of farmyard manure, household waste and compost; the more distant *mera* land receives no regular organic amendments.

The average farm had 27% *lepara* land but this varied by rainfall zone (Table 22.4). Byerlee et al. (1992) showed that 95% of the fields on *lepara* land received organic manure at least once a year but only 22% on *mera* land. The quantity of manure available depends on the number of animals in the household and on how much is used as fuel for cooking.

22.4.1.3 Crops Grown and Cropping Patterns

Wheat is the major crop on both land types, along with maize, sorghum/millets (often grown mixed for fodder), pulses, mustard and groundnuts. Flax is often mixed with wheat, mustard and lentil in mixed cropping stands, and is used for oil and fibre. Mustard and maize are grown more in higher rain areas, with sorghum/millets, groundnut, gram and lentil pulses in drier locations. Maize is mostly grown on *lepara* land and sorghum/millets and groundnuts on *mera* land. The crops serve as staple food and fodder. The residues from wheat and other cereals are collected and stored as the major animal feed. Mustard is often grown mixed with wheat and is thinned when green and fed to animals. Maize and sorghum/millet mixtures are grown as dual-purpose crops, for fodder first and for grain if any is left at harvest. Some summer pulses such as black gram (*Vigna mungo*) and green gram (*Vigna radiata*) are grown mixed with

Table 22.4 Lepara land as a percentage of farm area, by farm size and rainfall zone, Punjab (Byerlee et al. 1992)

Annual rainfall	Farm size		
Zone	<5 ha	>5 ha	All
Low (<500 mm)	32.6	11.9	23.6 b
Medium (500–750 mm)	26.6	18.0	25.0 b
High (>750 mm)	32.6	26.0	31.4 a
All	30.4 a[a]	16.6 b	26.8

[a] Means within a row or within a column followed by a different letter are significantly different at $P \leq 0.05$

Table 22.5 Distribution of major cropping patterns by rainfall zone and land type, barani areas of Punjab (Byerlee et al. 1992)

Year 1		Year 2		Rainfall zone			
Winter	Summer	Winter	Summer	Low	Medium	High	All
Lepara land				% fields in zone			
Crop	Crop	Crop	Crop	53	79	95	72
Crop	Crop	Fallow	Fallow	17	10	0	10
Crop	Fallow	Crop	Fallow	14	6	5	9
Mera land							
Crop	Crop	Crop	Crop	10	11	10	11
Crop	Crop	Fallow	Fallow	50	50	76	55
Crop	Fallow	Crop	Fallow	29	27	10	25

Minor patterns make up the difference from 100

Table 22.6 Reasons for leaving land fallow, barani areas of Punjab (Byerlee et al. 1992)

	Rainfall zones (% farmers in zone)			
Reason for fallowing	Low	Medium	High	All
Moisture conservation	34	29	15	26
Fertility restoration	50	46	21	38
Own livestock grazing	2	5	17	8
Communal livestock grazing	9	10	23	14
Lack of resources	5	10	25	15

the summer fodder crops. Overall, 23% of the land is devoted to fodder production, indicating the importance of animals in the rainfed farming system.

Table 22.5 shows a typical cropping calendar for *barani* areas by land type and rainfall. Wheat harvest is usually completed by May, leaving time to prepare land for the summer monsoon crop. The second crop used to interfere with wheat planting in October before the introduction of new quicker maturing and higher yielding varieties. Fallows are more common in the drier areas, whereas farmers can double crop every year in wetter areas. The farmers' main reasons for fallowing are for moisture conservation and plant nutrient restoration (Table 22.6), but the grazing needs of animals, both own and community (migrating tribal people), can be important. In many villages, half the land is planted to crops in a given year and then fallowed the next year. The villagers and migrating tribal people know which side of the village is fallow and hence available for communal grazing.

22.4.1.4 Cropping Intensity

Factors influencing cropping intensity, yields and fallowing include:

- Rainfall – higher cropping intensities with higher rainfall
- Land type – higher fertility and soil moisture on *lepara* land means higher cropping intensity

- Farm size – higher cropping intensities on smaller farms
- Power constraints – tractor owners can plough faster than animal-powered farmers and so can increase cropping intensity. Fast land preparation after the rains start is critical.
- Livestock ownership – the more animals a farm has the more fallow land is left for grazing. This includes the residues left after harvest of wheat or the summer fodder crop and some weeds that grow during fallowing.

In the survey, double cropping was more common in high than low rainfall zones, with cropping intensities rising to 129% from 108% in dry areas (Table 22.7).

On *lepara* land, 71% of the land was double cropped, with wheat yields higher and less variable. Yields did not differ between rainfall zones in 1985, a reasonably wet year but they would be expected to be lower in the drier zones. Only 20% of *mera* land was double cropped. The medium rainfall zone recorded the highest yields, reflecting the better soils and higher fertility in this sampled zone.

Cropping intensity in rainfed areas varies from year to year. In a wet year, farmers increase their cropped area to exploit the extra moisture; in dry years, they reduce it.

22.4.1.5 Mixed and Intercropping Systems

Intercropping or mixed cropping are common traditional systems in the *barani* areas. In the 1985 survey, wheat was mixed with mustard in 60% of the fields in the medium rainfall zone (Hobbs et al. 1986) (Table 22.8). Those that did not mix-crop had no animals to feed. More than 90% of the mustard was removed for fodder in January and February, with the rest left for oil seed. In drier areas, there is less

Table 22.7 Average wheat yields (t/ha) by rainfall zone and land type in 1985 in barani areas of Pakistan's Punjab (Number of samples in brackets) (Hobbs et al. 1989)

Rainfall zone	Lepara	Mera	All
High	1.64 (63)	1.31 (69)	1.47 (132) a[a]
Medium	2.04 (63)	1.57 (127)	1.73 (190) a
Low	1.79 (34)	1.37 (120)	1.47 (154) a
All	1.83 (160) a	1.44 (316) b	1.57 (476)

[a] Means within a row or within a column followed by a different letter are significantly different at $P \leq 0.05$

Table 22.8 Percent farmers using mixed or intercropping of mustard and wheat (Hobbs et al. 1986)

Rainfall zone	No mixtures	Mixed cropping	Intercrop in rows
	Percent of farmers		
Medium	35	61	5
Low	44	23	33

mixed cropping and more intercropping with farmers tending to plant a row of mustard in the wheat crop every 1–2 m. This reduces the competition with wheat and still gives a fodder harvest. Mixed cropping gives higher land equivalent ratios and net returns than sole cropping (Hobbs et al. 1985) with less wheat variation from year to year in intercropped fields. In wet years, mustard grows well, competing more with wheat; in drier years, mustard is sparser and has less effect on the wheat. Fodder yields, on the other hand are variable and depend on the rainfall, especially at planting, in any given year.

The method of planting is related to mixed cropping. In wetter areas, farmers broadcast the wheat and mustard seed together (100 kg/ha wheat + 2 kg/ha mustard), bury the seeds with another ploughing and follow this by planking (levelling and compacting with a heavy wooden plank). In drier areas, farmers have to use a traditional *pora* system (with animal power) where the drier surface soil is furrowed and the wheat seed placed into the wetter subsoil for better germination. The mustard is then planted using the same seed drill in furrows spaced a metre or more apart.

22.4.1.6 Livestock

Livestock are a vital component of the *barani* farming systems. The most common animals owned are buffaloes, milk and draught cows, sheep and goats. Larger farmers own more animals, but smaller farmers own more animals per unit of land. In terms of animal unit equivalents (calculated by weighting buffaloes by 1.5, cows and draught animals by 1.0, young stock by 0.5 and sheep and goats 0.25), total farm animals varied from 4.0 in wet areas to 8.3 in dry zones. Animal numbers per unit of land on small farms were over twice those on big farms, with 2.1 animals per hectare on farms smaller than 5 ha versus 0.9 on farms larger than 5 ha. The weighted number of animals reflected the proportion of *lepara* land, small farmers having more of this better land type. This was particularly true for the number of buffaloes, which are raised mainly for milk and stall-fed, and hence provide a reliable source of farmyard manure (FYM). As fodder is less reliable in dry areas, these farmers have fewer buffaloes and more draught animals, sheep and goats. Table 22.9 shows the composition of livestock herds as percent of animal units (expressed in cow equivalents) by rainfall zone.

Table 22.9 Percentage composition of livestock population in barani areas of Pakistan's Punjab (Byerlee et al. 1992)

	Animal population (as cow equivalents) composition (%)		
Animal type	Low rainfall	Medium rainfall	High rainfall
Buffaloes	21	21	36
Cows	43	44	41
Draught animals	23	23	16
Sheep and goats	13	12	8

Table 22.10 Percent farmers ranking a given cash income source as most important (Byerlee and Iqbal 1987)

	Rainfall zone			Farm size		
Most important source of cash income	Low	Medium	High	<5 ha	>5 ha	All
Sale of livestock products	42	21	14	18	39	25
Sale of food crops	26	15	4	6	17	8
Sale of cash crops	11	13	14	17	28	19
Off-farm work	20	44	66	55	17	44
Remittances	2	8	2	4	3	4

The greater proportion of buffaloes in the wetter zone also reflects the proximity of these farms to the urban areas and markets for milk products. In wetter zones, although most farmers use tractors for land preparation, they did not reduce animal numbers but instead bought more milk animals to generate cash income. This ensured continuing FYM output so essential for maintaining *lepara* land productivity and for cooking food. More farmers with larger land holdings tended to own buffaloes – 70% compared to 46% of smaller farmers. Farmers that owned more rangeland had more sheep and goats.

Animals are an important safety net for farmers and can be compared to a bank. In good years, farmers buy more animals; in poor years, they sell them for cash. Sales of young livestock and livestock products such as milk are a major source of farm income (Table 22.10). Average milk yields for buffaloes (8.7 L/day) and cows (3.3 L/day) are higher in wet areas than dry areas. For all zones, milk yields of cows are only 38% of the yields of buffaloes.

22.4.1.7 Fodder Systems

Fodder production is important for *barani* farmers who allocate an average of 25% of their land to it. This fodder is usually a crop of maize or sorghum/millet grown after the wheat is harvested in April. It uses the rain of the monsoon period from mid-June to mid-September. Farmers do not set aside land specifically for fodder legume crops, although some farmers in wetter areas will grow barley or oats for fresh fodder instead of wheat for grain. Crop by-products, especially wheat straw and maize stover, are also major sources of fodder supply. A market survey in 1987 showed that prices of dry fodder are higher in *barani* areas than in irrigated areas and the wheat straw may be more valuable than the grain (Byerlee and Iqbal 1987). Fresh fodder can be in the form of mustard, maize and sorghum/millets (often mixed with legumes such as black and green gram). Most farmers purchase animal feed concentrates; mainly oil seed cakes, to supplement home-produced green and dry fodders, especially for their milk animals. The effects of feeding good-quality fodder crops instead of poor-quality wheat straw needs to be assessed for the different rainfall zones; it would improve animal nutrition and also allow more residues to be applied to the soil.

22.4.1.8 Other Major Sources of Income

Other major sources of income for *barani* farmers include sale of food, cash crops (mainly vegetables and fruits), off-farm work (mainly in the towns) and remittances. The latter is a very important source of cash for buying land, tractors, implements (such as threshers and seed drills) and inputs (seed and fertiliser). Many *barani* households have family members in the army or working overseas who remit funds to support the family.

22.4.1.9 Changes Over the Last Two Decades

Mechanisation: There has been a major increase in mechanisation in rainfed areas of Pakistan in the last 20 years. Even small farmers hire tractors as it is expensive in time and money to maintain a pair of bullocks just for land preparation. Very few farmers now use animal power for transport. This power shift has not resulted in a decline in animal numbers, especially in wetter areas, since farmers have substituted milk and animal products as cash crops in place of draught animals. This means there is also enough FYM to maintain the productivity of the *lepara* land and supply household needs for the important energy consumed in cooking. *Barani* farmers estimated that they used 25% of their FYM for cooking in the 1980s but this will increase as fuel wood declines under population pressure. However, more farm households are using gas (bottled propane, and in some cases, farm-produced biogas) for cooking.

Other forms of mechanisation include threshers for wheat and seed drills (Hobbs et al. 1992). Threshers started to became popular in the mid-1970s with the introduction of new wheat varieties. Today, most wheat is threshed by portable threshers powered by tractors on a self-owned or rental basis. Combined harvester-threshers are also becoming popular in the *barani* areas on a rental basis. They make it more difficult to handle and store the wheat straw, resulting in a demand for straw bailers. Some farmers prefer using threshers because fine chopping makes the stiffer straw of modern varieties more palatable.

Deeper tillage: Deeper tillage with a mouldboard plough has significantly increased yields (Hobbs et al. 1986; Khan et al. 1986), but the effect on soil erosion needs to be assessed. Conservation agriculture (zero-tillage plus permanent ground cover) may be a better way to achieve the same goal.

Population: Population increase in Pakistan (more than 2% per annum) has led to more pressure on land and farming. The *barani* areas are more densely populated today, and urbanisation near the cities has reduced agricultural land significantly. Farmers have responded through higher cropping intensity and decreasing the area of fallow land. This interacts with the livestock activities and probably accounts for the increase in the number of stall-fed animals. Land on half of the village that used to be kept fallow and for grazing has been reduced, and migrating tribal herds now need to be more careful moving through the villages to prevent damage to land that is now cropped. Cash cropping, including production of green fodder crops, has seen subsistence farmers move towards a cash economy.

Management: Management changes in the *barani* tract include the adoption of short-stature cereal varieties and increased use of high nutrient content inorganic fertilisers such as urea and diammonium phosphate (DAP). Higher yields are meeting food security needs. With the introduction of more combines and seed drills and more specialty fodder production, mixed cropping has decreased, although mustard is still mixed with wheat since it can be harvested for fodder before the wheat matures. A few farmers in the dry regions do not use fertiliser but rely on fallowing to release nutrients through weathering.

The dryland areas of Pakistan contribute much to food production and food security and will continue to do so. The keys to increasing and sustaining production are efficient use of rainwater and maintaining soil fertility. *Barani* areas have also recorded the highest wheat yields (8 t/ha plus) in Pakistan (Hobbs et al. 1989) in a good rainfall area where moisture was not limiting and sunlight was abundant. There is still scope to make these areas more productive through more efficient water-harvesting techniques.

22.4.2 Pakistan Rainfed Farming Systems in the Mountains

Pakistan's mountain areas have both higher rainfall parts, where double cropping with maize and wheat is possible, and very arid parts where crops can be grown only with glacial and snow melt irrigation systems. These mountain areas are characterised by uneven topography, physical isolation, small, multi-enterprise farms with livestock as a major component and significant out-migration, especially of men. The reader is referred to various chapters in Byerlee and Husain (1992) for a better description of these mountain areas with their many microclimates.

22.5 India

Rainfed eco-systems play a critical role in Indian food security. Two-thirds of the 160 million hectares of arable land in India are rainfed (Table 22.1). These support 40% of the population of more than one billion and contribute 44% to the national food basket (CRIDA 2002–2003 annual report). Rainfed farming produces 91% of coarse cereals, 90% of pulses, 85% of oilseeds, 65% of cotton and 55% of rice, and rainfed areas support two-thirds of India's livestock production. India has a much larger and more diverse set of conditions for rainfed agriculture than other countries in South Asia, with an array of crops, cropping systems, agro-forestry and livestock. Farmers depend on livestock as a supplementary source of income. The rainfed areas are poor compared to the irrigated areas, and are home to many of the poorer rural people.

The main constraint, as in all rainfed situations, is the variable climate and unstable production. Crop failures are common due to drought, and these have profound impacts on food availability and also on livestock production and survival. If India is to feed its growing population in the years ahead, it must utilise the rainfed lands more efficiently through more efficient use of natural resources. Books written on dryland farming in India (Somani 1992; Kanitkar et al. 1960; and Venkateswarlu 2004) recommend improvements in these systems based on past research. This chapter will concentrate on the different farming systems found in different parts of India. Table 22.11 shows the various climatic zones in India, with their percent area.

The zones are sub-divided into hot and cold areas (Fig. 22.2a); annual rainfall is shown in Fig. 22.2b.

Soil quality, mainly reflected in the depth of soil and moisture-holding capacity, also affects cropping potential. Table 22.12 shows the percent distribution of soil types within the various climatic zones in India. The result is a whole array of agro-climatic

Table 22.11 Climatic zones and per cent area covered by each zone in India

Climatic zone	Percent land area
Arid	15.6
Semi-arid	37.0
Dry sub-humid	21.1
Moist sub-humid	10.2
Humid	7.8
Per humid	8.3

Source: Venkateswarlu (2004)

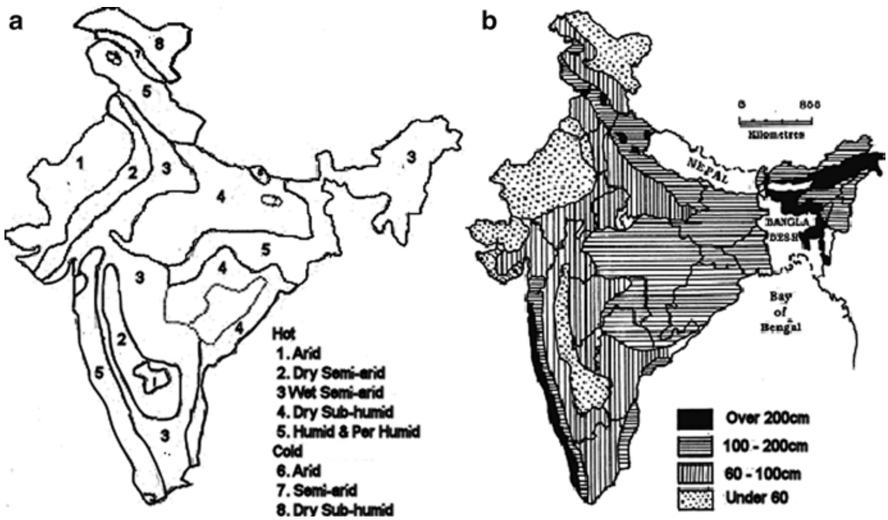

Fig. 22.2 The various hot and cold climate zones for rainfed agriculture in India (*left*) and mean annual rainfall (*right*)

Table 22.12 Per cent distribution of different soil types within different climatic zones

Climatic zone	Soil quality based on depth			
	Poor	Medium	Good	Total
Arid	9.8	4.1	1.0	14.9
Semi-arid	4.8	6.4	27.5	38.7
Sub-humid	–	5.4	25.5	30.9
Humid	0.4	4.9	10.2	15.5
Total	15.2	20.8	64.2	100.0

Source: Venkateswarlu 2004

Table 22.13 Potential cropping systems, annual rainfall zones and per cent rainfed area in India (Venkateswarlu 2004)

Potential cropping system	Annual rainfall (mm)	Per cent area
No crop	Less than 300	7.4
Single crop	300–700	18.9
Mixed/intercrop	700–1,100	40.0
Double crop	More than 1,100	33.6

zones; Venkateswarlu 2004 discusses the details and evolution of these zones in India. The latest classifications have 21 agro-ecological zones and 60 sub-zones.

Table 22.13 shows the per cent area for potential cropping by annual rainfall zones. No crop is grown where rainfall is less than 300 mm – unless irrigated. Single cropping occurs with annual rainfall between 300 and 700 mm and mixed cropping from 700 to 1,100 mm. Double, sequential cropping is possible when rainfall exceeds 1,100 mm. The data in Table 22.13 highlight the large proportion of land that is potentially available for mixed and intercropping, a major component of cropping systems in India.

Indian scientists have heavily researched rainfed systems with much information available from the Central Research Institute for Dryland Agriculture (CRIDA) centered in Hyderabad, Andra Pradesh. Figure 22.3 illustrates the huge diversity of cropping systems present in India. The reader is referred to Vittal et al. (2003) for a more detailed explanation of this figure. India has an All-India Coordinated Research Project for Dryland Agriculture (AICRPDA) coordinated by CRIDA. They conduct research in the following major cropping systems: rainfed rice, oilseeds, pulses, cotton and nutritious cereals.

There have been some significant changes in these different systems over the past half-century. The area under the coarse cereals (especially *kharif*[1] sorghum and millets) has declined significantly whereas there has been a surge in oilseed production (soybean, groundnut and sunflower) due to the government policy to provide a minimum support price for oil crops. The area under maize has increased even in low rainfall areas with low water-retaining soils. Cotton has declined in the Deccan area with sunflower grown instead, although *hirsutum* cotton did increase in some rainfed areas. This has resulted in an increase in crop diversity in rainfed India in recent years. Wherever irrigation was available from surface or groundwater, cropping is even more diverse.

[1] Autumn.

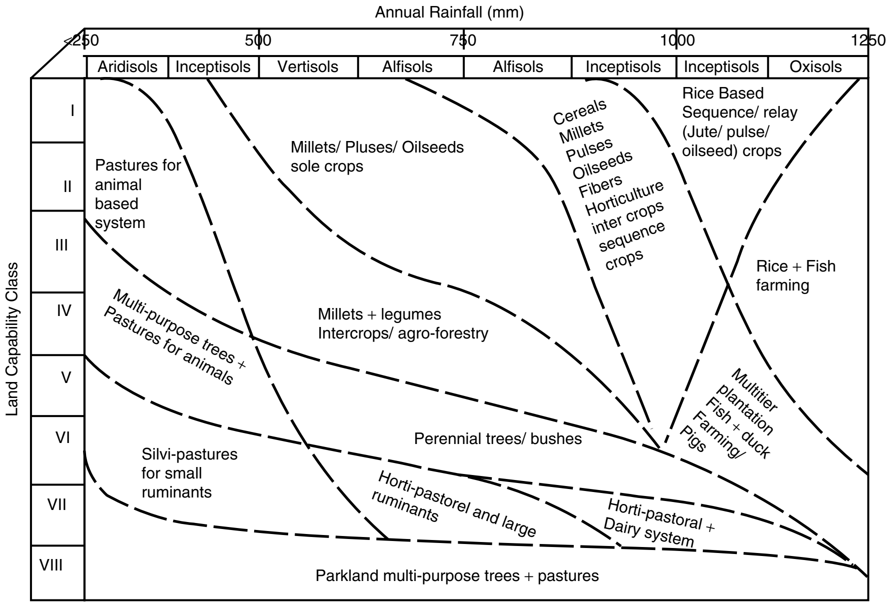

Fig. 22.3 Productive farming systems matrix in rainfed agriculture in India based on land capability class, annual rainfall and different soil orders (Vittal et al. 2003)

The main technology change in the rainfed areas has been adoption of improved varieties and some fertiliser, and some small pockets of water harvesting. In the following sub-sections are brief descriptions of the major cropping systems being researched by AICRPDA in India.

22.5.1 Rice-Based Rainfed Systems

Twenty-four million hectares (54% of rice grown in India) are rainfed, mostly in eastern and northeastern India where annual rainfall is above 1,000 mm. Four and twelve million hectares respectively are under upland and rainfed lowland rice (Fig. 22.4). In upland rice systems, rice is direct-seeded dry, much like other cereals and is often mixed with other rainfed crops such as pigeonpea, mung beans, and maize. Lowland rice is grown using seedlings raised in small seedbeds and transplanted into the main fields at the start of the monsoon rains; 3.6 million hectares are in deepwater ecologies (0.5–2.0 m flooding depth) in the riverine estuaries of many major rivers in India, but this system will be described in more detail in the Bangladesh section. Rainfed rice is important for the many millions of farmers and other people who rely on it for their income, employment and livelihoods.

Although rainfed rice is typically grown in areas with more than 1,000 mm of rain, it is still prone to spells of drought. To increase production and stabilise yields,

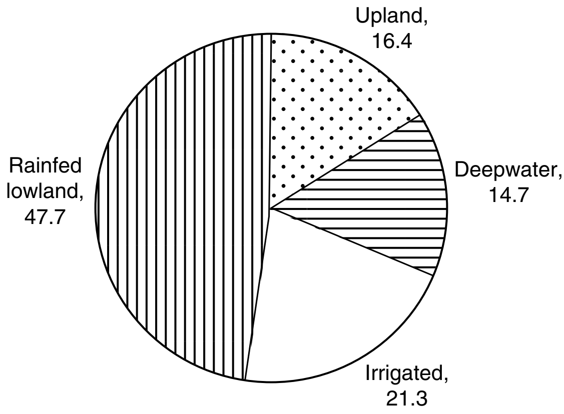

Fig. 22.4 Distribution of different rice types (% area) in Eastern India (24.5 Mha of rice) (Tomar 2002)

various water-harvesting techniques are used to provide surface storage water (ponds, tanks) or recharge aquifers that are then tapped through wells and groundwater pumping. Since this is similar to irrigated agriculture, it will not be discussed further.

The cropping patterns in the rainfed rice ecologies are either a single monsoon rice crop grown during the rainy season in June to October or a double cropping system where rice is grown in the monsoon season and a rainfed, non-rice crop in the post-monsoon, dry season. The many crops that can be grown in this dry season include wheat, linseed, mustard, chickpea, lentils, peas and vegetables in cooler regions, and pigeonpea, sunflower, sweet potatoes and maize in warmer climates. Rice-fallow is also a common cropping pattern although, with greater land pressure and new technologies such as zero-tillage, these fallow lands are being used more with various non-rice crops grown after rice harvest.

Mixed cropping is common in the *rabi* (winter) season after rice harvest, with sometimes three or four of the above crops grown mixed. Local markets for the diversified crops help provide the subsistence needs of the farmer households. In the higher rainfall areas near rivers, jute is commonly grown before the main monsoon rice crop or as an alternative to rice. It is a good complement to the rice system in that fields are left clean of weeds after harvest. Jute fibre extracted after retting by soaking in surface water is a valuable source of income.

Two other traditional rainfed rice systems are called *utera/piara* and *biasi/beushening*. The *utera/piara* system allows double cropping using residual moisture. Crops such as flax, lentil, lathyrus (Indian pea) and mustard are relay-planted into the rice fields 1–2 weeks before the rice crop is harvested, saving time and allowing the second crop to establish on residual soil moisture. Although yields may be poor if the rain ends early, they would be even worse if farmers waited until after the rice was harvested. *Biasi/beushening*, common throughout the rainfed rice regions of Eastern India (Tomar 2002), involves direct sowing rice at the onset of the rains. The fields are then ploughed 25–50 days later in standing water with a light plough and leveller. This serves to weed, thin the crop and distribute the seedlings in a more ordered fashion. Some gaps may be filled using the uprooted seedlings if the farmer has time. Although it sounds destructive, this traditional system is effective and results in reasonable yields, with minimal labour inputs for weeding or transplanting. In India, like Pakistan, rainfed farming systems involve livestock as a source of income and security.

22.5.2 Oilseed-Based Rainfed Systems

Three quarters of the oilseed crops in India are grown in rainfed areas; they include groundnuts (*Arachis hypogea*), sunflower (*Helianthus annuus*), safflower (*Carthamus tinctorius*), mustard (*Brassica campestris* and B. *juncea*) and castor (*Ricinus communis*). Some, such as groundnuts, sunflower and castor, are monsoon oilseeds whereas others, such as mustard and safflower, are post-monsoon *rabi* crops. India is the second largest producer of oilseeds in the world but is still a net importer of vegetable oil. Many of the oilseed crops in rainfed areas are inter- or mixed-cropped with cereals and pulses. Others are sole cropped or grown as a second sequential crop. By-products after the oil is extracted are important supplements in animal diets. Pests and diseases are common problems for these crops, and improvements are usually in the form of better varieties and integrated pest management systems. Aflatoxin is a major problem with oil seed storage, especially with groundnuts, and this affects India's ability to export this commodity.

Groundnut is grown on about 7.7 million hectares, mostly in the states of Andhra Pradesh, Gujrat, Karnataka, Tamil Nadu and Maharashtra. These are low-rainfall areas with 200–300 mm per month in the monsoon months. Alternate crops in the *kharif* (summer) season include millets, sorghum, pulses and cotton. Most of the groundnut is grown as a sole crop and rotated with cereals for soil fertility reasons. Soybean is also considered to be an oilseed as well as a pulse. It is grown on 6.5 million hectares in India but average production is low at 1.2 t/ha. It is commonly planted in several intercropping systems with maize, sorghum and millets.

22.5.3 Pulse-Based Rainfed Systems

More than half of pulses grown in India are rainfed. The most important rainfed pulse is pigeonpea (*Cajanus cajan*, 93% rainfed) but others include soybean, chickpea (*Cicer arietinum*), lentil (*Lens esculentum*), mungbean (*Vigna radiata*) and blackgram/urdbean (*Vigna mungo*). Many of these, apart from being sole crops, are sequential or mixed/inter-cropped with cereals and other rainfed crops; some (pigeonpea, soybean, *Vigna* spp.) are grown in the monsoon season, others (chickpea, lentil) in the post-monsoon dry season. The area of pulses under irrigated systems has decreased following the introduction of the improved varieties of rice and wheat but, in rainfed regions, pulse area has actually increased so as to maintain the total at 22 million hectares in 1970/1971 to 23 million in 2001/2002. The pulses suffer from many pest and disease complexes, and need better varieties and improved integrated pest management for these problems. The residues left after threshing the grain make good supplements for animal diets.

22.5.4 Cotton-Based Rainfed Systems

Two-thirds of the nine million hectares of cotton in India are on rainfed lands. Single cotton crops are common on the black soils (vertisols) of India and rely on the high moisture storage of these soils to finish the crop. They are also grown in inter-cropped systems with pulses and oilseeds. Cotton can be cropped as a sole, mixed, relay, intercrop and rotation crop in India depending on the amount and distribution of rainfall. A common traditional practice of cotton cultivation in central and southern India includes intercropping with pigeonpea and millets with 1–2 rows of pigeonpea after every 8–10 rows of cotton and 3–5 rows of finger millet. *Arboreum* and *hirsutum* types of cotton are planted under rainfed conditions. Many resource-poor farmers grow cotton as a cash crop, but it is susceptible to various abiotic and biotic limitations. Yields are low because of erratic rainfall, especially in the post-monsoon season.

A key to successful production of cotton, and other crops, in rainfed areas is efficient moisture conservation. One way to accomplish this is through the use of ridge and furrow systems across the slope; these conserve more moisture, reduce soil erosion and improve yield. Integrated pest management is also important for cotton farmers to reduce the costs of expensive pesticides. With the recent introduction of transgenic cotton (Bt cotton), farmers have experienced higher yields and lower costs for pesticides, despite high costs for seed. The area under transgenic cotton has grown from zero in 2000 to three million hectares in 2005 (although it is not known how much of this is rainfed).

22.5.5 Cereal-Based Rainfed Systems

Half of all cereals in India are grown on 50 million rainfed hectares. Although the total cereal area has remained at 100 million hectares (FAO Stat 2010), that under the coarse rainfed crops (sorghum and millets) has dropped from 38 million hectares in 1970/1971 to 22 million in 2001/2002. This is partly because of the introduction of higher yielding modern varieties of wheat, rice and maize, which are more remunerative than the coarse cereals. The main rainfed cereals grown in India are sorghum (*Sorghum bicolor*), pearl millet (locally called *bajra*) (*Pennisetum typhoides*) and finger millet (locally called *ragi*) (*Eleusine coracana*). Finger millet is the most drought-tolerant, followed by pearl millet and then sorghum while maize is grown where rainfall is higher. Wheat is grown in central India as a second, sequential crop after the above *kharif* dryland cereals. These rainfed cereals are grown as dual-purpose crops, for grain and fodder. The low quality by-product straw is fed to animals but often supplemented with oil cake, bran and pulse residues.

Under slightly higher rainfall and on soils with good water storage, these coarse cereals are often intercropped with oilseeds or pulses. This improves resource utilisation since the crops have differing times to maturity. The shorter-season crop utilises the light between the wide-spaced and slower establishing long-season crop. The latter uses any post-rainy season water to produce its harvest. Usually the cereal crop provides the subsistence needs of the farmer while the other species provides protein (legumes) or cash (e.g. cotton and castor). A description of mixed cropping systems in traditional Indian agriculture can be found in Aiyer (1949).

The amount of rainfall determines the type of cereal intercropping (Rao 1986). For example, when pigeonpea is intercropped with cereals, millets are sown in drier areas of 400–600 mm rainfall, sorghum with 500–750 mm, maize with 750–1,000 mm and upland rice with rainfall of 1,000–1,500 mm. Sorghum is the most common crop planted with pigeonpea. Both are planted at the beginning of the rains; sorghum takes 3.5–4.5 months while the pigeonpea takes 6–9 months depending on variety. Dry matter production (not grain yield) for sorghum and pigeonpea sole-cropped and for intercropped sorghum planted with two rows for every one pigeonpea row (45 cm) is shown in Fig. 22.5 (Willey et al. 1981). These crops were planted on vertisols that hold 200 mm or more of available water after the end of the rains – enough to produce 72% of the pigeonpea sole crop yield.

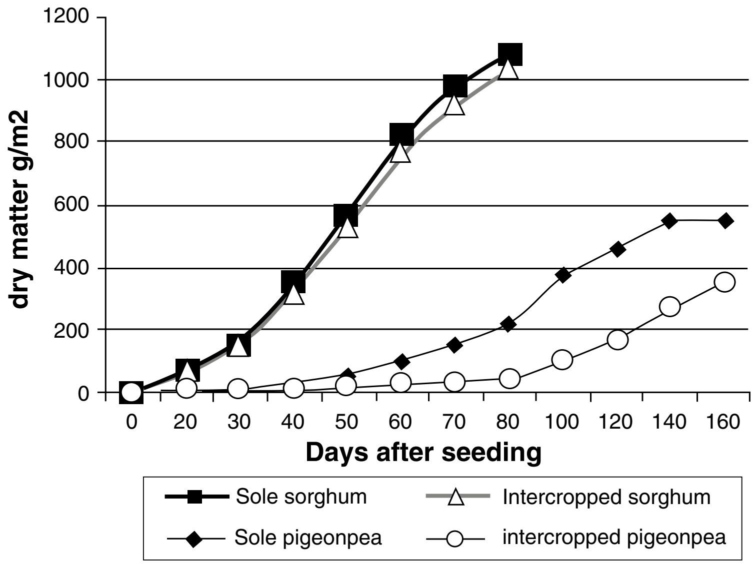

Fig. 22.5 Dry matter production of sorghum and pigeonpea in sole and intercropping (2:1 row arrangement) (Rao 1986)

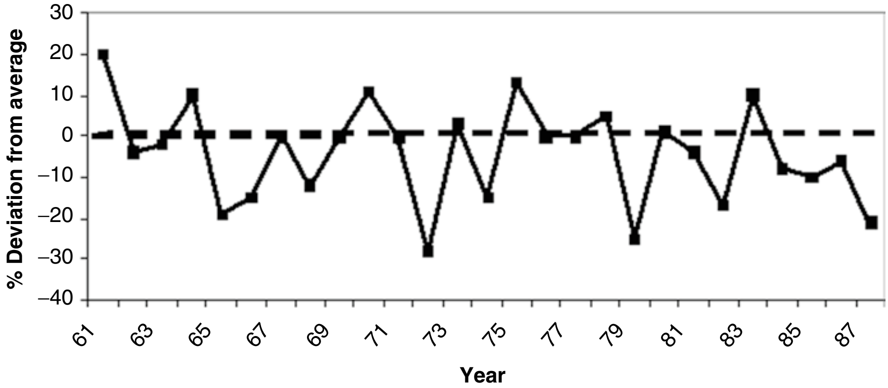

Fig. 22.6 Variation in rainfall from the long-term average for the SW monsoon in India. Indiastat, 2010. (http://www.indiastat.com/default.asp for data)

The intercropped sorghum yield was 94% of the sole crop, giving a land equivalent ratio (LER) of 166% for the intercropping.

These systems are suitable for hand-harvested crops, but would be impracticable if mechanical harvesters were to be used in these rainfed areas. While there may be sufficient moisture for two crops grown sequentially in good rainfall years, this system is more risky because of the variability in rainfall between and within years (Fig. 22.6).

The rainfed areas in India get most of their rain from the South-West monsoon. The determination of the growing period for the mean of this rainfall is illustrated in Fig. 22.7. The onset of the SW monsoon varies from year to year and location to location, but rains usually begin sometime in June and end in September. The problem for farmers is that rain can start and/or end early or late with disastrous effects on yield if the decision to plant is wrong. The combined variation in year-to-year rainfall, beginning and end of the growing season, and quantity that falls at any one time is enough to cause farmers to choose risk-reducing practices such as mixed and intercropping.

If sequential cropping was used, farmers would have to plough the soil after the harvest of the first crop (or use a zero-till system) and plant into soil that could be dry in the germination zone if rains had not fallen recently. The intercropping system with pigeonpea and sorghum has the legume crop already established when sorghum is harvested and its deep roots tap the residual soil moisture in the profile and provide a crop even if no further rain falls. In this system, fertiliser is applied basally for both crops and incorporated by the final tillage. Weeds are controlled by hand weeding, if at all. Diseases are handled by use of resistant varieties and are found to be less in mixed compared to pure stands.

On soils that have lower soil moisture storage, the advantage of intercropping is less. ICRISAT data also show that maize with pigeonpea is a good combination where rainfall is above 750 mm and LERs of 144–180% have been obtained

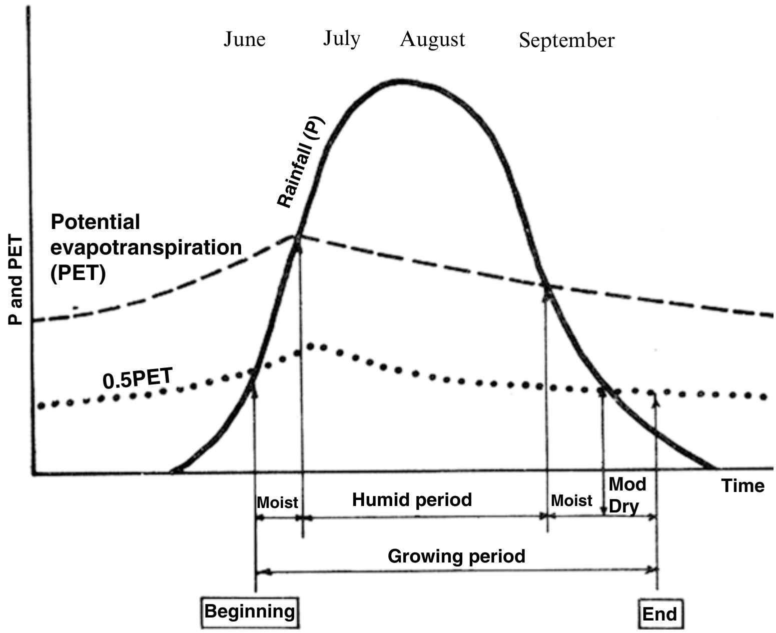

Fig. 22.7 Schematic diagram to show the growing period for rainfed crops in India for the SW Monsoon

(Chaudhry 1981; Rao and Willey 1980). The main millet used in the drier areas is the short duration pearl millet that is not affected by the pigeonpea. The LERs for this combination were as high as 178% (Rao and Willey 1983).

Figure 22.8 shows the various cereal cropping systems and length of growing season found in central India and the Deccan Plateau. Soil characteristics, especially the ability to store soil moisture (as in vertisols) and rainfall amounts are important factors influencing the crops grown, with many possible combinations, as shown in Fig. 22.8.

22.6 Bangladesh

Bangladesh is wedged between India and the Himalayas, and receives some of the highest rainfall in the world. Annual rainfall ranges from 1,400 mm in the mid-western side to almost 6,000 mm in the north-east (Fig. 22.9a).

The country is a vast riverine delta area with several of the world's largest rivers draining into the Bay of Bengal in its south. Two of these rivers are the Ganges, draining the Himalayan watershed from the south, and the Bramaputra that drains the Himalayas from the north; both originate in Tibet. This drainage system coupled

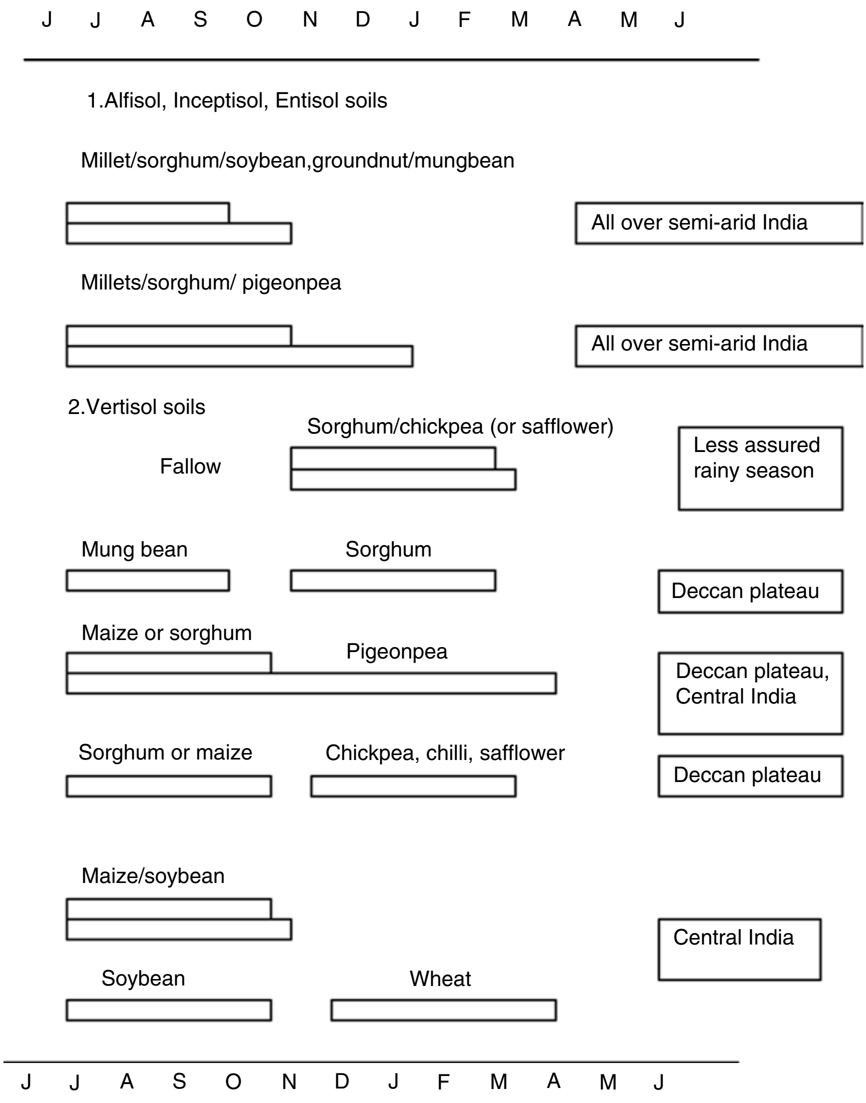

Fig. 22.8 Major cropping systems and lengths of growing season in rainfed areas of Central India and the Deccan Plateau. Two bars represent crops grown mixed or intercropped (Adapted from Rao 1986)

with the relatively high monsoon rainfall results in extensive flooding in the monsoon summer months as shown in Fig. 22.9b. Between 40% and 65% of the country may be flooded each year. The soils are mostly fertile alluvial deposits that sustain high crop production and large populations of people. Rice is the dominant crop, with the monsoon rice crop termed transplanted aman (*T. aman*) the most widely

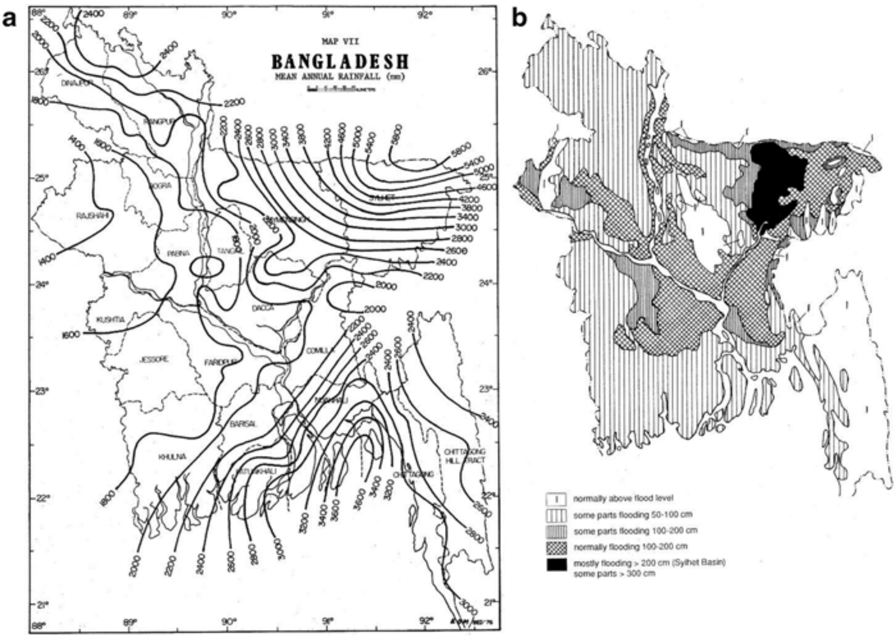

Fig. 22.9 Mean annual rainfall (mm) (**a**) and Flooding depths in Bangladesh in the monsoon, rainy season (**b**) (Manalo 1976)

grown rice type. With an abundance of rainfall, ground water and surface water, irrigation is common and has transformed the cropping systems in this country in the past 20 years.

This chapter briefly describes two major rainfed rice-based cropping systems under high rainfall. Other rainfed rice systems described previously for eastern India are also found in Bangladesh.

22.6.1 The Double Rice Cropping Aus – T. aman System

Traditionally, there are four different rice types grown in Bangladesh; these are shown as a function of water depth in Fig. 22.10:

- *Transplanted aman* (*T. aman*) is the normal rainfed, lowland, traditional monsoon rice crop that is transplanted in July–August when the monsoon has started and harvested in October–November. Seedlings are grown for 20–30 days in seed-beds before being planted in the main, puddled (ploughed when saturated) field.
- *Dry seeded aus* (*Aus*) starts as an upland short-duration rice crop that is sown dry in late March and harvested just before the *T. aman* crop is transplanted in late June–July.
- *Broadcast aman* (*B. aman*) is also known as deepwater or floating rice that is dry seeded in late April–early May before the monsoon starts and the fields flood.

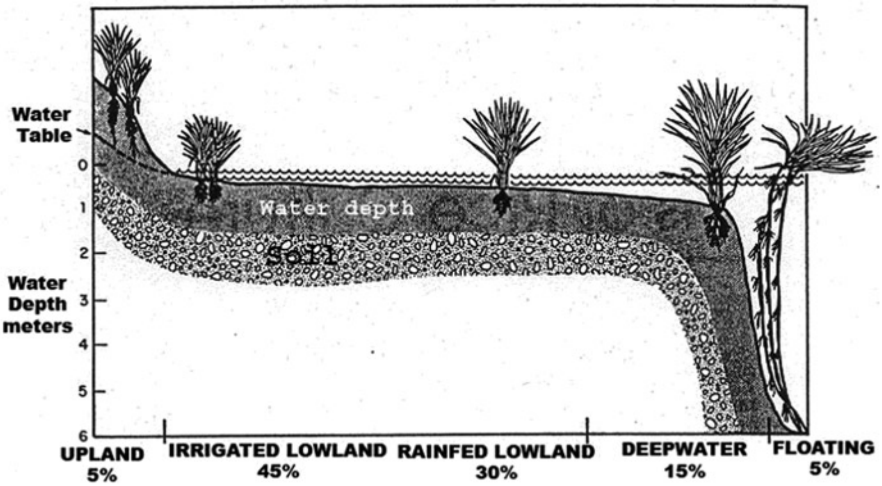

Fig. 22.10 The various types and percent of area of rice grown in Asia in relation to water depth, shown as the darker layer above the soil layer (Catling 1992)

- *Boro* is an irrigated lowland rice crop transplanted in the cooler winter season in January–early February in deepwater areas and irrigated with surface or groundwater.

In the lower rainfall areas on the western side of the country, *T. aman* followed by fallow or *T. aman* followed by a rainfed winter crop (called a *rabi* crop) of wheat, pulses, mustard or flax are common systems. The decision to grow a second crop is dependent on soil type, available soil moisture and the household needs of the farmers. With greater rainfall and heavier pre-monsoon rains that can start in late March, farmers opt for a quick-growing *aus* rice crop and follow it immediately with a transplanted *T. aman* rice crop. Traditionally, both rice types were local varieties; the *aus* crop was non-photoperiod sensitive and coarse grained whereas the *T .aman* crop was photoperiod-sensitive and fine and/or scented grain. Photoperiod sensitivity was important to prevent the rice flowering too late (October) when temperatures drop to levels that can cause significant sterility. Jute, as a direct-seeded fibre crop, is a substitute for *aus* in areas near the rivers.

With the introduction of more surface, canal and groundwater irrigation, these system have changed in the last 20 years to one of double transplanted rice where both are modern varieties and the *aus* crop is transplanted instead of dry seeded. In some cases, the *aus* crop is replaced with modern *boro* rice varieties established much earlier in January–February, since *boro* rice type is very high yielding. Agronomists have coined the term *braus* for this rice crop that overlaps the *boro* and *aus seasons*; *boro –T. aman* is now one of the most productive rice systems in Bangladesh. With proper management and variety selection, total yields can exceed 10 t/ha/year. In some areas, farmers have added a *rabi* dryland winter crop to the

T. aus–T. aman system, with irrigation to allow triple cropping of the land. Wheat is then the preferred crop, but potatoes, vegetables and maize may also be planted.

The recent introduction and adoption of maize is related to the high demand for feed for a burgeoning poultry industry as more people can afford to eat meat products. Milk and dairy is not as popular as in western India and Pakistan, but more farmers are rearing cows and buffalo for milking instead of as the main source of animal power for land preparation, transport and even threshing. Small, 2-wheel hand-operated tractors of 9–20 kW have substituted for much of the animal-powered tillage in the last 10–15 years. Residues from rice are a major source of animal feed as in other Asian countries, with supplementation from oilseed cake and pulse and grass fodder.

22.6.2 Deepwater B. aman Systems

This rainfed system is found in many of the flooded riverine deltas of the world including Bangladesh, Nepal and India. These lands are relatively fertile because of the silt deposits and they support high populations. In this system, the main crop is the broadcast aman (*B. aman*) with its unique ability to withstand and survive flooding. It is usually sown in April as a dry seeded crop. After the crop has established, some farmers give it one hand-weeding until the flood arrives – usually in June. The plants then elongate as the water rises, to stay above the water. When the water recedes in late September or October, the stems lodge on the ground and send up panicles into the air. After fertilising, the grains fill and the panicles fall to the ground where they are harvested by hand. In some areas where deeper waters recede late, farmers harvest the rice from boats as it floats on the water. This is an extreme case of deepwater rice where flooding depths are above 1.5 m (Fig. 22.10). The deepwater rice varieties are photoperiod-sensitive, and are selected by farmers depending on the position of the land in terms of depth and recession of the flood; photoperiod sensitivity allows varieties to flower after the floods recede. A more detailed description of this fascinating crop can be found in Catling (1992).

These deepwater, rainfed lands (DWR) are also used for other crops. The following major cropping patterns are found in these deepwater areas:

- A sole crop of *B. aman* (DWR), although this is not common. These pure stands are grown in low-lying areas, having earlier, deeper and more prolonged flooding.
- A mixed crop of *Aus* rice and *B. aman*. The two rice crops are sown on the same day, as a mixture. The early *aus* rice is harvested by hand before or just after the floods start in June; the *B. aman* continues growing until the floods recede. The *aus* allows farmers to harvest a rice crop before the floods. *Aus* mixtures significantly reduce the yield of deepwater rice (Catling et al. 1983) but the total grain yield from both crops can be 0.4–0.5 t/ha higher than pure stands. This common mixed system, grown in 30–60% of the deepwater fields is obviously a benefit, considering the farmer invests only a little seed and time (Catling 1992). Jute can substitute for *aus* rice.

- A mixture of non-rice crops with *B. aman* including millets (*Panicum miliaceum* and *Setaria italica*), sesame (*Sesamum indicum)* and chilli (*Capsicum annuum*). These are planted on only a small percentage of the land and are really late *rabi* crops. The DWR is relayed into these late crops. It is common on soils with coarser texture.
- In the dry season following the DWR harvest, a whole array of *rabi* crops are grown on the residual moisture. This includes pulses, oilseeds, cereals, spices and vegetables. Seventy percent of fields from a survey in 1977–1978 showed a *rabi* crop sown after DWR (Hobbs et al. 1979). Twelve different combinations of crops were identified with the choice of *rabi* crop dependent on the recession of the flood. Some sown as relay or zero-till crops onto the DWR crop or stubble include grasspea (*Lathyrus sativus*–for grain and fodder) and common pea (*Pisum sativa*), both being mixed with mustard (*Brassica* spp.). Grasspea is also grazed by animals after the seeds are harvested. Wheat and barley are grown mixed or pure as the main cereal crops after *B. aman* harvest. Other pulses include lentil (*Lens esculenta*), black gram (*Vigna mungo*) and chickpea (*Cicer arietinum)*. Spices and herbs include coriander (*Coriandrum sativum*), onion and garlic. Potatoes are also a popular crop.
- In the very deepest-water lands, *Boro* rice is transplanted after water depths fall sufficiently to allow transplanting into the standing water. It is traditionally a tall rice type locally adapted to cool temperatures. Sometimes a double transplanting system is used in which bunches of seedlings are planted in the shallower depths and these are then split and used to plant in deeper areas as the floods recede.

In the wet season, animals are kept protected near the home on land raised above the flood level, but are allowed to graze the stubble in the dry season. Crop residues are the main source of food for these animals.

22.6.3 Recent Changes in Bangladesh

Over the last 30 years, there have been significant changes in the cropping systems in these deepwater areas and other rainfed lowland areas. The area of *B. aman* has declined from 1.88 million hectares in 1969–1973 (Official Bangladesh statistics) to 1.29 million in 1986–1987 and to around 0.8 million today. Farmers have opted for the higher-yielding modern *Boro* rice with irrigation on much of this reduced DWR land. The farmers pump the groundwater and surface water to keep the rice irrigated. The seedlings are started from late November and transplanted to the main field in late January to early February when the fields are no longer flooded. The crop is harvested in May/June before the floods come. *Boro* rice is the highest-yielding rice crop in Bangladesh and is responsible for the rapid growth in rice production and self-sufficiency in rice. In the rainfed lowland system, boro rice is often followed with modern *T. aman* rice.

The other major change in Bangladesh has been the introduction of the small two-wheel tractor. Farmers use these for preparing their fields instead of animal power as it is cheaper to hire a two-wheel tractor than to keep a couple of bullocks fed and in health for a whole year. This innovation has speeded up farm operations and led to higher production and more efficient use of water and land. The most common tractor is imported from China since this simple machine can be easily repaired and spare parts are readily available and affordable. These power sources are also used for multiple farming purposes including land preparation, sowing, pumping water, driving a winnowing fan or thresher, and reaping. They are also a major form of transport when attached to a trailer in rural areas. The tractor can be used to make a bed and furrow configuration that further improves water use efficiency of cropping; the crop is grown on the top of the bed and the water supplied in the furrow.

Improved varieties and the use of high nutrient content fertilisers are now common and have helped make Bangladesh self-sufficient in cereal grains. Wheat is now extensively grown after *T. aman or B. aman* rice, and after *aus* rice or jute in some areas. Maize has recently been a popular choice of farmers since markets have developed for this crop in the poultry feed industry. There is much less mixed cropping and more sole cropping of rice or wheat. Pulse crop production has also declined as modern wheat and rice crops in pure stands, being more reliable and profitable, are planted instead. Yields of commonly-grown legumes in Bangladesh are poor because of many disease and insect problems. In wet years, the entire legume crop can fail. The scope for reversing this situation through improved legume genotypes could add more diversity to cropping systems in Bangladesh.

22.7 Nepal

Nepal is a land-locked country that nestles south of the Himalayas and north of India. Two thirds of its agriculture is rainfed but rainfall averages from 1,000 mm per year in western areas to 2,500 mm in the eastern side. This is sufficient to allow rainfed rice as the major system. The country is divided into three distinct agro-ecological zones based on elevation (Fig. 22.11):

- The *tarai* zone. This southern zone consists of the flat alluvial plains below 500 m altitude. It is sub-humid, with rice the main monsoon crop, followed in some places by *rabi* crops such as wheat, pulses and oilseeds, as in eastern India and Bangladesh. Sugarcane is grown where processing factories are close by and also for local sugar production (processing of the sugar using village/household level extraction systems). Animals have similar roles to those in eastern India and Bangladesh, and are used for agricultural power (ploughing, threshing and transport) although the recent introduction of 2-wheel tractors may result in their importance declining. However farmers substitute dairy cows and buffalo in the place of draught animals since dried dung is an important commodity for cooking.
- High hill and mountain zone. This northern zone lying above 2,500 m altitude is mainly a pastoral zone, almost 100% dependent on livestock that graze the grasslands and pasture in the summer and move south to feed on local village

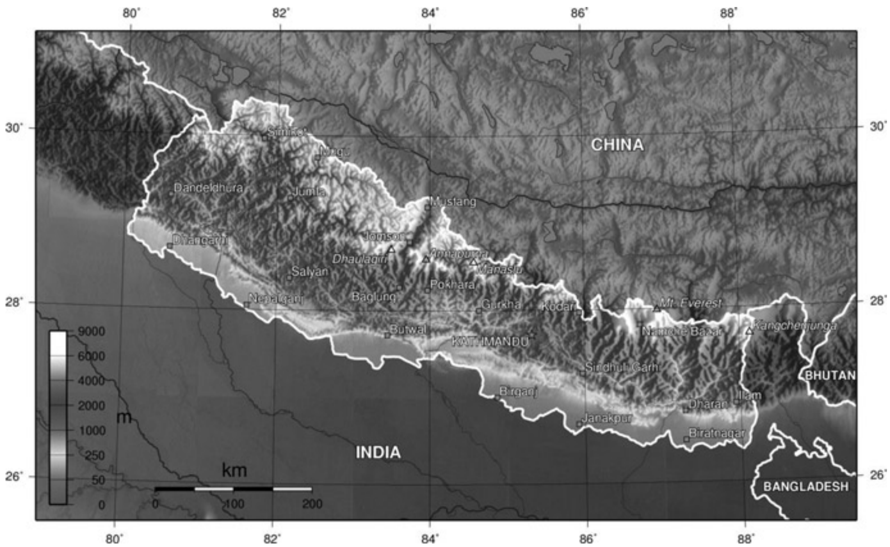

Fig. 22.11 Elevation zones for Nepal (Topographical Zonal Maps, 1:250,000, Topographical survey Branch, Dept. of Survey, HMG/Nepal 1988)

grazing areas, leftover crop residues and weeds in the winter. Some agro-pastoral systems are found in valleys and near rivers where potatoes and barley are the main crops.

- Mid-hill zone. The mid-zone lies between 500 and 2,500 m altitude in the central region of the country. This zone is discussed below in more detail, based on surveys conducted in the early 1990s in Kabre District near Kathmandu (Harrington et al. 1992; Adhikari et al. 1999).

22.7.1 *Cropping Systems in the Mid-Hill Zones*

The annual rainfall in this zone is higher in the east and lower in the west. In the surveyed Kabre District, annual rainfall of 1,350–1,450 mm is enough to support rainfed rice cultivation. However, in these hill regions, the cropping systems depend mainly on whether the land had been terraced or is sloping. Farmers in this region have put much labour into developing terraced fields called *khets* where rice is grown in the summer monsoon season. Depending on the slope of the land, these terraces may be just a few metres in width or much larger fields. The flatter river valley land is often terraced with relatively large fields. Figure 22.12 shows various terraced landscapes in the *rabi* season where mustard and wheat have been planted after rice harvest (left) or where land has been prepared for the *rabi* crop (right). Terracing is a soil conservation system that allows flat rice planting while also reducing major soil erosion problems.

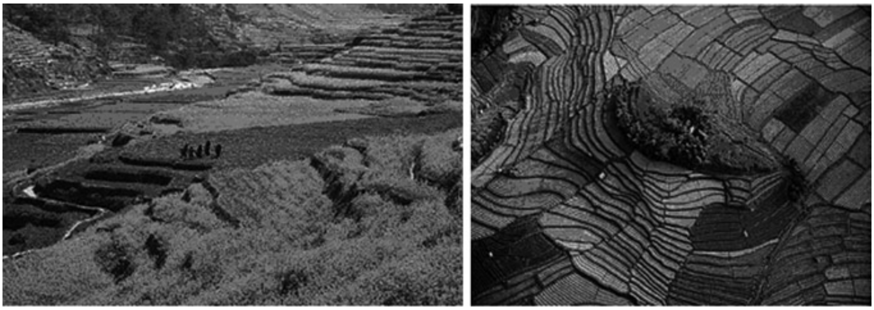

Fig. 22.12 Terraced fields in Nepal

In the hill region, temperatures are lower than in the *tarai* region and so only one rice crop can be grown each year in the main monsoon season. This is predominantly a rainfed system but water moving down the profile and from higher terraces provides sufficient moisture for the rice crop. After rice, the land may be kept fallow or, if sufficient moisture or spring irrigation is available, wheat, mustard or other *rabi* crops are grown. If available, modern high-yielding varieties and fertiliser are used on this land type to boost production. The residues from the crops are valuable animal feeds, and the animals in return provide valuable manure to sustain soil fertility. The farmers also compost household wastes and use these to manage soil fertility.

The second type of land is called *bari* land, and is gently sloping and not bunded. This *bari* land is used for maize systems although dry seeded upland rice is grown in some parts. Maize may be grown as a pure crop or, in some regions, is mixed and intercropped with finger millet (*Eleusine coracana*). The maize has multiple uses including as a staple cereal, green cobs or fodder. The finger millet is used for alcoholic preparations and fodder. Manure may be the only source of nutrients supplied by farmers on this land type. The land is often left fallow in the winter season since soil moisture is not sufficient and the land cannot be easily irrigated.

Potatoes have recently been adopted by hill farmers as an important cash crop. These are mainly grown on the wider terraces in the river bottoms (Fig. 22.12) for consumption, while virus-free seed stock is sold in other potato-growing areas. Vegetables are also important cash crops near major city and town centres. Other crops that are important, especially in the wetter eastern region, include tea, coffee, cardamom (*Elettaria cardamomum*) and mulberry for silk worm cocoon production.

Animals are a major component of the farming systems of hill farmers. They provide draught for land preparation and threshing, although much of the steeper land is prepared manually and the crops are threshed by hand. Recent introduction of milk collection points has helped farmers increase incomes through milk production from both cows and buffaloes. Sheep and goats are allowed to roam the countryside in search of food under the care of a young herder.

Forestry is an important income-generating activity in the hills of Nepal; trees are grown for timber and firewood, with some species providing leaves for animal fodder.

Citrus and apples are two introduced fruits that are providing incomes for some farmers. However, with population increases, loss of forest is resulting in soil erosion and degradation, leading to siltation in rivers.

The main agricultural improvements in these hilly regions come through introduction of better varieties of the crops grown. Researchers have used participatory farmer approaches with success. Fertiliser use is restricted to areas that have road access. Mechanisation is limited on the steep terraced lands and so is confined to the broader, lower valley lands. Although roads have helped link farmers to markets and to social structures such as schools and medical facilities, there are still many remote areas in Nepal. Nepal is one of the poorest countries in South Asia where agriculture is the main form of livelihood and source of income. Reducing poverty in this country will need improvements in rainfed farming, using appropriate technology that can be accessed by the farmers and used to improve their incomes. Policies that promote better market access and improved infrastructure in the country will also contribute to improved livelihoods.

22.8 Summary and Conclusions

This chapter has outlined the large diversity present in the extensive rainfed areas of South Asia. The three main determinants of the farming systems are rainfall (that ranges from below 300 mm to more than 6,000 mm/year), temperature (cool and warm areas) and soil properties (especially soil moisture holding capacity and depth). Systems vary from the temperate wheat-based systems in the north, to the more subtropical and tropical rice and sorghum/millet systems in the south and east.

These rainfed cropping systems have evolved over time and have provided sustainable food production and income for farmers for many decades. Their strength lies in their diversity to satisfy the multiple needs of the rainfed area farmers. Crops and livestock are both crucial components of these farming systems. The livestock activities provide a financial buffer and tide the farmers over difficult drought years. Crops provide both subsistence needs and also some excess for market and cash income. Mixed- or inter-cropping is a common feature in all the described rainfed systems when rainfall is sufficient. This is a resource-efficient practice that uses light, water and soil nutrients more efficiently than pure (mono) cropping and also reduces biotic stresses such as insect and disease attacks.

The increase in population pressure over the last half century in South Asia has resulted in increases in urbanisation, migration of labour to cities and much more pressure on the rainfed lands to produce more food. This has meant that changes have been needed to the traditional rainfed farming systems. The weakness of the traditional system is that it cannot provide sufficient food to meet the demands of the larger population without some technical interventions.

The main technical interventions have been genetic, nutritional and mechanical. New, higher yielding varieties of crops and animals have been introduced in the last 30 years. Wheat varieties with much higher yield potential when supplied with more nutrients and water were the basis of the green revolution. In the rainfed areas, adoption of these improved genotypes occurred later than in the irrigated lands, but has become popular in the last two decades. Improved breeds of dairy cows and also sheep and goats have increased animal production and farmer incomes. There is now a need for better fodder and grains to allow farmers to reach the potential available in these genetic stocks. Chemical fertilisers, especially those with concentrated nitrogen and phosphorus, are used extensively to replace nutrients removed in harvest. Plant protection products are also used more extensively than in the traditional system, although present emphasis is on integrated pest and disease management. Mechanisation has also increased substantially as labour has moved to the cities and farmers have needed to have more timely operations for higher production. Tractors, seed drills, threshers and combines have all appeared in the South Asian rainfed areas, although animal and manual power are still sometimes used. Mixed- and inter-cropping decline as mechanisation increases, because it is difficult to use machines to plant, harvest and thresh combinations of crops with different management requirements and maturity times. This has resulted in more single cropping in rainfed areas.

For the future, rainfed areas of South Asia will need to increase productivity in a sustainable way, while increasing the incomes of those involved in agriculture. Sustainable land management systems like zero-tillage with permanent ground cover will be needed to reduce soil degradation and erosion and increase soil organic matter and soil health. Water requirements for domestic and industrial purposes will continue to increase. Farmers will need to use more efficient water-harvesting systems and increase water productivity to compete with these other demands. Crop and animal diversity will be needed to improve farmer incomes using better marketing channels. Farm land near cities can benefit by providing many higher value crop and animal products to urban dwellers. This will require better market research, extension and farmer education. The introduction of mobile phones and internet kiosks in the region can be a logical means to this end, given suitable sources of information. Funding will be needed to support the research and development of the new technologies required by rainfed farmers of South Asia.

The rainfed areas are home to millions of the poorest communities in South Asia, since they are prone to the risks of variable climate. However, with the right policies in place and a greater emphasis on and funding for these rainfed areas, there is potential to improve livelihoods, and contribute significantly to the economies of South Asian countries.

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Chapter 23
Rainfed Farming Systems in the Loess Plateau of China

Gaobao Huang, Wen Chen, and Fengrui Li

Abstract The Loess Plateau is the most important region of rainfed farming systems in China. Most of the Loess Plateau is covered by deep loess soils with sparse vegetation and is dissected by eroded gullies. The Loess Plateau has a typical continental, monsoon climate, with most of the rain falling between June and September. The loess soils are deep, with high plant-available water holding capacity. They are easily eroded having low clay content and reduced organic mater from continuous cropping and intensive soil cultivation. A range of technologies are needed to improve productivity and sustainability of rainfed systems in the Loess Plateau. They include crop improvement, better land management, smart crop rotations, adoption of conservation tillage, better soil fertility management, and rainwater harvesting. Integrating these technologies could improve crop grain yields and water use efficiency, maintain soil resources and thus promote long-term crop productivity. Developing integrated livestock–cropping systems, and adopting water saving and conservation agriculture technologies are critical for improving crop productivity while maintaining healthy farming systems.

Keywords Loess Plateau • Rainfed farming systems • Soil erosion • Water use efficiency • Crop improvement • Crop rotation • Plastic mulching • Conservation tillage • Soil fertility • Rainwater harvesting agriculture

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_23,

23.1 Introduction

Rainfed agriculture in China dates back at least 8,000 years to the early Neolithic period. The ancient agricultural production system extends back to the early days of clan society. Originally, locally selected species such as millets were sown with the aid of simple tillage tools made from stone and wood (Xu 2001), and productivity was naturally low. During the Xia and Zhou dynasties (2200–2221 BC), new metallurgy provided improved tools, experience in crop production was accumulated and the 'Jingtian' system of land management was established; this indicates evolution from shifting agriculture to fallow farming (Xu 2001).

Better tools made from iron, the use of manure and the selection of new crop species (especially forage and grain legumes) led to the next evolution from fallow farming to rotational farming (Xu 2001). Progresses in science and technology over the last half century, and intensive land management (Deng et al. 2005) have greatly increased crop yields (Table 23.1) (Gao et al. 2005).

Grain crops for local consumption account for more than 80% of all crops with only a small proportion under forage and cash crops. Although forage crops contribute to sustainability and cash crops to farm income, more than 70% of the cropping area is planted to millet and maize in Zhaowudameng and Zhelimumeng, Inner Mongolia. Maize accounts for over one-third of the arable land in the Yanshan, Huanglong, Ziwuling and Taihang mountain regions, while more than half the cropping area is planted to wheat in Weibei and east Gansu.

Table 23.1 Historical development of rainfed farming in China (Gao et al. 2005)

Stage	Time span	Key technologies	Action	Grain yield (t/ha)	Environmental impact
Traditional	1949–1964	Cultivation, organic fertiliser application, sowing stress-tolerant varieties	–	<1.5	Water and soil loss
Terrace-building	1965–1983	Building terraces, deep plowing, applying manure and some chemical fertiliser	Retaining rainfall in-situ	1.50–2.25	Soil and water conservation
Fertiliser applied	1984–1995	Increasing chemical fertiliser application, selecting new varieties, optimising agronomic practice	Promoting plant growth	2.25–3.00	Preservation of vegetation
Rainwater harvesting	1996–present	Harvesting rainwater for supplementary irrigation, drought resistant crop varieties and more efficient water use	Better use of rainfall	>3.00	Emergence of a healthy ecosystem

However, instability of crop yields is a characteristic of rainfed farming systems and has been associated with poor crop management, unsustainable agricultural systems and periods of adverse climate, particularly rainfall. This year-to-year variability is illustrated by the coefficient of variation of crop yields in Dingxi being as high as 30–70%, and over 30% for spring wheat (Huang 2001). Another example of variation is the total production of grain in Shanxi, which was 10 million tonnes in 1993 but less than 7.5 m tonnes in 1991 (Huang 2001; Wang 2005).

23.2 Climate, Soils, Topography, Crops and Rotations

In China, the arid and semi-arid regions account for 53% of the land area. Rainfed farming systems occur across almost the whole country, especially in the Northwest and North China, the Loess Plateau and the Sichuan Basin (Figs. 23.1 and 23.2) (Luo 2004). The total area of arable land is 128 million hectares, of which about 60% is rainfed. Rainfed agriculture is divided along the boundary of the Kunlun Mountain and Huai River into ten zones (I–X):

Climate, soil type, crops and cropping rotations in the ten regions of rainfed farming systems are summarised in Fig. 23.1 and Tables 23.2 and 23.3.

I. Sub-humid, temperate. Annual mono-cropping of cool-season crops in northeast plain and mountain areas.

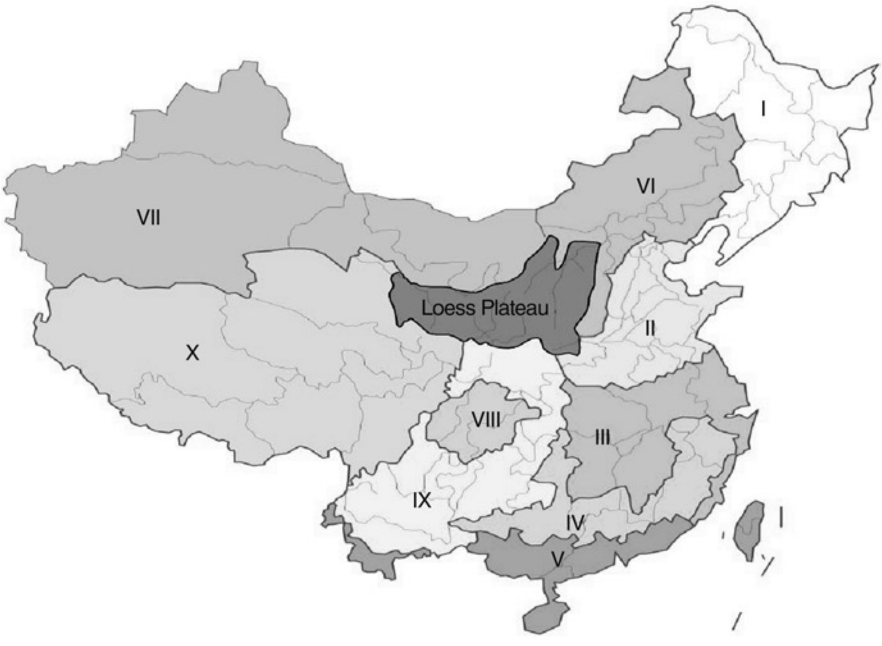

Fig. 23.1 Map of rainfed agricultural regions in China (Liu and Chen 2005)

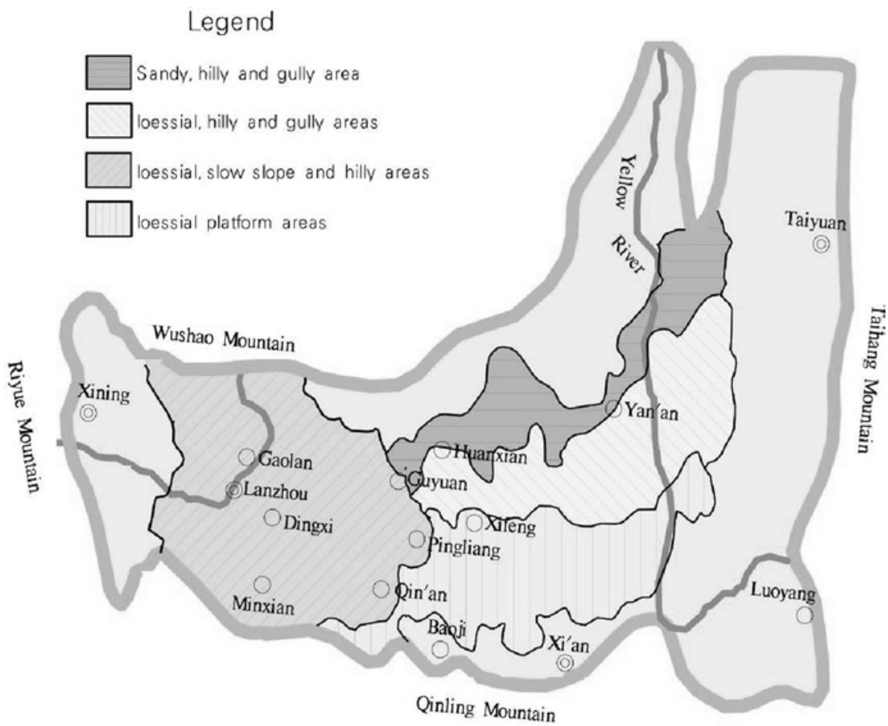

Fig. 23.2 Map of the Loess Plateau of China (Dili 2008)

II. Sub-humid, temperate. Irrigated temperate crops in the Huang, Hai and Huai River Plains.
III. Humid, subtropical. Paddy fields, intensive farming and subtropical crops in Changjiang River middle and lower reach Plain and hilly areas.
IV. Humid, subtropical. Paddy fields with double or triple cropping and subtropical crops in the hilly and mountainous regions to the south of Changjiang River.
V. Humid, tropical. Paddy field double or triple cropping with tropical crops on plains and in hilly regions of coastal South China.
VI. Semi-arid, temperate. Rainfed farming and pastoral regions with cool-season crops in the northern China's lower and middle plateau including the Loess Plateau.
VII. Arid, temperate. Irrigated oasis farming and desertified pastoral regions and temperate crops in North-west China.
VIII. Humid, subtropical. Wheat and rice double cropping and subtropical crops in the Sichuan Basin.
IX. Humid, subtropical. Extensive rainfed crops and rice double cropping and subtropical crops in the middle plateau of South China.
X. Arid, semi-arid, cold. Alpine pastoral regions and valley mono-cropping in Qingzang Plateau.

Table 23.2 Climate and soil conditions in the 10 rainfed agricultural regions (Liu and Chen 2005)

Region number[a]	Mean annual temperature range (°C)	Annual accumulated temperature (≥0°C)	Annual frost-free period (days)	Annual rainfall (mm)	Arable land per capita (ha)	Main climate types	Main soil types
I	-5–10.6	2,500–4,000	140–170	480–870	0.20	Sub-humid medium-temperature	Chernozem, meadow soil, Baijiang soil, dark brown soil
II	8–15	4,000–5,400	170–200	460–1,000	0.08	Sub-humid warm temperature	Moisture soil, cinnamon soil, brown soil, loam, black soil
III	14–19	5,300–6,500	230–290	900–1,500	0.05	North and middle subtropical	Yellow brown soil, yellow soil, red soil, lithosoil
IV	16–21	5,700–7,100	270–320	1,300–1,900	0.05	Middle subtropical	Yellow brown soil, yellow soil, red soil
V	18–25	6,500–9,300	330–365	1,100–2,500	0.05	South subtropical	Laterite, red soil
VI	2–11	2,000–4,300	80–180	100–630	0.20	Temperate continental	Chestnut soil, sierozem, brown calcic soil, aeolian sandy soil
VII	4–13	3,300–4,900	130–200	50–400	0.15	Warm temperate	Chestnut soil, sierozem, meadow solonchak, brown desert soil
VII	16–18	5,900–6,700	280–320	950–1,300	0.05	Middle subtropical	Purple soil, alluvial soil, lithosoil
IX	12–18	3,600–8,000	210–365	800–2,000	0.06	North subtropical	Yellow soil, red soil, purple soil, lima soil
X	-4–8	1,500–2,900	50–150	30–700	0.09	Cold temperate	Alpine and sun-alpine meadow steppe soil, brown calcic soil, sierozem

[a]Note: Region numbers are the same as in Fig. 23.1

Table 23.3 Crops and their rotation systems in the ten rainfed agricultural regions (Liu and Chen 2005)

Region number[a]	Major grain crops	Major cash crops	Main rainfed farming systems	Main crop rotation systems[b]
I	Spring wheat, maize, soybean, millet, sorghum	Sugar beet, sunflower, fibre flax	Half-mechanised agro-pastoral farming, large scale farms	Spring maize → Spring maize → sorghum (millet) → soybean (peanut); Spring maize / soybean → Spring maize → soybean (potato, tobacco)
II	Winter wheat, maize, soybean, cotton	Peanut, sesame, tobacco, vegetables	Double and mono-cropping	Winter wheat-summer soybean (sweet potato, millet, peanut, sesame); Spring maize/soybean → Spring maize; Spring maize /leguminous crop → sorghum (millet) → spring sweet potato (peanut); spring peanut → spring sweet potato → spring sesame → wheat/ peanut → spring sweet potato
III	Winter wheat, sweet potato	Cotton, fibre flax, rape	Double and mono-cropping	Winter wheat (winter rape, barley, broad bean)/cotton; snake melon → snake melon; spring peanut → spring sweet potato → spring sesame; winter crops (broad bean, wheat, barley) – sweet potato
IV	Barley, wheat, sweet potato, maize	Peanut, sugarcane, vegetables	Mono-cropping annually or double cropping. Hillside double cropping	Snake melon → snake melon; winter crops (potato, broad bean, wheat) → summer sweet potato (summer maize); spring peanut – autumn sweet potato (maize)
V	Maize, soybean, sweet potato	Peanut, litchi, sugarcane, tangerine	Extensive double cropping	Spring peanut → summer sweet potato → Spring maize/ soybean summer sweet potato; snake melon → snake melon; sugarcane → sugarcane
VI	Wheat, maize, millet, highland barley, naked oat, potato, naked oat	Linseed, rape	Mono- cropping annually and triple cropping in 2 years agro-pastoral systems	Spring maize/soybean → millet → Spring maize / soybean → sorghum; potato → spring wheat → potato → naked oat → fallow; potato → naked oat → pea (sunflower); millet → pea
VII	Spring wheat, potato, pea, millet	Sunflower, linseed, rape	Extensive rainfed farming	Sunflower → potato → sunflower → linseed → rape → pea; spring wheat → spring wheat → millet → mixed cropping with pea, barley and highland barley; Winter wheat → maize → cotton → rape /cloverÐspring rape → linseed

VIII	Winter wheat, maize, sweet potato, broad bean, potato	Sugarcane, tangerine, peanut, rape, vegetable	Double intercropping Hillside mixed cropping systems with field crops, fruit trees and vegetable	Winter wheat/summer maize – summer sweet potato (peanut, soybean); snake melon → snake melon; Winter wheat (broad bean, potato, rape) → summer maize (summer sweet potato); spring sweet potato → spring sweet potato → peanut (soybean)
IX	Winter wheat, maize, potato	Rape, tobacco, sugarcane, tangerine, sisal hemp, shellac	Extensive double cropping Multistory cropping in middle and lower mountain regions	Potato/maize/leguminous crop → Winter wheat (rape) → summer maize, Winter wheat (potato) – summer sweet potato (summer maize); Winter wheat / maize // soybean → Winter wheat (rape) – summer maize // soybean
X	Highland barley, wheat, pea, potato	Rape	Mono-cropping annually	Spring highland barley → winter highland barley; spring rape → spring wheat → spring rape → fallow; pea → spring highland barley → spring rape → potato → fallow; spring highland barley → spring wheat (naked oat) → pea (rape) → fallow

[a] Region numbers are the same as in Fig. 23.1 (see Glossary for botanical names of crops)

[b] Spring maize/soybean or springmaize/legumes refer to intercropping. Crops in brackets indicate alternatives. Alternative rotations are separated by semicolons

The northern rainfed farming regions include arid, semi-arid and drought-prone sub-humid areas, cover 16 provinces with total arable land of 33 million hectares (Li 2004; Luo 2004; Gong 1999). The southern rainfed farming regions, that include areas with a tropical and subtropical climate, cover 14 provinces with total area of 15.2 million hectares (Huang 1995).

Productivity of rainfed agriculture in the northern rainfed regions especially in the far north, is low and precarious, and is characterised by frequent drought, fragile natural ecosystems and socio-economic constraints. Severe water deficits result from low total rainfall, (with about 70% falling between June and September), irregular distribution, and high rates of evaporation in summer.

The semi-arid Loess Plateau is the most important region of rainfed agriculture (Wei and Wang 1999), and rainfed agriculture remains the most widespread land use system, occupying 80% of the total cultivated land area (Shan 1994). The remainder of this chapter will focus on the Loess Plateau region.

23.3 Characteristics of Rainfed Farming Systems in the Loess Plateau of China

23.3.1 Climate, Soil and Topography

Most of the Loess Plateau is covered by deep loess soil dissected by eroded gullies. The sparse vegetation has a much lower proportion of forest cover than the average of the whole country (Niu and Liu 2001). The pasture area is vast and is dominated by a number of indigenous plant species that are found in arid and semi-arid regions, with a few high-quality steppe and meadow species. Most of the pasture land has been moderately or severely degraded in recent years (Ding 2001).

The Loess Plateau has a typical continental monsoonal climate, with most of the rain falling in summer and early autumn (June to September) (Table 23.4). The quantity of heat units in the Loess Plateau is less than in North China, but is sufficient for

Table 23.4 Mean rainfall (mm) of each season and its percentage of the total annual rainfall in several typical sites of the semi-arid Loess Plateau of Gansu (Wei and Wang 1999)

	Spring rainfall (Mar–May)		Summer rainfall (Jun–Aug)		Autumn rainfall (Sep–Nov)		Winter rainfall (Dec–Feb)		Annual rainfall (Jan–Dec)
Sites[a]	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)
Gaolan	47	19	144	58	56	22	3	1	249
Lanzhou	66	21	171	54	75	24	5	2	316
Dingxi	90	22	215	53	102	25	8	2	415
Huanxian	81	18	237	53	123	27	9	2	449
Qinan	102	20	250	50	137	27	14	3	503
Xifeng	115	20	281	49	165	29	14	2	574

[a] See Fig. 23.2 for location of each site

successful annual cropping. As topography rises from south-east to north-west, there is decreasing influence from the south-east monsoon, and a clear transition from a sub-humid to a semi-arid climate (Chen 1998). Rainfall varies greatly from year to year.

The loess soils are deep, free-draining and able to store considerable plant-available water. However, a combination of low clay content and intensive cultivation has resulted in low levels of organic matter, structural instability (encouraging erosion) and nutrient fertility (Zhu 1983). The adverse effects of serious soil erosion in the Loess Plateau have led to fragile agricultural systems with low and variable crop yields.

23.3.2 Crop Production Potential

The low annual rainfall (300–600 mm) cannot meet the potential crop requirements for water as determined by the productive capacity of light and heat. This leads to relatively low and erratic grain yields (Table 23.5) (Hu and Huang 1991). Crops in rainfed farming yield 43–67% and 10–20% of those on the irrigated farmland in the south-east and north-west respectively (Hou and Liu 1991). Although light intensity and duration are sufficient, heat energy is moderate, and soil fertility can be improved as required, soil water from limited rainfall is the main constraint for crop production in the Loess Plateau.

The data in Figs. 23.3 and 23.4 show wheat production potential in different regions of the Loess Plateau from 1968 to 2000. Estimations are based on the Food and Agriculture Organisation (FAO) calculations (see Table 23.5 for further details). The results indicate higher variation of the yield potential when rainfall is included than when only solar radiation and temperature are used (Zhao et al. 2003). This illustrates that crop yield potential is primarily determined by rainfall.

23.3.3 Structure and Operation of Rainfed Farming Systems in the Loess Plateau

Most farms in the Loess Plateau are operated by farm families, and the average family farm area ranges from 0.7 ha to 1 ha. Mixed crop–livestock farming systems

Table 23.5 Crop potential productivity in the Loess Plateau (t/ha) (Hu and Huang 1991)

Crop potential productivity based on:	Wheat	Maize	Potato	Millet
Solar radiation	8.5[a]	11.8	13.8	14.3
Radiation and temperature	7.0	7.5	9.4	8.0
Radiation, temperature and precipitation	4.4	3.8	4.7	5.7

[a]Crop potential is determined using calculations in endnote 1 (Hu and Huang 1991; Li 1988; Doorenbos and Kassam 1979)

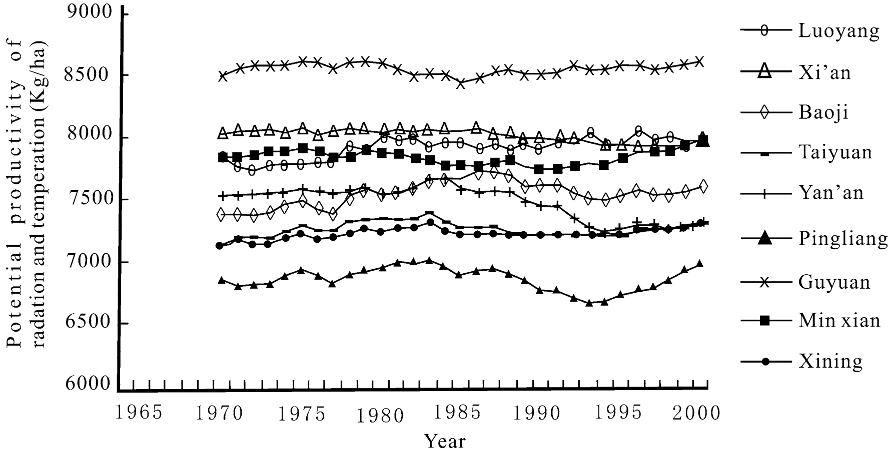

Fig. 23.3 Crop yield potential as a function of combined radiation and temperature at different locations on the Loess Plateau of China during 1960–2000 (see Fig. 23.2 for location of each site) (Zhao et al. 2003)

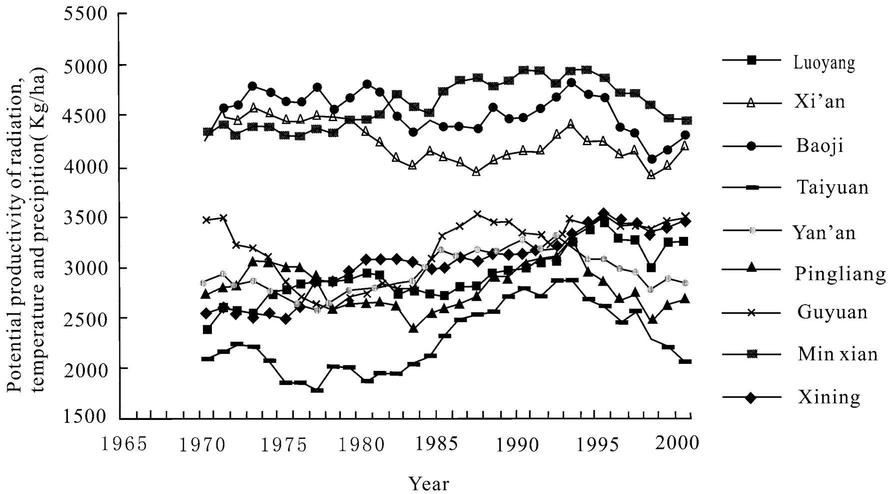

Fig. 23.4 Crop yield potential as a function of combined radiation, temperature and precipitation at various locations in the Loess Plateau during 1960–2000 (see Fig. 23.2 for location of each site.) Mean annual rainfall (mm) for the sites: Luoyang 610, Xi'an 600, Baoji 668, Taiyuan 466, Yan'an 520, Pingliang 644, Guyuang 400, Min xian 600, 360 mm Xining 360 (Zhao et al. 2003)

are prevalent – over 80% of farms have livestock (Nolan et al. 2008). The dominant crops grown are winter wheat in the eastern part of the Loess Plateau and spring wheat in the western part. Once household grain production is satisfied, remaining land is allocated to cash crop and livestock production to generate farm income. Inputs for crop production include fertilisers (organic and inorganic), seed, pesticides, herbicides and, in some cases, plastic mulch for soil water conservation.

The average input cost of production for the main crops (winter wheat, spring wheat, maize, soybean and field pea) is from 60 to 200 $US/ha depending on crop type (Nolan et al. 2008). Machinery is gradually replacing draft animals and human labour for farm operations such as planting and harvesting.

Rainfall is summer-dominant in all parts of the Loess Plateau and often occurs as intense thunderstorms which cause severe soil erosion. Soil erosion and low water availability are two major constraints for crop production.

The **eastern** part of the Loess Plateau comprises hills, ravines and flat land, receiving 400–550 mm of annual rainfall. Rainfed annual single cropping systems are widely used in this region, with the major crops being winter wheat, maize, millet and sorghum. Winter wheat is sown in late September and harvested at the end of June or in early July. Maize, millet and sorghum are all sown in late April and early May and harvested in late September.

The **western** part of the Loess Plateau is characterised by hilly land and 350–480 mm of annual rainfall. The main farming system is rainfed annual single cropping with the cereals (spring wheat, naked oat, highland barley, millet, buckwheat and maize), lablab and some cash crops of rape, pea, linseed and potato.[1] The region historically has limited grain supply, especially in the central Gansu, and many farmers are unable to provide for their own subsistence grain needs.

The **southern** part of the Loess Plateau consists mainly of flat loess land with a semi-humid climate, receiving 530–620 mm annual rainfall. The farming systems are dominated by rainfed annual single cropping and biennial triple cropping (three crops over 2 years) with an agro-pastoral combination. Winter wheat is the main crop, accounting for 49% of total cropping area, followed by maize and soybean (for livestock feed). Rape is the main cash crop and the area grown is increasing rapidly. Quick-maturing crops such as millet and buckwheat can also be grown after the winter wheat is harvested.

The **northern** part of the Loess Plateau is composed of hilly land with a sandy loess soil, receiving about 400 mm of annual rainfall. Erosion losses of water and soil are severe. Rainfed annual single cropping is the common cropping system, as a wheat–fallow rotation, because of the low annual rainfall.

In summary, crop yield potential in the Loess Plateau is primarily driven by annual rainfall and its distribution. Development of technologies for improving crop water use efficiency is critical for sustainable crop production.

23.4 Management for Productivity and Sustainability of Rainfed Farming Systems in the Loess Plateau

The rainfed farming systems in the Loess Plateau are classified into two main types depending on annual rainfall: (1) the northern rainfed farming system occurring in semi-arid and sub-humid areas, and (2) the southern rainfed farming system in hilly

[1] See Glossary for botanical names.

regions with high but variable rainfall. Water shortages resulting from inadequate rainfall in the north and water losses from runoff in the south require development of different rainfed farming systems. In the north, crop water use efficiency (WUE) could be improved by crop genetic improvement, better agronomic management and soil water conservation technologies. In the south, crop WUE could be improved by reducing runoff and soil erosion using both engineering and agronomic means. Water use efficiency (WUE) is defined in this chapter as grain yield per unit of evapo-transpiration (ET) per unit of area[2] i.e. kg/mm/ha. Assuming runoff and deep drainage to be negligible in most rainfed flat cropping land situations, ET is defined as the amount of rainfall over the period between sowing and harvesting the particular crop plus or minus the change in soil water storage in a 2–3 m soil profile.

23.4.1 Crop Improvement

Higher yield and WUE can be achieved through crop breeding to produce cultivars with drought-resistant traits – including improved transpiration efficiency, rooting depth and osmotic adjustment. Improved transpiration efficiency has been shown to increase yields by up to 40% in wheat grown at low-rainfall sites (Condon et al. 2002; Richards 2006). Genotypes with high transpiration efficiency usually grow more slowly because of reduced stomatal conductance at the vegetative growth stage, thus conserving more soil water for later use. This is beneficial if wheat is grown partly on stored moisture from summer rainfall. As the wheat grows, genotypes with deeper roots can extract more water down the soil profile. Osmotic adjustment in wheat has been demonstrated to be under the control of a single or major gene. It can increase yields in water-limited environments by increasing water uptake from deeper in the soil profile (Morgan and Condon 1986).

In the Loess Plateau of Gansu, drought-resistant wheat Dingxi-8275 improved WUE by 2.6 kg/mm/ha and yielded up to 40% more than the local Hongmang variety (Shag et al. 1999). In east Gansu, new drought-resistant varieties increased yields by between 7% and 110% (Zhang et al. 2000; Xie et al. 2005). The drought-resistant maize Hanyu 5, bred by Shanxi Academy of Agricultural Sciences, can be sown to a depth of 20 cm (making full use of deep soil moisture and nutrients) and in dry years (with less than 300 mm annual rainfall) it still can yield 8.7 t/ha (Wang et al. 2004). Zhang et al. (2005) found that, in China, WUE was improved by 10–15 kg/mm/ha for winter wheat and by 14–20 kg/mm/ha for maize – through increased kernel numbers per unit area rather than weight of the kernels in both crops.

[2] See Chap. 1 for detailed explanation.

23.4.2 Land Management and Changing Farming Systems

The main land management systems in China are irrigated terraces in the south and non-irrigated terraces on the Loess Plateau (Bray 1984). The benefits of terraces include: (1) easier cultivation in hilly topography; (2) water retention and erosion prevention, for example in Shaanxi province, terraces can reduce runoff of water and silt by about 90%; (3) retention of plant nutrients in the soil.

Because of improved availability of water and nutrients, yields from terraced land are substantially higher than those from sloping land. In Gansu Province, terraces increased yields by an average of 25% (Zhao 1995). However, it may take a few years from the construction of terraces for these benefits to eventuate.

Management options for improving productivity, WUE and sustainability of rainfed farming systems include adjusting the proportion of each crop in a rotation. This may be achieved by increasing the use of crops and cultivars with higher WUE, using perennial legumes with broad ecological adaptation in rotations, and integrating cropping systems with livestock production.

An example of the development of a more sustainable farming system is in Lumacha, a small catchment region located in Dingxi County of the south-eastern part of Gansu with hilly loess soils and initially, typical rainfed farming systems (Huang et al. 1997). In 1983, integrated best crop management practices were proposed for the use of fertiliser and soil water. Over the next 3 years, as crop yields increased, more sloping, cropping land could be 'retired' to grassland to reduce soil erosion and improve farm income through livestock production. The proportion of land used for cropping was halved, and that for forestry and animal husbandry increased from 10% to 60% (Table 23.6) (Hu 1997; Hu et al. 2002; Luo 2004).

Soil erosion was reduced significantly as the area under terracing increased from 126 ha to 152 ha, conservation tillage was adopted and the area under forest and grass increased from 5% to 46%. The application of chemical fertilisers with manure improved soil fertility markedly, and soil organic matter increased from 0.7% to 1.4%(Hu 1997). Grain yield on terraced areas averaged 1.8 t/ha over 1987–1991, being 310 kg/ha higher than the average over 1983–1986. For the same time periods, grain yield per capita increased from 424 to 567 kg, and net income per capita (per person in a family) improved as well (Table 23.7).

23.4.3 Crop Rotations

Previous studies in the regions of the Loess Plateau have demonstrated that crop rotation practices play an important role in improving WUE and crop yield in water-limited semi-arid and sub-humid environments (Peng 2000a; Li 1998; Li et al. 2000b, 2002; Huang et al. 2003a, b).

A long-term rotation study comparing 16 alternative rotations with continuous wheat cropping was conducted in Gansu province, north-west China (Li et al. 2000b).

Table 23.6 The outcome of changing farming systems, developing terraces and better managing crop inputs on crop yield and farmers' income in the Case Study conducted in the Lumacha village, Gansu, China (Hu 1997)

Item			1983	1984	1985	1986
Arable land (ha)			513	483	391	385
Terrace land (ha)			126	134	142	152
% of total area	Arable land		42	36	32	31
	Grass land		4	12	33	33
	Forest		1	6	11	13
	Wasteland		40	32	11	9
	Other		14	14	14	14
Animals (head)	Large domestic animals		247	315	385	400
	Pigs		365	445	528	550
	Sheep		594	242	316	300
	Hens		12,155	13,436	17,000	20,005
Input	Chemical fertiliser	N	4.5	6.0	6.0	19.6
(kg/ha)		P	0.8	4.5	6.0	18.0
	Manure	N	13.5	19.5	22.5	24.0
		P	7.5	12.0	12.0	15.0
		K	15.0	22.5	25.5	27.0
Grain yield (kg/ha)			1,110	1,343	1,608	1,806
Income (¥ per capita)			100.13	130.13	265.44	301.00

Table 23.7 The impact of increased terracing on crop yield and farmers' income over time in the Lumacha village, Gansu, China (Hu 1997)

	1987	1988	1989	1990	1991
Arable land (ha)	385	385	385	370	367
Terrace land (ha)	162	173	189	215	237
Grain yield (kg/ha)	1,437	1,428	1,898	2,091	2,052
Grain yield (kg per capita)	424	403	542	581	567
Income (¥ per capita)	315	484	515	518	586

For each rotation, grain and biomass yields were determined for each crop first, and then grain yield for a given entire rotation. WUE, expressed as yield per unit evapotranspiration (ET[3]) was first calculated for each crop of the rotation system, and then the value for each entire rotation was determined based on the data of individual crops. Runoff was estimated using a simple model and percolation loss below 2 m was assumed negligible in the study area. The results showed that the 16 alternative rotations produced consistently and significantly higher ($P<0.05$) grain yields and WUE than continuous wheat cropping (Table 23.8). Similar results were also reported in the other long-term (1984–1996) field study conducted on the Loess Plateau (Huang et al. 2003b).

[3] Defined earlier.

Table 23.8 Comparisons of averaged annual yield and WUE between the 16 distinct rotational systems and continuous wheat cropping in Xifeng, Gansu (Li et al. 2000b)

Rotation	Grain yield (t/ha)	WUE (kg/ha/mm)
Wheat monoculture	3.85	9.4
Maize–maize–wheat	5.70	13.4
Maize–potato[a]–wheat	6.70	15.6
Maize–soybean–wheat	4.44	11.0
Maize–millet–maize	6.19	15.7
Maize–maize–millet	6.24	16.7
Maize–potato–soybean	5.89	15.9
Maize–soybean–maize	5.77	15.4
Maize–millet–potato	5.64	15.0
Potato–potato–soybean	5.53	15.7
Potato–maize–millet	6.11	17.2
Potato–soybean–maize	5.46	15.3
Potato–millet–potato	5.56	15.5
Millet–millet–maize	5.52	15.6
Millet–maize–potato	5.53	15.7
Millet–potato–soybean	5.79	16.6
Millet–soybean–millet	4.82	14.4

[a] For this calculation 5 kg fresh potatoes =1 kg grain yield

Potential use of environmental resources (i.e. rainfall, temperature and solar radiation) for alternative rotations and continuous wheat cropping was evaluated by comparing their relative resource use, which is expressed as a percentage of growing season rainfall, accumulated temperature above 5°C and solar radiation relative to annual values (Li et al. 2002). The relative resource use of the seven selected alternative rotations was 35%, 28% and 18% higher than that of continuous wheat cropping for rainfall, temperature and solar radiation, respectively. However, the economic returns from these selected rotations for farmers depend on profit margin of each crop in the rotations, which can vary significantly depending on government policies and market demand.

23.4.4 Plastic Mulching[4]

Soil evaporation is an important cause of low crop WUE. With a wheat cropping system, water loss through direct soil surface evaporation can account for 40% of the total annual rainfall. Thus plastic mulching (using plastic sheeting) should

[4] The plastic mulch is usually placed on the ridge to help rain water flow into the ditch where the crop is planted and grown.

Table 23.9 Effects of plastic mulching on plant available soil water, grain yield and water use efficiency (WUE) of winter wheat and maize in the long-term study (1997–2003) of Zhengyuan, in Gansu, China (from data in Fan et al. 2005b)

	Wheat			Maize		
Variable	W1	W2	W0	C1	C2	C0
PAWC[a] at planting, to 2 m depth (mm)	123.4a[b]	61.7b	61.7b	91.3a	54.6b	55.1b
Evapotranspiration (ET) (mm)	416.5a	380.4b	384.3b			
Grain yield (t/ha)	4.74a	3.73b	3.04c	10.00a	8.19b	6.20c
WUE (kg/ha. mm)	11.3a	9.8b	7.7c	24.8a	19.4b	15.2c

[a] Plant available soil water content

[b] Means within a row followed by the same letter within a crop are not significantly different ($P \leq 0.05$). W0 – no plastic cover, W1 – plastic applied to the soil surface in early August, W2 – plastic applied in mid-September, C0 – no plastic cover, C1 – plastic applied to the soil surface in early November, C2 – plastic applied in mid-April

significantly reduce evaporation, enhance soil water storage and improve crop WUE. The plastic mulch is usually placed on the ridge and the crop planted in the ditch (Mu et al. 2000). For maize, plastic mulching improved WUE by 42–65% and yield by 66–100% (1.5–2.25 t/ha) (Peng 2000b).

Highly significant effects of different plastic treatments were obtained on grain yield, WUE and plant available soil water content (PAWC) at planting, for wheat and maize (Table 23.9). The study clearly showed that covering the soil surface with plastic mulch can greatly enhance soil water storage and increase maize and wheat yields (Table 23.9). The higher yields obtained with plastic mulch are due to higher amounts of plant available water at sowing and more effective use of stored soil water due to prevention of soil evaporation by the plastic (Fan et al. 2005b).

Plastic mulching has been used widely for crops and vegetables in China because of its benefits in improving soil water and soil temperature. There have also been economic benefits to farmers using this technique. For example, in Weiyuan, Gansu, 60 kg/ha of plastic mulch costs 600¥/ha but could increase yield of corn by 3.5 t/ha and returns by 4,317¥/ha, (Cheng 2006). However, plastic fragments in soils are slow to degrade, and it is estimated that 105 kg/ha mulching plastic remains in the soil (Li 2004), this can lead to hard-setting soil and environmental pollution. Stubble retention would be preferable to plastic mulching.

23.4.5 *Conservation Tillage*

Over the last several decades, Chinese scientists have studied and promoted conservation tillage systems. In the Northeast Shanxi Province (Tunliu and Shouyang), minimum tillage and no-tillage with stubble retention increased precipitation storage by 25–30% and yield by 20–50%. Similarly, minimum tillage with stubble retention and no-tillage with stubble retention enhanced rainfall storage by 25–30% in

Heyang, Shanxi Province (average annual rainfall of 550 mm). In the 8-year wheat and 5-year maize experiments, crop yields were 7.1 t/ha for wheat and 8.6 t/ha for maize, which are 73% and 76% higher respectively than from conventional tillage with no stubble (Wang et al. 2004).

The Australian Centre for International Agricultural Research (ACIAR) project ‘Improving the productivity and sustainability of rainfed farming systems for the western Loess Plateau of Gansu province’ has been implemented in Gansu Province since 2001 (Huang et al. 2003a, b). Its aim has been to evaluate potential benefits of conservation tillage in improving crop water use and yield in spring wheat–field pea rotation systems. The experimental treatments are detailed in Table 23.10. Results for grain yields and WUE are summarised in Table 23.11.

Grain yields. For spring wheat, the treatment with plastic cover produced higher grain yields than the non-plastic treatments in some years. Without plastic, the

Table 23.10 Details of treatments used in the ACIAR long-term conservation tillage experiment in Dingxi, Gansu (Huang et al. 2003a, b)

Code	Treatments	Description
T	Conventional tillage with no straw	Fields were ploughed 3 times and harrowed twice after harvesting. The first ploughing was in August immediately after harvesting, the second and third ploughing were in late August and September respectively. The plough depths were 20, 10 and 5 cm, respectively. The field was harrowed after the last cultivation in September and again in October before the ground is frozen. This is the typical conventional tillage practice in the Dingxi region.
TS	Conventional tillage with straw incorporated	Fields were ploughed and harrowed exactly as for the T treatment (3 passes of plough and 2 harrows), but with straw incorporated at the first ploughing. All the straw from the previous crop was returned to the original plot immediately after threshing and then incorporated into the ground.
NT	No-till with no straw cover	No-till throughout the life of the experiment. The straw was removed from the field and used as fuel or feed.
NTS	No-till with straw cover	No-till throughout the life of the experiment. The ground was covered with the straw of previous crop from August until the following March. All the straw from previous crop was returned to the original plot immediately after threshing.
TP	Conventional tillage with plastic mulch	The field was ploughed and harrowed exactly as for T treatment (3 passes of plough and 2 harrows), but covered with plastic after the last harrow in October. Plastic film was laid out between crop rows and the covering belt width (the width of the ridge) was 40 cm.
NTP	No-till with plastic mulch	No-till throughout the life of the experiment. The plastic film was laid out in October using same machine as for TP treatment. To avoid damage to the plastic film, the crop residue was mown after harvesting.

Table 23.11 Effects of different tillage and stubble management treatments on crop water use efficiency (WUE) and crop grain yield in Dingxi, Gansu (Huang unpublished data)

			Treatment[a]					
Variable	Crop	Year	T	TS	NT	NTS	TP	NTP
Grain yield (t/ha)	Spring wheat	2002	1.81b	1.75b	1.41c	2.15a	1.39c	1.26c
		2003	1.42d	1.65 cd	1.55d	1.83bc	2.03ab	2.14a
		2004	2.19b	2.16b	1.66c	2.38ab	2.63a	2.17b
	Field pea	2002	1.65ab	1.53bc	1.42c	1.79a	1.61ab	1.53bc
		2003	0.88bc	0.82c	0.80c	1.27a	1.06b	1.02b
		2004	1.71a	1.68a	1.50a	1.67a	1.76a	1.51a
WUE (kg/ha/mm)	Spring wheat	2002	6.9b	6.5b	5.8 cd	8.1a	5.6 cd	5.1d
		2003	4.8d	5.8c	5.6 cd	6.2bc	7.0ab	7.4a
		2004	7.8ab	7.9ab	6.4b	7.8ab	9.0a	7.7ab
	Field pea	2002	9.0ab	8.5b	8.3b	9.9a	9.0ab	8.8ab
		2003	5.0 cd	4.7d	4.7d	6.7a	6.0ab	5.7bc
		2004	8.6ab	8.6ab	7.7b	8.0ab	9.4a	7.7b

Different letters in the same row represent significant difference at $p \leq 0.05$ between treatments in same year

[a]Refer to Table 23.10 for the details of each treatment

no-till, stubble retention treatment yielded significantly higher than the other treatments in all 3 years. Field pea showed similar trends to wheat, except that in 2004, grain yields were similar in all treatments of the experiment. In the lower rainfall year (2002), no-till with stubble retention gave similar pea yields to conventional tillage.

WUE. WUE was usually significantly higher, for both wheat and peas, under the plastic cover with tillage treatment than for other treatments. However, no-till with stubble retention was generally the best treatment increasing grain yield by 27%, WUE by 27% and the ratio of output to input by 68% compared with the conventional tillage (Huang et al. 2003a, b; 2006; Li et al. 2005).

While no-till was not consistently superior to plastic mulching for improving grain yield and WUE, it may be as effective as plastic cover in rainfall-limited regions by directly reducing soil evaporation and conserving soil water. Improvements to winter wheat yield and water use efficiency using a no-till system were also reported in a long-term (1999–2005) experiment conducted in the eastern part of the Loess Plateau (Su et al. 2007).

23.4.6 Soil Fertility Management

Low soil fertility often limits crop yield in the rainfed farming systems of the Loess Plateau. Better fertiliser management is critical to optimising WUE in water-limited environments. Shan (1996) reported that, for wheat in rainfed farming systems, WUE improved from 8 to 9 kg/mm/ha in low-fertility soils to 15 kg/mm/ha in high-fertility soils.

Table 23.12 Grain yield and WUE in the long-term (1979–2002) fertiliser experiment in Pingliang, Gansu, China (from data in Fan et al. 2005a)

	Wheat[a]		Maize[b]	
Treatment[c]	Grain yield (t/ha)	WUE (kg/ha/mm)	Grain yield (t/ha)	WUE (kg/ha/mm)
CK	1.29	3.2	2.29	4.7
N	2.36	5.7	3.02	6.3
NP	3.87	9.9	4.75	10.0
SNP	4.15	10.8	4.75	10.2
M	3.54	9.1	4.39	9.4
MNP	4.71	12.2	5.61	11.9

[a]Mean annual grain yield of 16 year of wheat and associated WUE
[b]Mean annual grain yield of 6 year of maize and associated WUE
[c]CK–unfertilised; N–nitrogen fertiliser annually; NP–N and P fertiliser annually; SNP–3.75 t/ha wheat straw (S) plus N (90 kg N/ha as urea) added annually and P (30 kg P/ha as superphosphate) added every second year; M–farmyard manures added annually (75 t/ha) as a mixture of manures (pig and cattle) with loess soil (the ratio of manure and soil is 1:5); MNP–farmyard manures plus N and P fertiliser added annually

A long-term fertiliser experiment was conducted from 1979 at Pingliang, Gansu, China. The data for the 16 years of wheat and 6 years of corn are summarised in Table 23.12. Fertilisers (N 90 kg N/ha, P 30 kg P/ha and M, manure 75 t/ha) improved grain yields significantly for both crops, being consistently highest in the MNP treatment and lowest in the unfertilised control treatment. Grain yield in the nitrogen-only treatment was consistently lower than the M and NP the treatments (Fan et al. 2005a).

The trend in WUE was similar to that of grain yield, thus correcting crop nutrition limiting factors with the combined application of N, P and organic materials resulted in the most efficient use of soil water (Table 23.12) (Fan et al. 2005a). The study also indicated that the application of manure should be combined with inorganic fertilisers to maximise crop productivity, WUE and agricultural sustainability (Fan et al. 2005a).

In rainfed cropping systems, soil water status also needs to be considered and closely monitored when designing and implementing best fertiliser management practices. For example, in a 15-year experiment with four fertiliser treatments (control, manure only, NP, NP plus manure) in the Changwu of the Loess Plateau, increased chemical fertiliser and farmyard manure inputs in the continuous wheat cropping system resulted in depletion of soil water down the soil profile to 300 cm. Therefore when the depleted deep soil water could not be replenished through rainfall, wheat yields could be affected, particularly in dry seasons (Huang et al. 2003a).

One of the important limiting factors affecting grain crop yield and water use efficiency in the Loess Plateau of China is low soil fertility. The above examples reveal that correcting major nutrient deficiencies (such as N and P) is critical for maintaining high yield and water use efficiency. When designing and implementing best fertiliser practices, manure application should be integrated with the use of chemical fertilisers. Furthermore, avoiding soil water depletion, particularly to depths below 300 cm through regulation of nutrient inputs also needs to be considered. With varying seasons, sustainable use of soil water for crop production may be achieved by varying fertiliser rates to match soil water availability. This would also require quantifying plant available water capacity of soils and splitting applications of fertiliser (such as N) in response to seasonal conditions and yield potential.

23.4.7 Rainwater Harvesting Agriculture

Harvesting rainwater involves the collection and storage of that part of the rainy season precipitation that would have been lost through deep drainage or run off into streams. It is an old technique that was probably developed as early as 4500 BC (Bruins et al. 1986; Cullis and Pacey 1992; Frasier 1985; Lavee et al. 1997). Although earlier rainwater harvesting systems were designed primarily to meet domestic needs for water, in recent years scientists in many parts of the world such as Sub-Saharan Africa, the Middle East and South-east Asia, and especially India, have made efforts to design and develop a wide variety of techniques to collect, store, and use natural precipitation for agricultural purposes (Agrawal and Sunita 1997; Li et al. 2000a). China has a long history of rainwater harvesting techniques in many water-limited areas such as the Loess Plateau, dating back to the Qing and Han Dynasties 2,000 years ago (Zhao et al. 1995). While it enabled people to survive in drought-prone environments, the water yield from early rainwater harvesting techniques is not sufficient for agricultural purposes. Rainwater harvesting agriculture (RHA), which was first developed by scientists in Gansu province in the mid-1980s, is an integrated system for water management on rainfed land in semi-arid areas (Cook et al. 2000; Li et al. 2000a). This system consists of three main components: rainwater harvesting, water-saving for irrigation, and effective crop production management (Fig. 23.5).

The system can provide farmers in water-limited regions with access to water for domestic and agricultural water purposes. For an average farm in Gansu, potentially, about 10% (or 0.1 ha) land could be irrigated with this method if developed properly. The preliminary implementation of RHA in Gansu and other provinces in northwest China suggests that it has the potential to improve performance in rainfed farming systems.

A series of field experiments with application of RHA system have demonstrated the effectiveness of limited irrigation for improving crop yield and water use efficiency (Kang et al. 2002; Luo and Robinson 2005; Fox and Rockstrom 2000; Li et al. 2004; Li 1998). For example, a field study was conducted in the semi-arid region of Dingxi, Gansu Province, on the effects of supplementary irrigation with harvested rainwater on grain yields of three main crops (spring wheat, corn and millet). When spring wheat was irrigated (45 mm) once in the jointing stage, it yielded 37% higher than the unirrigated spring wheat; when spring wheat was irrigated twice in both the jointing and heading stages, it yielded 50% higher than the

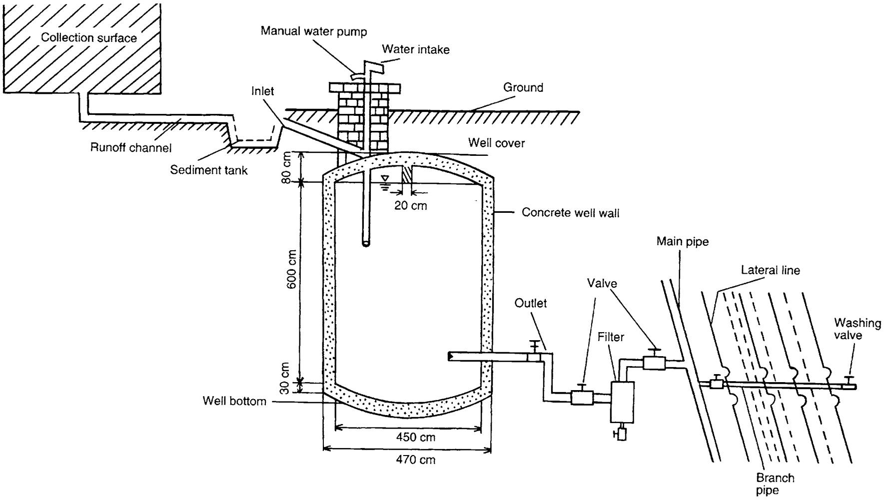

Fig. 23.5 A schematic diagram showing the small-scale rainwater harvesting system being widely used by small scale farmers in semiarid areas of Gansu province (Li et al. 2000a)

unirrigated control (Li 1998). Another field experiment with four cultivars of corn receiving supplementary irrigation (75 mm) during the grain filling stage yielded between 20% and 90% higher than the unirrigated crops (Li et al. 2000a). Wheat yield and water use efficiency could be further improved if limited irrigation is combined with straw mulching to reduce soil evaporation (Huang et al. 2005).

However, to be successful, RHA needs to be integrated into a comprehensive agricultural management system with suitable crop varieties and rotations and an irrigation system. Spreading RHA over large areas would involve a range of technological, hydrological, ecological, social, cultural, economic and institutional factors. In particular, there is a need to provide extension services and training for farmers, to assist them to adopt more effective and affordable types of RHA technologies, and to design and develop alternative government policy that can facilitate adoption of RHA practices.

23.5 Conclusions, Challenges and Future Prospects in the Rainfed Farming Systems of Loess Plateau of China

23.5.1 The Current Situation and Challenges

Farmers have accumulated much practical experience which, combined with modern science and technology, will ensure the improvement of profitable rainfed farming systems in the Loess Plateau. However, there are many challenges.

Low and variable rainfall along with periodic drought continue to be the major constraints in rainfed farming systems and the associated rural economy. The efficient use of water will continue to be a priority.

A good agro-ecosystem is characterised by a rational structure, complete function, high performance, and sustainable productivity. However, in the Loess Plateau, overpopulation has resulted in over-cultivation and a transfer of considerable areas of grassland to arable agriculture. This has unbalanced the ratio of cropping, forestry and animal husbandry. Destruction of the natural vegetation not only speeds up soil erosion, but may also has a negative influence on climate, resulting in more frequent drought. Thus, production systems are in a vicious circle characterised by the adage "the poorer the farmer, the more cultivated land; the more cultivated land, the poorer the farmer".

23.5.2 Future Prospects

With the current population explosion and economic development in China, there is urgent need to improve crop production per unit of area while maintaining the health of farming systems – including rainfed farming systems in the Loess Plateau. The key to developing healthy farming systems is better matching economic and social development with the region's natural resources This should enable high production and profitability to be achieved while conserving the resource base of soil, and water, and achieving a balance of cropping, grasslands, forests and native fauna and flora.

23.5.2.1 Integrated Livestock-Cropping Systems

Productive forages/pastures are the foundation for the development of animal production. Appropriate use of forage grasses and legumes could effectively link animal production with cropping through providing feed for livestock production, increasing soil nitrogen and organic matter, improving soil structure and reducing soil erosion. Animal production in China accounts for less than 30% of agricultural production. In rainfed farming systems in the Loess Plateau, planting more forages could improve land utilisation, rainfall utilisation and biomass production by up to 40%, and this could lead to significant improvement in agricultural production efficiency (Huang 2006). Establishing forages and integrating animal production with crop production will be two of the important options for China's rainfed farming systems.

With the integration of cropping and animal production, multi-level use of by-products can be made more efficiently. For example, a proportion of the straw produced in rainfed cropping systems could provide feed for livestock. Animal manure may be used to improve soil fertility for crop production (Huang 2006). Integrating cropping with animal production can not only make full use of by-products but also enhance the productivity and sustainability of the whole farming system.

23.5.2.2 Water Saving Agriculture

As water is the major limiting factor for crop production in rainfed farming systems, utilisation of as much of the growing-season rainfall as possible is critical for improving crop yield. With the development of rainwater harvesting technologies, WUE can be improved greatly by collecting rainfall runoff to provide supplementary irrigation to crops during the water-stress period. Farmland area in China has been reduced due to the population explosion and increased urbanisation. As a result, food security can only be achieved by improving the output per hectare of arable land. A key to increasing crop yield in rainfed farming system is to make best use of limited water by adopting water-saving agricultural technologies.

23.5.2.3 Conservation Agriculture

Conventional rainfed farming systems in the Loess Plateau are characterised by intensive cultivation and deep tillage, and long periods when the soil surface is bare. This has resulted in soil erosion, loss of soil organic matter and loss of production. When compared with conventional tillage, no-till can save time and costs while increasing potential productivity. 'Three times plough and two times harrow' after harvesting is the conventional tillage practice in the Loess Plateau of northwest China, which is gradually being replaced by conservation tillage. Lower production costs and more stable yield are possible if there is a wide adoption of conservation agriculture. However, instability of crop yields is a characteristic of rainfed farming systems that cannot be avoided in either traditional or conservation-type rainfed agriculture.

As indicated earlier, continuous development of technologies to improve crop water use efficiency is a key to sustaining long-term crop production in the Loess Plateau of China. Such technologies include crop improvement, efficient land management, sustainable farming systems through smart crop rotations, better management of soil fertility, adoption of conservation tillage and rainwater harvesting. In the face of the challenges from the current population explosion, degradation of limited natural resources and the uncertainty of future climate, developing integrated crop–livestock systems, and adoption of water saving and conservation agriculture technologies are critical for sustaining crop production and increasing farm income on the Loess Plateau of China.

23.6 Conclusion

The Loess Plateau is the most important region of dryland farming in China. Most of the Loess Plateau is covered by deep loess soils with sparse vegetation and dissected by eroded gullies. The Plateau has a typical continental monsoon climate with most rainfall falling from June to September. The loess soils are deep, with high plant available water holding capacity. However, they are easily eroded due to low clay content together with low organic mater resulting from continuous cropping and intensive soil cultivation. Overpopulation results in over-cultivation and degradation of natural vegetation – which speeds up soil erosion. A review of recent research and development clearly reveals that productivity and sustainability of rainfed farming systems in the Loess Plateau may be significantly improved through crop variety improvement and diversification, more sustainable land management practices, smart crop rotations, adoption of plastic and/or stubble mulching and conservation technologies, rainwater harvesting, improved soil fertility management and sustainable farming systems management. Research also suggests that developing integrated livestock-cropping systems and no-till conservation technologies are important strategies that need to be considered.

A key to developing healthy farming systems is to better match economic and social development with natural resources in the Loess Plateau of China.[5]

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[5] Endnote 1 Determination of crop potential (Hu and Huang 1991; Gao and Yu 2003; the Food and Agriculture Organization (FAO)).

1. Potential productivity of radiation: the maximum yield of the crops determined by solar radiation and in which the temperature, moisture, soil fertility and agricultural technique are optimal

$$Y_1 = CeQKG$$

e = Light use efficiency,

Q = effective solar radiation energy,

C = economic coefficient,

K = unit transform coefficient,

G = days of growth stages,

2. Potential productivity of radiation and temperature: it refers to the maximum yield of the crops determined by solar radiation and the temperature, in which moisture content, soil fertility and agricultural technique are optimal.

$$Y_2 = Y_0 \times C_L \times C_N \times C_H \times G \times A_0$$

Y_0 = total dry matter

C_L = the correction coefficient of leaf area

C_N = the correction coefficient of net dry matter

$C_{H=}$ the correction coefficient of the harvested organ

G = total days of the whole growth stages

A_0 = unit transform coefficient

3. Potential productivity of radiation, temperature and precipitation: refers to the maximum yield of the crops determined by solar radiation, temperature and precipitation, in which soil fertility and agricultural technique are optimal.

$$Y_3 = Y_2 \times \prod_{i=l}^{m} \int (i)$$

Y_2 = Potential productivity of radiation and temperature

f(i) = Influence coefficient of drought stress on grain yield in the i growth stages

m = total stages divided in the whole growth period

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Chapter 24
Farming Systems in the Valleys of Central Tibet

Current Status and Strategies for Their Improvement

Nicholas Paltridge, Jin Tao, John Wilkins, Nyima Tashi, and David Coventry

Abstract In southern central Tibet, a network of valleys with intensive agriculture has been defined as Tibet's 'crop-dominated zone'. This chapter describes current systems of crop and livestock production in this zone, and considers possible ways to boost production. Most of Tibet's 2.7 million people live in this crop-dominated zone at altitudes between 3,500 and 3,900 m and on farms of 1–2 ha. Most of the grain and animal products from these farms is consumed on farm, and incomes are low (less than US$ 1 per adult per day). Winters are cold and dry but summer and autumn provide ideal conditions for crop growth, with plentiful sunlight and warmth, reliable rainfall and the potential to irrigate much of the land. Farming systems focus on the production of spring barley and winter wheat, with small areas sown to oilseed rape, pulses, winter barley and potatoes. Mechanisation is limited; most farmers plough using draught animals, and plant, harvest and thresh by hand. Typical grain yields are 2–3 t/ha for spring barley and 4–6 t/ha for winter wheat. The raising of livestock is also important with most valley-based farmers keeping two to six cattle tethered or corralled near the household. Cattle are fed diets based heavily on crop residues and weeds, but are generally malnourished, showing low growth rates, low milk production and high rates of mortality. It is suggested that research and extension in the areas of plant nutrition, weed control,

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_24,

seeding method and crop variety could help improve grain production, and that boosting cattle production will require better supply of good-quality fodder. Cereal/fodder intercrops or double crops sown using zero-till seeders are proposed here as strategies to enable the production of useful amounts of fodder without jeopardising food grain security. Programs to boost incomes and productivity on Tibetan farms need to involve farmers at every step, to ensure activities align with farmer priorities.

Keywords Tibet • Agriculture • Crop • Fodder • Farming system

24.1 Introduction

The Tibet Autonomous Region of China (the TAR or Tibet) is best known for its towering mountains and high-altitude plateau where human inhabitants are few and nomad pastoralism is the only land use possible. Less well-known is that in southern and central Tibet there are about 230,000 ha of fertile valley floors and lower hill slopes where intensive agriculture is practiced (see Fig. 24.1). About half of Tibet's 2.7 million people live in and around these valleys (TSY 2006) at altitudes between 3,500 and 3,950 m (Tashi et al. 2002). While the winters in these regions

Fig. 24.1 The Nyachu valley, pictured in August after cereal harvest, is typical of the arable valleys of central Tibet. The Baxue Agricultural Research Station, run by the Tibet Agricultural Research Institute, is in the foreground

are cold and dry, summer and autumn provide ideal conditions for crop growth with plentiful sunlight and warmth, reliable rainfall, with the potential to irrigate much of the land.

The predominant farming system is focussed on crop production – around three quarters of the cropped area is sown to cereals, mainly spring barley[1] and winter wheat – and yields are comparable to those achieved in many of the world's more commercial cereal-growing areas. However, potential yields could be higher in this climate, given optimal management. Most grain produced is kept for family food, and only after domestic needs are met is any excess grain used for barter or sale.

Livestock are important in Tibetan agriculture, with most of the valley-based farmers keeping two to six cattle tethered or corralled near the household and fed mainly on crop residues and weeds. These animals are an integral part of the farming system as they utilise most of the by-products of the cropping operation, produce dairy products and meat, and represent a major 'asset bank' for farmers. However, by global standards, the productivity of these cattle is very low. In Tibet, milk is used primarily to make butter for butter tea or religious use and, in 2007, levels of production did not satisfy local demand.

Across Tibet, authorities are concerned about the sustainability and productivity of food production, and have developed specific goals to boost grain and dairy production, as well as rural incomes (8th TAR People's Congress 2006).

In this chapter, we summarise the important attributes of central Tibet's prevailing farming system and describe possible strategies to improve production levels and sustainability. Where possible, we use information published in the English and Chinese literature; however, given the dearth of refereed journal articles on Tibetan agriculture, we relied on unpublished data and the observations we accumulated whilst working on agricultural projects in Tibet over the period 2005–2007.

24.2 Resource Base – Human and Agroecological

The valleys of the Yalongzangpo River and its two main tributaries, the Nyachu River and the Lhasa River, constitute what has been defined as Tibet's 'crop-dominated' production zone (Tashi et al. 2002). In the main, the Yalongzangpo and its associated valley runs from west to east across southern Tibet, at elevations ranging from approximately 3,900 m in the west to 3,500 m in the east.

According to the Tibet Statistical Yearbook (TSY 2006), there are about 2.7 million permanent residents in Tibet of whom about 2.2 million are farmers, most living in and around the Yalongzangpo valley. Thus only about 20% of Tibetans are urbanised. Although large numbers of non-Tibetan migrants have moved to the TAR over the past 40 years, most settle in urban areas, and nearly all farmers in Tibet are ethnic Tibetan (Goldstein et al. 2003; Fischer 2006).

[1] Botanical names of crops may be found in the glossary at the end of the book.

Average farm size in the farming zone is between 1 and 2 ha and, under the current system of land tenure, land cannot be bought or sold. The average number of people per farming household is around seven. As a result of population growth and fixed land area, per capita land holdings have decreased by about 20% over the past 20 years. Most farming households sell only a small proportion of the crop and livestock products they produce, and are thus regarded as subsistence farmers (Goldstein et al. 2003; Dreyer 2003; Fischer 2006; Goldstein et al. 2008).

The average per capita income of rural Tibetans is around 2,000 yuan per year (TSY 2006), or less than US$1 per adult per day, putting these farmers amongst the world's poorest. Another indicator of poverty is the proportion of income expended on simple living expenses; according to the FAO, poverty is indicated if this proportion exceeds 59%. In rural Tibet, living expenses constituted 64% of total incomes in 2002 (Lu Qi et al. 2005). Further, the disparity between rural and urban incomes is marked – city-dwellers earn around four times as much as their rural counterparts (Lu Qi et al. 2005; TSY 2006). On many farms, at least half of the income received comes from off-farm sources (for example, through construction work in the cities) indicating there to be significant competition for farm labour (Goldstein et al. 2008).

The climate in the valleys of central Tibet is temperate (Leber et al. 1995). In the central reaches of the crop-dominated production zone – for example, around Lhasa – daytime mean temperatures range from around −2°C in the coldest months to 15°C in the warmest. During winter, mean minimum temperatures range from −5°C to −10°C, with daily maxima reaching 5–10°C. In summer, temperatures range from minima of 5°C to 10°C to maxima of around 20°C. Days are generally sunny, with daily percent sunshine averaging 70% across the year (Tashi et al. 2002). The higher western reaches of the zone are 1–2°C cooler and the lower eastern reaches are 1–2°C warmer.

Annual precipitation across the crop-dominated zone is in the range 400–440 mm, with most falling in June, July and August; in Lhasa, around 90% of precipitation falls in the months June to September. The main source of rainfall for the region is the summer monsoon, which brings moisture up from the Indian Ocean and the Bay of Bengal. However, as the Himalayas act as a barrier to this flow, much of Tibet is effectively in a rain shadow (Leber et al. 1995). Total precipitation from October to April is typically less than 20 mm.

Because of its high altitude, humidity in the region is generally low, annual evaporation potential is high (1,500–2,000 mm), and radiation intensity is high – with mean daily radiation at 25 MJ/m^2 across the growing season, Tibet has one of the highest radiation environments in the agricultural world.

In geological terms, the soils under cultivation in Tibet are relatively new. While uplift and mountain building processes began in the region about 55 million years ago, the alluvial fans and river terraces cultivated today are of the quaternary period. Soils are generally mildly alkaline, and are alluvial, loamy clays and clay loams with little horizon differentiation. They have low organic matter and under-developed structure. Government research work over the past 40 years has indicated that soils are generally fertile, but that nitrogen and phosphorus fertilisation is necessary to boost productivity on much of the agricultural land. Potassium is considered to be in abundant supply (Hu Sonjie 1995; Zhong Zhengchang et al. 2006).

24.3 Agriculture in the Crop-Dominated Zone

24.3.1 Crops and Rotations

According to travellers to Tibet (for example, Downs 1964), the crops that were traditionally grown in the region's central valleys were barley, wheat and oilseed rape for cooking oil. Potatoes, buckwheat, radishes, turnips and some pulse crops are also likely to have been grown, along with the legume Trigonella (*Trigonella foenum-graecum*), which was used for forage and fodder. All these crops were sown in the spring and harvested in autumn. Barley has been the predominant crop grown throughout Tibetan history. As with the barley traditionally grown in other parts of the Himalaya, most Tibetan barley is of hull-less or naked form. It is eaten mainly as parched or roasted flour (*tsampa*), and has provided the staple food for most Tibetans for millennia (Tashi et al. 2002). Most farming households also use some home-grown barley to brew barley beer (Goldstein et al. 2003). Today, most of the traditional crops continue to be grown, and spring barley continues to be predominant, although higher yielding winter wheat varieties introduced in the 1960s and 1970s have largely replaced spring wheat varieties, and small areas of winter barley are also sown. The relative areas sown to the major crops are approximately 50% barley (mostly of spring type), 20% wheat (mostly of winter type), 10% oilseed, and 15% pulses, vegetables, tubers and forages (Tashi et al. 2002; TSY 2006).

Despite relying heavily on spring barley to meet their food grain needs, Tibetan farmers have always used crop rotations to avoid build-up of pathogens and pests, and to maintain soil fertility. Traditional rotations included monocultures of spring barley – or less commonly spring wheat – followed by mixed plantings of any two of spring barley, oilseed and a legume. Some fields may have also been left fallow at the end of a rotation or sown to a monocrop of oilseed. Tuber or vegetable crops are likely to have been only minor components of these rotations with relatively small areas sown (Hu Songjie 1995). In recent years, and probably as a consequence of TAR government policy targeting self-sufficiency in grain, the emphasis in cropping has shifted towards the monoculture of spring barley and winter wheat.

24.3.2 Irrigation

Extensive use of flood irrigation has been made throughout Tibetan history, with water sourced from streams originating in mountains, or from channels that divert water from the main valley rivers. More recently, some systems using underground water have been installed.

Tashi et al. (2002) write that much gain in grain yield has been achieved over the past 40 years through the improvement and expansion of irrigation infrastructure. Available information today suggests that around 70% of cultivated land in Tibet is set up for irrigation (TSY 2006). However, Tashi et al. (2002) indicate that not all fields can be irrigated optimally, either because irrigation systems have fallen into disrepair or because of limited irrigation water. Irrigation is normally required before fields can be cultivated for either winter or spring crops, and anywhere between three and ten irrigations occur on most cropped fields.

24.3.3 Cultivation

Cultivation in Tibet has traditionally been carried out with wooden or metal-tipped ploughs pulled by yaks or other draught animals (see Fig. 24.2). Whereas the traditional wooden ploughs cultivated only to around 15 cm depth, metal-tipped ploughs cultivate to around 20 cm. Fields to be sown to spring crops are generally ploughed twice to control weeds and prepare a seed-bed. The first ploughing typically takes place directly after a first spring irrigation. Ploughed fields are then left for a couple of weeks to allow weeds to germinate before being ploughed again (Hu Songjie 1995). For winter crops, fields are generally ploughed only once, probably because weeds are not a great problem leading into winter.

Over the past decades, some farmers have started using two-wheeled, or less commonly four-wheeled, tractors to pull their ploughs, which remain single furrow and of the mouldboard type. According to Tashi et al. (2002), mechanised cultivation may have peaked during the commune era, during which large groups of farmers

Fig. 24.2 A farmer ploughing his field in the Nyachu valley of central Tibet using a single furrow plough and two yaks. He is accompanied by sheep and goats which browse the tilth for the roots and rhizomes of weeds, and presumably effect some level of weed control

would share a machine. By the mid-1990s, many agro-machines from the commune era were in disrepair and the area mechanically ploughed had dropped to 29% (Tashi et al. 2002).

Before planting, the ploughed fields are levelled, either manually with rakes or by pulling a heavy plank of wood behind a tractor or draught animal.

24.3.4 Planting

Traditionally, seed is dropped by hand in furrows formed during cultivation, or broadcast by hand then covered using rakes. This hand-sowing leads to irregular sowing depths. The area planted mechanically (i.e. using small seed drills pulled by a two- or four-wheeled tractor) was 35% in 1996, a lesser area than had been mechanically planted during the commune era (Tashi et al. 2002).

In the vicinity of Lhasa, farmers plant spring barley and winter wheat at the very high rates of 180–225 kg/ha, probably to ensure adequate plant populations despite poor seed quality, poor emergence of imprecisely placed seed or high seedling mortality.

Sowing times for spring crops range from mid-late March, in the lower-altitude areas, to mid-April in the higher reaches of the crop-dominated zone. Winter wheat and barley are sown in late September or early October.

24.3.5 Fertiliser Use

Historically, the only forms of fertiliser applied to agricultural fields were animal manures, collected from corralled animals or adjacent rangelands, and domestic waste.

Over the past 40 years, chemical fertilisers have been introduced by the TAR government and they continue to be promoted and subsidised. Indeed, in some areas, the purchase of fertiliser is compulsory (Goldstein et al. 2003). Details of what fertilisers are used and when are not accurately known (in official records, the main fertilisers are simply referred to as ‘nitrogenous’ and ‘phosphate’). However, in some areas urea and di-ammonium phosphate (DAP) are used as basal applications of at least 200 kg product/ha, with one or two follow-up top-dressings of urea at around 75 kg product/ha. Manure is still commonly spread, though a general decline in fuel-wood resources over the past 40 years has led to increased use of the dung of yak and cattle for fuel, thus reducing its availability for use as fertiliser (Zhang Rongzu 1989; Tashi et al. 2002).

24.3.6 Weed and Pest Control

Traditionally, the only weed control strategies used were cultivation, described above, and hand weeding – a practice still common today that not only helps control weed competition but also provides valuable fodder for cattle during spring and summer. More recently, the use of broadleaf, grass-selective and broad-spectrum herbicides has become commonplace, applied using backpack or hand-held spray units. However, fields remain generally quite weedy.

Research and extension work over the past 40 years has also led to the introduction of some agrochemicals for controlling pests and fungal diseases, but few details are available.

24.3.7 Harvest

Practically all grain crops in Tibet are hand-harvested using a sickle although, in some areas, machine mowers are starting to become common. The mown crop is bound into sheaves with straw before being made into stooks. These are left to dry in the field before being carted to a village threshing area where they are spread out. The crop was traditionally threshed by driving cattle over the dried cereal to separate grain and chaff from straw (Downs 1964), but tractors are now more commonly used for this task. Grain and chaff and are then swept and winnowed using a combination of pitchforks, baskets and wind (sometimes generated by an electric fan).

Winter wheat harvest time ranges from late July in the lower, eastern reaches of the cropping zone to late August in the western reaches. Winter barley is harvested about 2–3 weeks earlier wherever it is grown (the eastern half of the crop-dominated zone). For spring barley, harvest time ranges from early August in the east to late August in the west.

24.3.8 Crop Yields

According to official TAR data, wheat crops yield around 7 t/ha, barley around 5.1 t/ha (no distinction is made between spring and winter cereal types), and oilseed 2.3 t/ha (TSY 2006). However, official yields may often be over-stated, either because of inconsistencies with land and grain measurement units or inconsistent record-keeping practices.

Unofficial sources put typical farmer yields for the main cereal crops at around 4–6 t/ha for winter wheat (Panam Integrated Rural Development Project, unpublished data), and 2–3 t/ha for spring barley (Goldstein et al. 2003; Fischer 2006). These cereal yields are at least 30% less than the yields that are able to be attained on well-managed government research stations (Kaiser and Zhan Dui 2005), suggesting there is considerable scope for increasing wheat and barley yields across Tibet. Tashi et al. (2002) agree that there is a large gap between potential grain yields and those typically seen on farms in the cropping zone.

24.4 Animal Husbandry in the Crop-Dominated Zone

24.4.1 Animals Kept

Cattle are the most economically important livestock animals kept on farms in Tibet's crop-dominated zone. Nearly all farms keep cattle, with most farms keeping two to six. These are mostly *Bos taurus* stock of the type bred by Tibetan farmers for centuries. About 30% of Tibetan cattle are of the type locals describe as 'improved' – the result of crosses, promoted by government, between local cattle and western breeds (mostly Simmental, Jersey or Holstein-Friesian). Cattle are, by western standards, very small (around 250 kg adult live-weight), though it is not clear whether this is genetic or a consequence of inadequate nutrition. Adult cows make up about half the herd on crop-dominated farms, the remainder being males or young animals. In addition to these cattle, there are significant numbers of yaks and yak/cow hybrids (the males, which are sterile, are known as *dzo*, and the females, which are fertile, are called *dzomo*). Yaks and *dzo* or *dzomo* are kept primarily as draught animals and make up approximately 10% of the large-animal herd on farms in the cropping zone.

About half the farmers in the crop-dominated zone also keep sheep in flocks of between 5 and 20 animals. These animals tend to be grazed in rangelands or road-sides for most of the year rather than be fed on-farm. Most households also keep chickens within the household enclosure, and a few keep one or two pigs (Fig. 24.3).

Fig. 24.3 A typical scene outside a Tibetan farming household. Cattle are kept tethered and fed cereal straw for much of the year

24.4.2 Animal Feed

In summer, harvested weeds from cereal fields form a major component of the diet given to Tibetan cattle. At all other times of the year, the main feed is cereal straw, which may be supplemented with grain (usually milled barley or wheat), weeds, oilseed meal, brewer's grain (i.e. the barley residue from household beer brewing) and sometimes vegetable waste or hay. Most cattle in the zone are allowed to browse cereal stubble and weeds for a month or two after harvest in summer; at other times, they are kept tethered or corralled near the household. Most animal feed is sourced on-farm, few farms in the cropping zone having access to mountain pastures. It is estimated that around a third of farmers do buy in some feed (straw, bran, brewer's grain,[2] oilseed or vetch), and some farmers may also supplement their animals' diets with salt.

24.4.3 Production Levels

Whereas the cropping sector is producing grain yields that are at least similar to yields obtained in many of the world's cropping areas, milk production in the crop-dominated zone is, by global standards, extremely low. Reliable data on milk production are very limited, but suggest most cows produce only 3–5 l of milk per day – a level likely to be much below their genetic potential, and brought about by inadequate nutrition. Most milk is consumed on farm, usually in the form of butter or cheese. Few farmers ever sell milk, and around one-third of farmers sell butter or cheese.

Calving rates are understood to be low, with average inter-calving interval approximately 18 months, and only around 60% of calves surviving their first year. Growth rates of surviving young cattle are also very low, with yearling animals only weighing 150 kg or less. Cow mortality is high – perhaps 10–15% per annum. Only a small proportion, perhaps 5%, of the total herd on farms in the crop-dominated zone is sold each year (J. Wilkins, C. Griffiths., unpublished data).

24.5 Boosting Grain and Dairy Production in Tibet

24.5.1 Introduction

Given the interest in bridging the gap between current farmer yields and potential crop yields, and in boosting dairy production in Tibet, it is worth considering the main constraints to grain and dairy production, how they might be overcome, and

[2] See Glossary.

what knowledge gaps should be targeted in further research. This section begins with separate focus on grain and dairy sectors before examining the farming system as a whole to identify practice changes that could lead to overall improvement in production and sustainability. The focus of the cropping section is on cereal grains production since these are the principal food crops. Finally, current understanding of some of the socio-economic factors that may constrain overall production is presented.

24.5.2 Grain Production

24.5.2.1 Cereal Varieties

The varieties of spring barley, winter wheat and winter barley preferred by farmers in Tibet all have long straw and a low harvest index, primarily because farmers value straw as fodder. The predominant winter wheat variety, Fei Mai, is of German origin, was introduced to Tibet in the 1960s and became widely grown in the 1970s. The predominant barleys grown in Tibet, well adapted to the local environment, are largely derived from Tibetan genetic material and are the product of local breeding programs in the 1970s and 1980s. It is likely that a thorough search of the international cereal germplasm, or a concerted cereal breeding effort, could lead to improved wheat and barley varieties for Tibet.

24.5.2.2 Irrigation Practice

Irrigation practice on most farms in Tibet is less efficient than it practically could be; while water is not always freely available, poorly leveled fields and yearly disruptions to field levels from deep ploughing lead to uneven and inefficient irrigation (P. Hobbs, personal communication). No mechanised method for leveling fields is available to Tibetan farmers at present, but it is possible that field level could be better maintained, once manually attained, if land was cultivated less.

24.5.2.3 Nutrition and Soil Factors

The sale of grain from farms in Tibet has probably increased over the past 40 years without a proportionate increase in the return of animal and human waste to fields. At the same time, government has focussed almost exclusively on nitrogen and phosphorus nutrition – indeed, urea and DAP are the only fertilisers widely available in Tibet. Recent observations in the field and preliminary soil and plant nutrition tests suggest that some fields may be deficient in a number of nutrients, including potassium. Across China, efforts are underway to test soils and develop more specific fertiliser programs at a regional level. The effective deployment of this program in Tibet would likely lead to improved cereal yields with minimal extra effort by most farmers.

Levels of organic matter in Tibet's cropping soils are also known to be low – due, at least in part, to the need to feed most crop residues to animals and to use animal manure for fuel for cooking and heating. Low soil organic matter leads to poor soil structure, reduced nutrient- and water-holding capacity, and low levels of microbial activity. If alternative sources of fodder and fuel could be found, more organic matter could be retained in the soil for improving soil physical properties, microbial activity and crop nutrition (Hobbs 2006a, 2007). The TAR government is aware of the household fuel problem, and regards replacement of traditional fuels with alternative energy sources – for example, solar energy or biogas – as a high priority (8th TAR People's Congress 2006).

24.5.2.4 Weeds

Typical farms in Tibet do not effectively control weeds. In part, this may be because farmers rely on weeds as a source of fodder in the spring and early summer, and thus see their presence as beneficial. Alternatively, it may be because weed control is too labour intensive, because suitable herbicides are not available, or because farmers lack the resources and know-how to use herbicides effectively. There is a need to identify the most important weeds on Tibetan farms, the yield penalties they bring, and then herbicide-based strategies for their effective management. A program to improve the availability and affordability of herbicides to Tibetan farmers, and to train farmers in their use, could lead to yield increases. Across Tibet, there is a need to promote integrated weed management practices, combining herbicide use with cultural and manual control methods, the use of clean seed and the targeted use of rotations (Hobbs 2006b). Given the current importance of weeds as animal fodder, any program to improve control of weeds would have to be introduced in combination with a strategy to provide an alternative source of fodder.

24.5.2.5 Crop Planting

Planting rates in many fields appear excessive. High plant numbers may be desirable as insurance against poor emergence, arising through imprecise seed placement, and/or high seedling mortality, brought on by drought, inefficient irrigation or, in case of winter cereals, winter kill. More precise seed placement through the use of seed drills or zero-till machines may circumvent the need to sow at such high rates. Research to investigate seed quality and optimise sowing rates and methods should be a priority in Tibet. Research could also be conducted to assess any benefits associated with having seeds unevenly distributed through the soil profile – for example, to investigate whether uneven sowing depth offers some insurance against winter kill for winter crops.

According to Tashi et al. (2002), timeliness of planting may also be an issue in Tibetan cropping systems, particularly for winter cereals, which have only been grown by Tibetans since the 1970s. Late planting can mean plants go into winter without acquiring their proper level of cold tolerance, leading to increased incidence of winter-kill. Increased levels of mechanisation and farmer access to it at the proper time would lead to timelier and speedier planting. Though small seed drills are occasionally seen in Tibet being drawn by yaks or cattle, their use generally requires farmers to have access to two- or four-wheeled tractors. Currently, about one-third of farmers in Tibet have access to either of these tractor types (Tashi et al. 2002; Fischer 2006). The formation of small cooperative farmer groups to buy tractors and seed drills would be one way of extending the level of mechanisation to greater numbers of farmers.

In the longer term, and assuming individual or groups of farmers could afford to buy suitable machinery, zero-till seeders could offer many benefits within the Tibetan cropping system; namely, more timely planting, reduced labour inputs, less disturbance to soil structure, and the option of retaining more stubble without impeding the planting process (for review, see Hobbs 2007). Greater stubble retention would probably only be embraced by farmers if they had alternative fodder supplies, or if improved agronomy led to significant increases in overall biomass production. After a number of years, it would be expected that soil carbon would increase and overall soil structure would improve.

An additional benefit the above technology could provide is that reduced labour input and earlier sowing may enable a fodder crop to be planted after the main cereal crop (see below). Further, zero-till technology, as opposed to deep ploughing, brings with it only minor disturbance to field level. Thus, with a zero-till approach farmers would be able to level their fields and better maintain this level for improved irrigation efficiency (Hobbs 2006a).

24.5.3 Dairy Production

24.5.3.1 Main Constraints

The major limitation to the productivity of cattle on farms in central Tibet is undoubtedly inadequate nutrition. While green feed given in the summer and autumn helps to improve the diet at these times of year, rations in winter and spring are based heavily on cereal straws, with generally limited supplements (J. Wilkins, C. Griffiths unpublished data). The metabolisable energy of straw is in the order of 5–6 MJ/kg DM, with protein typically only 2–4%. Feedstock with approximately 8–12 MJ/kg DM and 12–15% protein is required for optimal milk production or growth of young animals; animals fed diets containing a high proportion of straw simply cannot eat enough to meet their energy and protein needs. The fact that cattle are exposed to overnight temperatures of around −10°C in winter, when feed supplies are at their worst, must also be a factor in high cow mortality. Seasonal patterns in feed availability lead to a cycle, described anecdotally by Tibetans, in which 'cattle grow fat in summer and autumn, lose weight in winter and die in spring'.

Nutritional problems are exacerbated by the fact that many cows calve in the spring time before weeds become available in the fields; thus the associated peak in feed demand occurs in the months with least available feed. Poor cow nutrition during pregnancy and lactation leads to low birth weights, high calf mortality and low calf growth rates. In addition, a cow's first milk, or colostrum, is commonly taken for human consumption. Given the importance of colostrum for early calf nutrition and immune system development, this practice is likely to contribute to high calf mortality and be to the lifelong detriment of cattle.

A survey of Tibetan sheep, yaks and cattle conducted in 2003–2004 revealed that many livestock are deficient in a number of major and trace minerals, particularly sodium, phosphorus, copper and selenium (Nyima Tashi et al. 2005). While the study indicated deficiencies are more likely to be marginal than acute, they could still significantly constrain productivity, particularly in summer and autumn when energy and protein supply may be adequate.

Less significant impediments to production may arise because few farmers use any kind of feed trough, instead spreading fodder on the ground, leading to wastage and soiling of significant amounts of feed. In addition, few farmers offer cattle free access to water across the day, so that daily water intake is well below daily requirement, particularly for milking cows.

24.5.3.2 Simple Strategies to Boost Cattle Production

The simplest approaches to improving cattle performance and dairy output are likely to be those that do not require wholesale changes to the farming system, but simply promote the best existing practices. Initial, inexpensive interventions that may boost production include the provision of feed troughs for cattle to reduce feed wastage, more water for cattle, shade in summer and, if possible, some degree of warmth in winter (some farmers do tie blankets around their cattle in winter). Given the heavy reliance on straw-based diets, and consequent malnutrition, another simple approach to improve intake and digestibility of straw would be to cut it into short lengths using a simple straw guillotine. Providing non-protein nitrogen to cattle in the form of urea feed supplements is another practice that can improve rumen function and the utilisation of low energy/ low protein diets for relatively little cost, though amounts fed must be controlled carefully to avoid poisoning. Raising farmer awareness of the importance of allowing calves at least some colostrum is another intervention to consider, though it would be important to first understand exactly what the current use is for harvested first milk. The provision of deficient mineral nutrients as free-choice mineral supplements is often cheap relative to the benefit attained, and could boost productivity in Tibet. However, further research is required to determine likely productivity gains and the most cost-effective methods of supplementation (Tashi et al. 2005). Progression to cost-effective diets that meet the specific nutrient demands of animals for growth or lactation should be an obvious long-term goal of the dairying sector in Tibet.

Finally, it is not anticipated that genetic strategies to boost cattle production in Tibet should be a high priority in the current production environment. The practice of cross-breeding locally adapted genotypes with breeds such as Holstein-Friesian and Simmental produces larger-framed animals with higher production potential, but higher maintenance requirements. Such animals do not even approach their milk production potential when malnourished, and their ability to survive, produce and reproduce under Tibetan conditions is not well understood. Thus, as found in other countries, genetic approaches will need careful evaluation to find the most suitable genotypes for the Tibetan production environment, and will not succeed without accompanying nutritional strategies. It is noted, however, that cross-breeding local cattle to the Jersey breed has been tried by one project near Shigatse and reported as a success (Kaiser and Zhan Dui 2005). Since Jerseys are smaller-framed and produce milk high in butter-fat (suitable for butter and cheese making), this breed may well be suitable for Tibet, provided reasonable quality feed is available.

Although the simple interventions discussed above may lead to useful improvements in dairy performance, none address the chief limitation to dairy production in Tibet – a basic lack of good-quality fodder, delivering adequate energy and protein to cattle. The provision of more, higher quality fodder is likely to require significant changes to farming methods in central Tibet, and needs to be considered at the whole farm level.

24.5.3.3 Opportunities for Better Integration of Crop and Livestock Production Systems

The remaining approaches to boosting dairy production all rely on the production of dedicated fodder crops providing high-quality feed supplements to dairy cattle. Some of the approaches proposed are likely to have minimal impacts on grain production; others involve a trade-off between grain and fodder production. Fodder production systems that reduce grain production should only be widely applied if cereal yield gains can be achieved *via* improved agronomy, so that overall food security in Tibet is not jeopardised. Alternatively, if dairying is found to be more profitable than growing cereals, it may be best to import grain from other areas such as central China.

Some strategies for boosting grain production (for example, greater stubble retention after cereals and better weed control) might only gain acceptance in Tibet once straw and weeds are no longer essential as fodder. Thus, one or more of the following strategies for fodder production may actually be prerequisites for improved cereal agronomy.

The first approach proposed is one in which farmers would broadcast vetch seed into maturing cereal stands in June. Provided farmers could irrigate at this time, or given adequate rainfall, vetch seedlings would germinate and establish among cereal plants before cereal harvest. Since cereal harvesting and threshing are most often done by hand, the green material of the young vetch plants would not impede cereal harvest. Vetch plants would then grow away in the weeks after harvest and produce useful amounts (2–5 t/ha, by our reckoning) of vetch dry matter by the end of September, when winter crops need to be planted. Vetch growing in fields to be sown to spring crops the following year could be left to grow until the growing season effectively ends (late October in most districts). Farmers are already used to storing cereal straws as animal feeds; it should only take only a day or two for farmers on a typical farm to hand harvest vetch, dry it, then store it with cereal straw as a high-quality supplement to straw-based diets. If an average 1 ha farm produced 2 t of vetch hay using this method, this could provide 400 kg of vetch hay per cow for five cows – or 2 kg of high-quality hay per cow each day for 200 days. The higher energy and protein content of the vetch hay would improve the overall quality of straw-based diets, leading to probable increases in general health and productivity. This improvement in diet quality and production level would be achieved at minimal cost and with minimal extra work.

Another more obvious approach to boost cattle performance would be for farmers to dedicate a small proportion of their land, say, 0.1 ha on a 1 ha farm, to fodder production. This is an approach already seen in some areas of the TAR, which may be viewed more favourably in future as increases in cereal yield are attained through improved agronomy, and less land is required for cereal sufficiency. Lucerne (*Medicago sativa*) is already grown by a few farmers in the TAR and can be recommended immediately (Fig. 24.4). This species has already been shown to produce around 3–4 t/ha of dry matter per cut across four cuts in the Tibetan environment (i.e. 12–16 t/ha each year; Mr Yu Dailing, pers. com.). This level of

Fig. 24.4 Over the past decade, lucerne crops have started to be grown in some areas of Tibet's cropping zone – in this case as part of a TAR government program. Lucerne is cut three to four times a year and yields 3–4 t/ha dry matter per cut. Harvest is by the 'cut and carry' method

production from 0.1 ha could provide five cattle with at least 1 kg of high-quality hay per day for 200 days – a level of supply also likely to substantially boost cattle and cow performance. Given the primary importance of grain production for household food security, many farmers may have misgivings about dedicating part of their land to fodder production. However, 0.1 ha would typically only yield about 300 kg of grain – worth 600–800 yuan in Tibet in 2007. The current market price for fresh cut lucerne is such that farmers will pay 800 yuan for around 400 kg DM of lucerne (the product of a single lucerne cut from 0.1 ha). Thus, in today's market, a farmer could earn as much from a single cut of lucerne as from a typical year's winter wheat or barley crop.

Another possibility for lucerne production, already being practiced in one or two areas in the TAR (Fig. 24.4), is for whole communities to set aside areas of land for lucerne production. At these larger scales of operation, possibilities exist for cost-effective investment in machinery and storage facilities, though this has yet to be seen.

A third approach to fodder production may be suitable for those districts in Tibet where at least some cereal crops are harvested by mid-late July (approximately the eastern half of the zone, where altitudes are below 3,550 m). This would be to sow a second crop immediately after cereal harvest. In areas where harvest is particularly early, and labour is not in short supply, this could be done using traditional methods of cultivation and sowing. However, with labour in short supply on many farms (see below), and given the need for sequential crops to be sown as quickly as possible after cereal harvest, sequential cropping will probably only be practical using zero-till technology. In this case, a fodder crop could be drilled directly into cereal stubble in mid-July to early-August to yield useful amounts of fodder by the end of the season. Green fodder crops such as vetch could be stored as hay after drying, just as straw currently is. Any tuber crops grown for fodder – for example, turnips – could be stored whole or cut into chips and dried (Lane 2006).

Finally, the identification or breeding of shorter-season cereals suited to Tibetan conditions could be useful. Given the value placed on straw, farmers currently favour tall cereal varieties even if they are later maturing – and it is unlikely shorter season varieties could be developed with tall stature. However, if a system that produces high-quality fodder by double cropping or intercropping could be developed, the importance of straw for animal feed would diminish. In this case, short-stature, shorter-season cereals with high yield potential would be of great value as they would free up more of the growing season for growing a fodder crop.

24.5.3.4 Socio-Economic Factors

Given that many of the factors typically constraining agricultural production around the world are not physical, but a consequence of social or economic circumstance, it is worth considering what social or economic factors may constrain agriculture in Tibet. Based on initial field observations, there appear to be two obvious and related impediments to production that will need to be considered as agricultural development is planned in Tibet in future.

Firstly, with farm size only 1–2 ha across much of the cropping zone, farmers in Tibet do not benefit from economies of scale, and can rarely afford to buy their own machinery; thus, mechanisation can only really be achieved using rented or community-owned equipment. As land is unable to be bought and sold under its current system of tenure (Goldstein et al. 2003), this situation is unlikely to change. Small per unit production gains that would be of great financial interest to large-scale farmers may not be of much interest to small-scale farmers in Tibet. Identifying interventions that offer clear benefits even to small scale-farmers should therefore be a priority.

Secondly, many farmers in Tibet take the opportunity to work off-farm for a wage, most often on construction sites or in the transport sector (Goldstein et al. 2008; Fischer 2006) – and this trend is likely to continue, at least until 2010, given the emphasis on construction in the Central Government's current 5-year plan for Tibet (8th TAR People's Congress 2006), and given government efforts to promote off-farm employment to boost rural incomes (Zhou Chunlai 2005). With off-farm income providing most of the income for many rural households, there is considerable competition for farm labour. It is therefore important that plans to boost grain and dairy production should not be labour-intensive.

In addition to these more obvious constraints, other factors that may need to be considered include social pressures to keep as many cattle as possible, given their importance as an asset bank and indicator of wealth, even at the sacrifice of overall production; and a reluctance or inability of most Tibetans to fence their land. Current practice for most farmers in August and September is to let animals graze unrestrained across not only their land but neighbouring land as well. For fodder production to work, either fences would need to be erected, or animals tethered or, at the very least, farmer groups would need to work together to sow large areas of fodder at once so that grazing could be shared.

The various constraints outlined above probably only represent only some of the socio-economic factors likely to impact on agriculture in Tibet. A more thorough understanding is required of the constraints farmers perceive and of farmer circumstances, motivation and attitudes to change, before strategies for boosting grain and dairy production in Tibet are widely deployed. This understanding will come only through engagement with farmers in workshops, interviews and surveys. Agricultural research and development agencies in Tibet acknowledge there is a need to build stronger links with farmers, both to ensure research and development programmes meet farmer needs and to provide a platform for wider extension.

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Chapter 25
Rainfed Farming Systems of North-Eastern Australia

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Abstract The main climatic features and the principal soils used for rainfed cereal and oilseed production systems in north-eastern Australia are described, with their limitations on crop distribution. While rainfall and temperature provide opportunities for both summer and winter crops, available moisture supply is unreliable and generally limits production. Alleviation of the effects of a highly variable climate requires application of techniques such as fallowing, varying of plant population density, and geometry and selection of appropriate cultivars. Simulation models and decision support systems provide an opportunity to investigate alternative production strategies. Animal production tends to be on separate pasture land or in feedlots rather than integrated into the crop rotation.

Keywords Rainfed • Field crop • Production systems • North-eastern Australia • Cereals • Oilseeds • Climate • Soils

25.1 Introduction

Field crop production in north-eastern Australia presents challenges and opportunities that do not occur in other parts of Australia, but do occur elsewhere in the world, for example in parts of the Deccan of India, Blackland Plains of Texas and parts of eastern Africa because of similarities of climate and soils. The rainfed cropping area of north-eastern Australia is generally considered to stretch from Clermont and Peak Downs north of the Tropic of Capricorn in Queensland to approximately Quirindi south of Tamworth in northern New South Wales. The Atherton Tablelands, a high-rainfall,

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_25,

higher altitude area in far north Queensland that produces peanuts, maize and horticultural crops may also be included (see Fig. 25.1).

These areas occur on the slopes and plains west (inland) of the Great Dividing Range, and are generally less than 500 m above mean sea level. A slightly elevated higher rainfall, sub-coastal area, the Burnett, to the East of the Great Dividing Range, is also included, but not the higher rainfall coastal areas where cropping is dominated

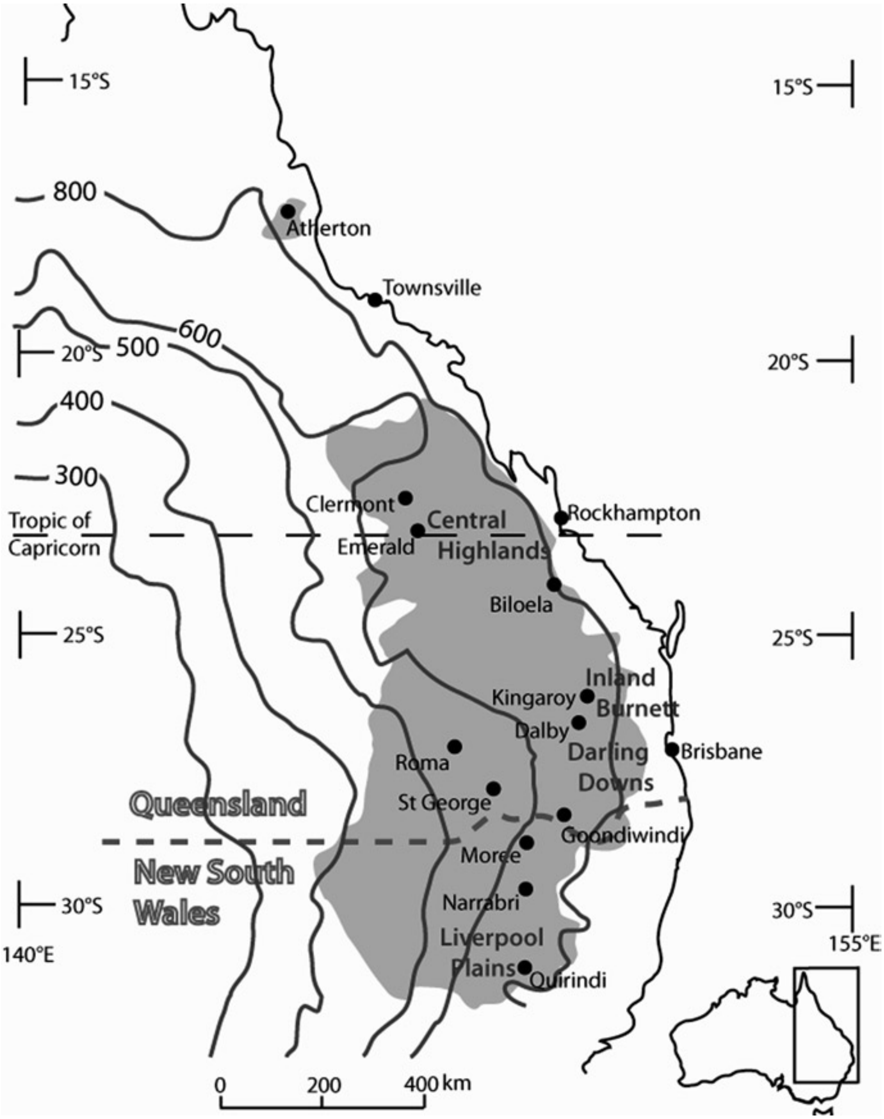

Fig. 25.1 Map of north-eastern Australia. 300–800 mm isohyets shown. Annual rainfall is much heavier near coast especially in the north (Cairns 1,992 mm)

by sugar cane and horticulture. This chapter briefly outlines the climate and soils of the region before considering the major agronomic systems used.

Both summer and winter crops are grown under rainfed conditions. Winter crops include cereals (predominantly wheat and barley) and chickpeas,[1] faba bean and, in the southern part of the region, some canola. Summer crops include grain sorghum with lesser areas of maize, peanuts, sunflower, soybean and mung bean. A significant area of rainfed cotton is grown adjacent to irrigated cotton where specialist infrastructure is accessible. All these crops, except peanuts, are grown on heavy cracking clay soils (vertosols[2]); peanuts (with some other cereals, oilseeds and legumes) are grown mainly on the friable red earths (ferrosols) of the Burnett region.

25.2 Climate

The region (shaded area in Fig. 25.1) is located in the sub-humid, sub-coastal zone with the climate described under the Koppen classification system as Cwa (long, hot moist summer, mild dry winter), Cfa (uniform rainfall, long hot summer, mild winter) and Cfb (uniform rainfall, long hot summer, cool winters) (Pittock 1986; Bureau of Meteorology 2008).

25.2.1 Rainfall and Evaporation

Annual rainfall of the region averages around 700 mm, falling from 800 mm in the east, towards 600 mm further inland in the northern half and 500 mm or less in the southern half. In the north, rainfall is warm season dominant (October–March) but it becomes more evenly distributed over the year to the south (Table 25.1). Although cool season rainfall is important for winter crops because of the lower evaporation rates, it is usually inadequate and can only be considered to supplement water stored in the soil under fallow.

However, rainfall is highly variable, both within seasons and between years, with year-long droughts or abnormally wet years usually driven by the El Niño–Southern Oscillation (ENSO) phenomenon.[3] Management of the climatic impact on agricultural systems must involve consideration of this phenomenon and associated seasonal outlooks (Clewet et al. 2002; George et al. 2007; Hammer et al. 2000; Meinke et al. 2003; Partridge 2001; Stone and Auliciems 1992).

Rainfall is variable in terms of: (1) total received annually, and over the cropping season, and (2) timing and intensity of rainfall. Most rainfall is received during the west–east passage of troughs in the upper atmosphere, from depressions originating

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[1] For botanical names see Glossary.

[2] Australian soil classification http://www.clw.csiro.au/aclep/asc_re_on_line/soilbgro.htm.

[3] See Glossary and Chap. 3.

Table 25.1 Median annual rainfall and level of summer distribution at representative centres in the north-eastern rainfed cropping region of Australia

Site	Latitude (°S)	Longitude (°E)	Median annual rainfall (mm)	Oct-Mar rainfall (% of mean annual)
Atherton	17.3	145.5	1,308	79
Clermont	22.8	147.6	623	60
Emerald[a]	23.5	148.2	618	62
Biloela	24.4	150.5	685	63
Kingaroy	26.6	151.8	762	61
Roma	26.6	148.8	581	52
Dalby[a]	27.2	151.3	677	56
Pittsworth	27.7	151.6	704	58
St George	28.0	148.6	497	49
Warwick	28.2	152.0	692	59
Goondiwindi[a]	28.5	150.3	608	51
Moree	29.5	149.9	553	49
Narrabri	30.3	149.8	663	49
Gunnedah	31.0	150.3	649	51
Tamworth	31.1	150.8	610	48
Quirindi[a]	31.5	151.7	689	51

[a] See Table 25.2 for Pan evaporation and temperatures for these representative locations
Source: Rainman (see Clewett 2005 for details of program)

in the tropics and from storms along surface troughs that also move from west to east. The majority of Queensland and even into northern New South Wales can be affected by the north-west monsoon and by low pressure systems often originating as cyclones embedded in the monsoonal trough between November and March; however, monsoonal rains are unreliable. The region is particularly prone to droughts and floods associated with the ENSO phenomenon, which generally lasts for 9–10 months. Timing of rainfall may be influenced by passage of the Madden-Julian Oscillation, which passes at intervals of about 6 weeks, triggering rainfall events in tropical and subtropical regions (Meinke et al. 2003).

Most winter rainfall is associated with low pressure systems that form in the mid-latitudes and have associated cold fronts (Meinke et al. 2003). These extend from low pressure systems and most winter rainfall moves from the south-west to north-east. As these influences move north, winter rainfall becomes increasingly unreliable, and the cold fronts may deliver little more than dry wind changes.

Pan evaporation usually exceeds rainfall, resulting in plant water stress. Under hot, dry north-westerly winds, open Class A pan evaporation can exceed 10 mm per day. Water stress is a common production limitation, the onset and frequency of which depends principally on the amount of water stored in soils at planting and the amount and timing of in-crop rainfall. The unreliability of rainfall (amount and timing) means that agronomic practices (such as reduced and zero tillage, soil management to ensure optimum storage of water and choice of planting time, cultivars and plant populations) assume critical importance for managing canopy volume and water consumption in order to ensure sufficient water is available during grain filling (Hammer 2006a, b) (see also Chap. 7).

25.2.2 Temperature

Mean monthly maximum and minimum temperatures are shown in Table 25.2. Heat waves during summer (maximum temperatures exceeding 40°C) and severe radiation frosts during winter and early spring are relatively common throughout the region (Bureau of Meteorology 2007). While it is perhaps surprising that frosts occur so far north at these low altitudes, clear skies during winter and associated cold air masses from the south create conditions where outgoing radiation at night results in a sharp drop from generally moderate daytime temperatures to levels where freezing occurs. The frosts rapidly disappear after sunrise as daytime temperatures increase. Clear skies, and thus longer frost-affected periods, are associated with El Niño patterns. Processes affecting weather and climate in the region are discussed by Meinke et al. (2003).

25.2.3 Planting Options in Regard to Temperature and Rainfall

In the northern section of the north-eastern cropping region, there is a wide planting window (up to 7 months) during which temperatures are suitable for summer crops. However, the number of planting opportunities depends on water supply. Therefore

Table 25.2 Mean maximum and minimum monthly temperatures and pan evaporation for some representative locations in the north-eastern Australia cropping region

	Quirindi			Goondiwindi			Dalby			Emerald		
	Temperature (°C)		Pan[a]	Temperature (°C)		Pan[a]	Temperature (°C)		Pan[a]	Temperature (°C)		Pan[a]
	Max	Min	E	Max	Min	E	Max	Min	E	Max	Min	E
Jan	31.8	16.8	9	33.5	20.1	9.9	31.6	18.8	7.7	34.1	21.5	8.9
Feb	31.1	16.5	7.7	33	20	8.7	31.1	18.5	6.8	33.2	21.3	7.5
Mar	29.3	13.9	6.1	30.8	17.9	6.8	29.5	16.8	5.7	31.9	19.7	6.4
Apr	25.3	9.1	4.5	27.3	14.1	4.8	26.7	13.3	4.4	29.5	16.5	5.3
May	20.5	5.5	2.9	22.4	9.8	3.2	22.5	9	3.2	25.7	12.5	4
Jun	16.7	3.3	2.3	19.1	6.5	2.7	19.3	5.7	2.6	22.7	8.9	3.6
Jul	16	1.7	2.6	18	5.1	2.8	18.6	4.4	3	22.4	7.6	3.8
Aug	17.9	3	3	20	6.4	3.6	20.3	5.5	3.6	24.6	9	5
Sep	20.9	5.3	3.9	23.8	9.4	5	23.9	8.7	4.9	28.3	12.3	6.7
Oct	24.8	9.3	5.5	27.7	13.6	6.9	27.2	12.8	6.2	31.8	16.5	8.4
Nov	27.7	12	7.3	30.6	16.6	8.7	29.9	15.8	7.6	33.7	19.4	9.7
Dec	30.9	15	9.4	32.8	19	9.6	31.4	17.8	8.3	34.5	20.9	9.8
Year	24.4	9.3	5.3	26.6	13.2	6	26	12.3	5.3	29.4	15.5	6.5

[a] Class A Pan evaporation in mm/day

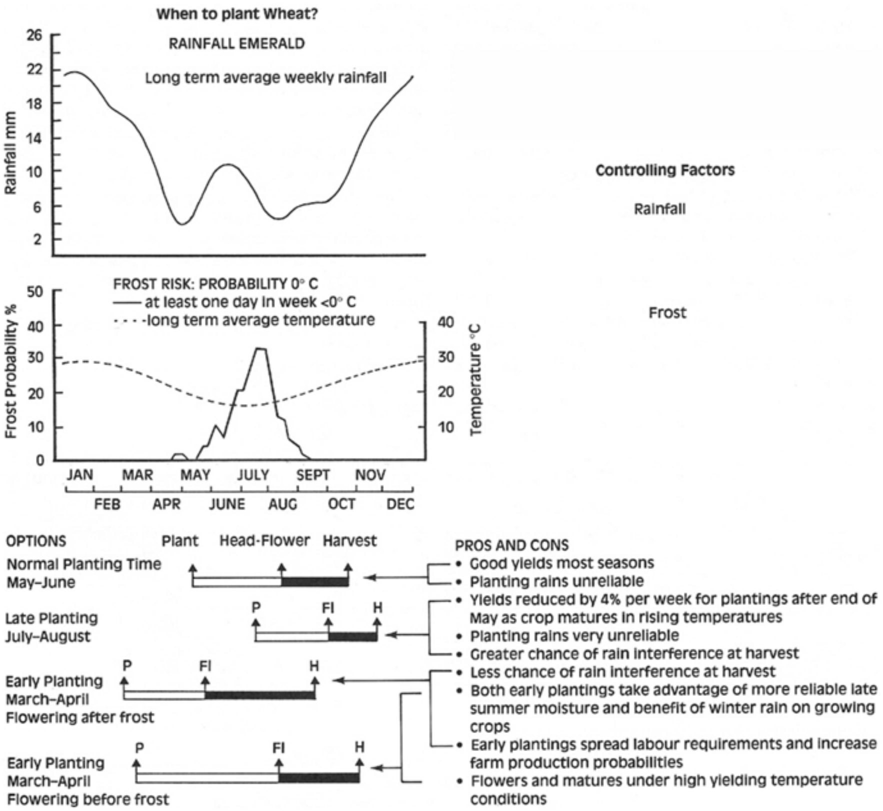

Fig. 25.2 Wheat sowing options, Central Highlands, Queensland. (Tow and Schultz 1991)

planting times of summer crops need to take into account both water supply (see later) and the risks of extreme high and low temperatures during the reproductive stages of crop development in early- and late-planted crops respectively.

The duration of conditions that suit winter crops is shorter, with a significant risk of yield limitations due to high temperatures and water stresses in late spring and early summer. For example, Fig. 25.2 shows that planting options for wheat are available from March to June in Central Queensland, and that planting through this period exposes the crop to differing consequences and risks. Appropriate choice of variety may avoid flowering during the period of greatest frost risk.

In the more elevated and more southerly parts of the north-eastern region, the summer planting window is shorter and winter planting window longer. High temperature stress is less likely, although frosts can damage winter crops severely if they coincide with anthesis.

25.3 Soils

The principal soils used for cropping in the north-eastern region are the black and grey vertosols[4] (Black Earths, Black Cracking Clays, Grey Clays). Limited areas of ferrosols (Krasnozems, Friable Red Earths) in the South and Central Burnett around Kingaroy and on the Atherton Tableland are used to grow peanuts, maize and a range of other crops (Natural Heritage Trust 2001). Other soils may be used in limited areas where rainfall is at the higher end of the range mentioned, or where irrigation (not covered in this book) is available.

The vertosols used for agriculture are moderately deep to deep (0.6 m to several metres), have high clay content, moderate to high plant available water-holding capacity (PAWC) of 150–300 mm to a depth of 2 m (APSIM data base, Keating et al. 2003) and moderate fertility. The clay is predominantly montmorellonitic with related clay minerals (which have 2:1 lattice structure that swells on wetting and shrinks on drying), and have high cation exchange capacity (CEC).[5] They are susceptible to erosion by water but not wind. Some areas have relatively high exchangeable sodium percentages and elevated magnesium concentrations, and are thus structurally unstable. There is substantial local variation in colour (usually grey to black), texture, organic matter content, depth, water-holding capacity and inherent fertility. Useful general descriptions of vertosols are available in Storrier and McGarrity (1994), with specific information for a substantial number of local variants in Biggs et al. (1999), Harris et al. (1999), Dalgleish and Foale (1998) and in the APSIM soils data base (Keating et al. 2003).

The ferrosols have lower PAWC than the vertosols, but occur in the more elevated and/or higher rainfall parts of the region that are also more humid and have lower evaporation. Although less fertile, they have generally favourable structure and moderate water-holding capacity, making them desirable soils for agricultural cropping. Soil characteristics are described in Crosthwaite (1994), Storrier and McGarrity (1994), and the APSIM data base (Keating et al. 2003).

The moderate to high initial fertility of the vertosols has declined under continuous cropping. Many had moderately high organic matter content and sufficient nitrogen, phosphorus and other nutrients to meet the needs of rainfed crops. However, burning crop residues, and the use of bare fallowing and long fallowing for around 50 years reduced soil organic matter content (Dalal et al. 1991a, b; Dalal 1992; Dalal and Chan 2001) and resulted in significant to severe soil erosion (Loch and Silburn 1997). Nutrient removal in harvested products, soil erosion and the impact of various cyclic loss pathways for nitrogen (such as significant denitrification from waterlogged vertosols) and leaching from lighter-textured soils has led to widespread deficiencies of nitrogen and phosphorus. Deficiencies of zinc and sulphur have also emerged over substantial proportions of the region. There may be small areas of other nutrient deficiencies such as potassium, manganese, copper and molybdenum (in ferrosols).

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[4] Australian Soil Classification http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm

[5] See Glossary.

25.4 Limitations to Rainfed Cropping in the North-Eastern Region

The north-eastern region is regarded as more “risky” for crop production than southern Australia, with high variability resulting in lower average yields over the long term. However, the adoption of techniques that maximise water availability can result in consistently good yields in both summer and winter crops.

The principal limitation to crop production, water supply, arises from variability in rainfall, both within and between seasons. But both high and low temperature extremes can also adversely affect crop performance, especially if they coincide with sensitive stages in crop development. Finally, soil characteristics, particularly soil fertility and water-holding capacity constrain locations of crop production and the frequency and reliability of cropping. Climate-related constraints are expected to become more important because of the predicted effects of climate change – increases of 2–4°C in mean daily temperatures are projected over most of the area by the mid-twenty first century (Pittock 1990; Meinke et al. 2003). Consequently, from a system perspective, the aim is to manage climatic limitations to sustain productivity, profitability and stability of farming enterprises.

25.4.1 Practices for Mitigation of Water Supply Limitations

25.4.1.1 Fallowing

The single most important practice for mitigating water limitations has been the use of “bare” fallows in which soil is kept free of crop or pasture plants and weeds to allow water to accumulate in the profile. Weeds were formerly controlled by cultivation but now with herbicides. Crop residue is now normally retained on fallow land, either by use of no-till (zero till) or stubble mulching (in which limited tillage is used, and residue is retained on the surface of the soil) (Freebairn et al. 2006). For effective water storage, the soil must have a high clay content, as it has in the Darling Downs region, Central Queensland and north-western New South Wales. These vertosols can hold up to 300 mm of plant available water to depths of 2 m, but more typically hold 180–250 mm. In the areas with summer-dominant rainfall, summer rainfall is accumulated in the soil for use by winter crops growing during the period of lower and less reliable rainfall, but lower evaporation. Water must also be stored in the soil prior to growing summer crops because of the highly variable rainfall in summer and the probability of extended periods without rain—even though summer is the “wet” season.

From the late nineteenth century, bare fallowing in southern Australia was associated with a rapid decline in soil fertility and an increase in soil erosion, resulting in a decline in cereal crop yields. Fallowing also reduces fertility in vertosols in northern Australia, principally through mineralisation of organic nitrogen and through erosion. Inevitably, organic matter and nitrogen status have declined.

25.4.1.2 Plant Population Density and Planting Geometry

Water supply limitations can also be mitigated by regulating plant density and planting geometry. Numerous experimental and modelling studies in both winter and summer crops consistently show that low plant populations produce acceptable yields in north-eastern Australia. The yield response to increasing plant population is essentially flat, and low populations should always be used in summer cereals (Wade and Douglas 1990; Spackman et al. 2001; Hammer 2006; Robertson et al. 2003). While low populations may sacrifice some yield in favourable seasons (Birch et al. 2006; Robertson et al. 2003), they improve reliability. Higher populations may be appropriate for sites with higher yield potential because of more reliable water supplies (Anon 2003; Doyle 1980; Thomas et al. 1981; Holland and McNamara 1982).

Winter cereals compensate for low plant population by increased tillering, thereby producing substantially more reproductive sites (heads, ears) than implied by the initial plant population. Where there is use of stored soil moisture, tiller survival on low population crops is higher, meaning that fewer resources are used in producing structures that will either senesce or be infertile. Further, low populations constrain early season water consumption (provided weeds are controlled) through delaying target leaf area production (target leaf area indices discussed in Hammer (2006a, b)), and leaving more water available for use during grain-filling. This contributes to water use efficiency (WUE) and final crop yield. In winter crops other than cereals, compensation for low population is usually by increased branching – with similar effect to cereals on leaf area production and water consumption patterns.

Summer cereals and sunflowers also compensate for low population – individual plants usually produce larger reproductive structures with more grain sites. Sorghum may tiller, especially at low population density or when temperatures are low during the seedling stage (Downes 1968; Lafarge et al. 2002; Lafarge and Hammer 2002; Hammer and Broad 2003), but it can also increase grain size under favourable water supply conditions. Cotton compensates by producing larger branches with more fruiting sites on individual plants.

Clearly, no single option will suit all circumstances – comprehensive analysis and risk assessment must be used to assist with the agronomic decisions.

In more marginal rainfall areas, modifying planting geometry can provide significant benefits in grain sorghum (Robertson et al. 1993, 2003; Routley et al. 2003; Spackman et al. 2003; Broad and Hammer 2004;) and cotton (Marshall et al. 1994; Goyne 2000; Bange et al. 2002); Milroy et al. 2004. In these crops, skip row techniques are used in which 1 or 2 rows of crop are not planted (see Fig. 25.3), with the pattern repeated across the field.

The soil under the unplanted rows provides a reserve of water for use by the remaining plants during the critically important reproductive stages; thus water extraction and water use efficiency are improved. However, maize does not respond to skip rows, and yield is likely to be compromised (Robertson et al. 2003; Madhiyazhagan 2005). The difference in response between sorghum and maize has been attributed to different root geometry (Madhiyazhagan et al. 2004; Madhiyazhagan 2005); management of water supplies in maize has to depend on plant population density rather than planting geometry.

Fig. 25.3 "Skip-row" grain sorghum near Dalby, Queensland. Note the wide spacing between rows where one row has been omitted

25.4.1.3 Cultivar Selection

The variability of the production environment, especially in relation to water supply, implies that a wide range of cultivars is needed, and plant. Plant breeders and seed retailers have provided a wide range for most crops grown in the region. Most cultivars used in rainfed production systems are classified as early maturity (or short-season) to medium maturity (mid-season), with late maturity (full-season) cultivars sown only in a few favoured areas where water supply is greater and more reliable. Even in these areas, there has been a trend to medium-maturity cultivars, probably because of a decline in annual rainfall in north-eastern Australia over recent decades (BOM 2007).

In selecting a cultivar, the important considerations include:

- planting time – hence the thermal, photoperiod and anticipated water supply (i.e. water stored in the soil plus rainfall) conditions under which the crop will grow
- plant-available water in the soil at planting – as a contributor to total water supply during crop growth
- capacity of the cultivar to adapt to stress conditions, e.g. possession of the "stay green" characteristic in grain sorghum
- insect and disease resistance – a response to expected insect pest and disease incidence
- quality characteristics of the cultivar – for example bread or biscuit flour
- end use of the crop (i.e. market segment for grain – malting or feed barley).

The availability of a large range of crop cultivars allows producers choice of one or more cultivars according to soil water supply at planting time, the perception of the seasonal climate forecast and their attitude to risk. Producers may use decision support software to assist with selection of cultivars and to assess risk of failure of crops due to seasonal conditions (including frost) (see Sect. 25.6 of this chapter).

25.5 Practices for Mitigation of Nutrient Limitations

The most common nutrient deficiencies in north-eastern Australia are nitrogen, phosphorus and zinc, with increasing incidence of deficiencies of sulphur, potassium and other micronutrients, such as molybdenum in ferrosols and other acidic soils. Throughout the region, N deficiencies are corrected with fertiliser, with some N supplied by pulses grown in rotation with non-legume crops. Grain legumes such as chickpeas (*Cicer arietinum*), mung beans (*Vigna mungo*) and faba beans (*Vicia faba*) are grown in rotation with cereals, but the total area is comparatively small. The N benefit of the legume grain crop is usually around 50–75 kg/ha N, though higher benefits have been shown (for example Doughton and MacKenzie 1984; Strong et al. 1986; Dalal et al. 1991c; Hossain et al. 1992; Holford 1993; Holland and Herridge 1992). However, the benefit generally does not persist beyond a single crop because of the shortness of the grain legume crop cycle, usually being only of one year's duration (Doughton and Holford 1997).

Fertilisers are generally applied before or at planting, though some post-plant nitrogen is applied to soil or foliage in conditions that favour high yield. Post-planting application is usually in response to better seasonal conditions than expected at planting. Gypsum, or another source of calcium, may be applied to peanuts to meet the specific needs for direct uptake of calcium by the developing nuts (Birch 1994).

Rates of fertiliser application vary widely throughout the region depending on the soil water-holding capacity, soil fertility, crop grown, yield potential, soil water status at planting and the farmers' attitudes to risk. However, most farms are probably in net negative nutrient balance – more nutrient is being removed than replaced in fertilisers or by N fixation by legume crops. For example, Bell and Moody (2005) demonstrated that there have been increasing net negative balances for nitrogen, phosphorus, potassium, calcium, magnesium and sodium in sorghum on the Darling Downs in each decade since 1960 (Fig. 25.4). This indicated continuing long-term exploitation and thus reduction in the nutrient status of soils. These authors also found negative nutrient balances in maize–peanut rotations in the inland Burnett region from 1984 to 2000 (Fig. 25.5). Although the results may vary among farms, net removal of nutrients probably remains the norm rather than the exception. Under such a regime, it is inevitable that widespread nutrient deficiency will increase.

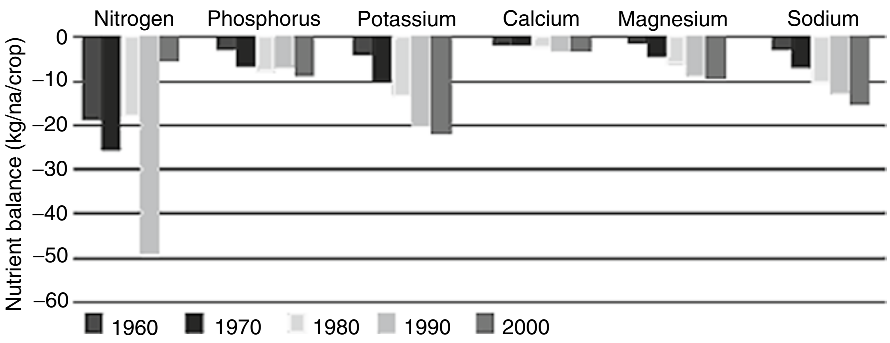

Fig. 25.4 Nutrient balance for sorghum crops on the Darling Downs for five successive decades from 1960. (Source: Bell and Moody (2005))

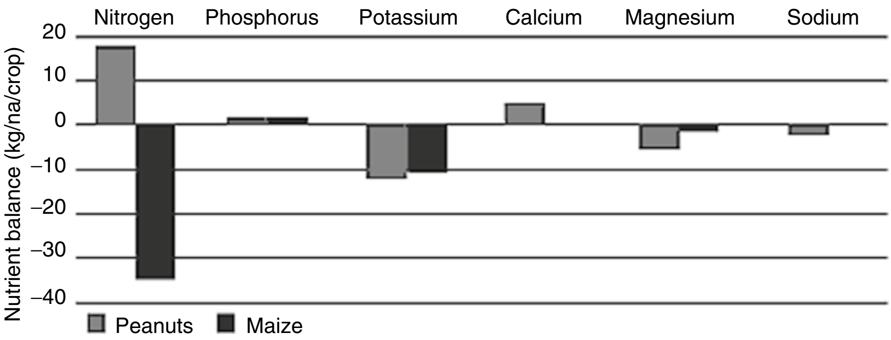

Fig. 25.5 Net nutrient balance for peanut/maize cropping in the Inland Burnett District between 1984 and 2000. (Source: Bell and Moody (2005))

More extensive information about diagnosing nutrient deficiencies or about fertiliser practices is included in Chaps. 5 and 7. A comprehensive review of fertiliser and manure use in subtropical agricultural systems has been presented by Strong and Holford (1997), and the impact of long-term use of nitrogen and phosphorus fertilisers on crop yield is examined in Lester et al. (2008).

There has been considerable research into the use of tropical legumes in rotation with crops (for example Pengelly and Conway 1998). However, legume-based pasture–crop rotations are little used to improve soil nitrogen status. Few perennial pasture legumes, with the exception of lucerne, are adapted to vertosols (Neale et al. 2004). Yet lucerne is not widely used in rotation with rainfed crops, being mainly confined to irrigated systems for production of hay. In long-term rotation trials in northern New South Wales and southern Queensland, lucerne was shown to improve yield and protein content in subsequent rainfed crops of wheat (Whitehouse and Littler 1984; Holford 1981) for as much as 9 years (Holford 1980; Littler 1984). However, crop yields may be more variable after lucerne because it can extract water from deep in the profile, leaving none for use by the following crop (Cooper et al. 2004). Further, lucerne persistence is adversely affected by wet soil conditions in summer and by continuous grazing; rainfed lucerne stands, being sparse, leave soil bare and subject to erosion.

Annual *Medicago* spp. (medics) will also increase soil N under rainfed and irrigated conditions, but the effects have been inconsistent and related to duration of the medic ley phase of the rotation (Clarkson 1987; Dalal et al. 2004). However, some studies have shown the beneficial effects of a range of pasture and crop legumes leading to improvement in both sustainability and profitability from soil restorative effects of legumes (Dalal et al. 1996). Medic leys have advantages over other ley options in drier seasons on marginal soils because of the greater persistence of these legumes under water-stressed conditions (Weston et al. 1996).

25.6 Use of Crop Simulation and Decision Support Systems

Decision support systems (DSS) currently provide guidance on cropping options and agronomic decisions. They include APSIM (Keating et al. 2003) and WHEATMAN plus Barleyplan (Cahill et al. 1998) used in conjunction with climate analysis systems such as RAINMAN (Clewett et al. 2003; Clewett 2005) and the “HOW” series of HOWWET (Dimes et al. 1993; Freebairn 2006) and HOWOFTEN (Wockner and Glanville 2000; Freebairn and Glanville 2007). They may be used by farmers, consultants or advisers, their effectiveness being enhanced through development of competency among these groups (George et al. 2007).

Issues able to be explored with these DSS include:

- the probability of a nominated amount of rain being received over a selected period
- impact of ENSO
- frost risk
- cultivar selection
- fertiliser rate
- estimating future water balance
- impact of crop cultural conditions on crop yield
- the concentration of grain protein.

They are also a means of incorporating new research findings in a readily accessible medium, and so contribute to adoption of new practices, as well as to reassessment of previous practices (Cahill and Strong 1996).

DSS are being used to model and assess the impact of a range of decisions on crop productivity. They are also widely used to assess the projected impact of climate change on cropping practices and crop productivity. They can be used to explore production capability and options for cultural practices in future climate scenarios.

Products of the Agricultural Production Systems Research Unit in Australia, for example APSIM (Keating et al. 2003), Whopper Cropper (Cox et al. 2004) and Yield Prophet (Hunt et al. 2006), can be used to assess management options for cropping either in a single season or over the long term. Modelling studies with maize, wheat and sorghum (Birch et al. 2006; Cox and Chudleigh 2001; Hammer 2006a, b) explored ways of improving yield and yield reliability. Retention of water in the soil profile long enough to maintain canopy photosynthesis for the duration of grain filling improved predicted yield of grain sorghum (Hammer et al. 2006a, b). The concepts explored by Hammer apply to crops which are at risk of exhausting water supplies early in the vital grain-filling stage. Other modeling studies have examined the importance of water supply at planting, cultivar type and planting time for the success of crop production in the region under historical or possible future climates (for example Robertson et al. 2003; Birch et al. 2006).

As the capabilities of models and the prediction of future climate improve, so too will guidance to crop production in the increasingly variable climate projected under climate change. The overall objective will be to improve reliability, stability, profitability and sustainability of agricultural systems.

Birch et al. (2006), using long-term modelling studies (>100 years data), argue for full profiles of PAWC at planting, low plant populations and short-duration cultivars of maize especially when grown in marginal rainfall environments. Fig 25.6 shows examples of predicted dry grain yield (kg/ha) of two maize cultivars, at two plant population densities on a full and partially full profile in representative soils at eight locations, planted on 15th November. The I bar represents the range in predicted yield, horizontal solid line predicted median yield, horizontal broken line predicted mean yield, and the box, the range from 30 to 70 percentile of predicted yields. Though there is considerable variation among sites, most being due to variation in rainfall and PAWC, important trends emerge when individual sites are compared. The diagrams show that the lower plant population is expected to be more reliable (with smaller range in predicted yield and smaller range from 30 to 70 percentiles). They also show that planting on less than a full profile of PAWC reduces predicted yield in most years. Risk of failure is usually higher with medium-maturity cultivars planted at the higher plant population, especially on less than a full profile of PAWC.

Hammer (2006a, b) has argued for management of canopy development to ensure that sufficient water remains in the soil for the - all-important grain-filling in sorghum. He used modelling to show substantial yield benefits by having a lower leaf area index at anthesis (Fig. 25.7), thus retaining water for the grain-filling period, especially when in-crop rainfall is relatively low. The increase in yield as in-crop (i.e. post-planting) rainfall increases for each of the LAIs is shown by the solid line at the upper boundary of each shaded area. For example, at low in-crop rainfall, a low target LAI of 1.0 produces the highest predicted yield and reaches a maximum yield at around 175 mm of in-crop rainfall (the first vertical dotted line in Fig. 25.7). However, at a target LAI of 5, zero yield is predicted for up to 150 mm of in-crop rainfall and then increases up to 400 mm of in-crop rainfall, at

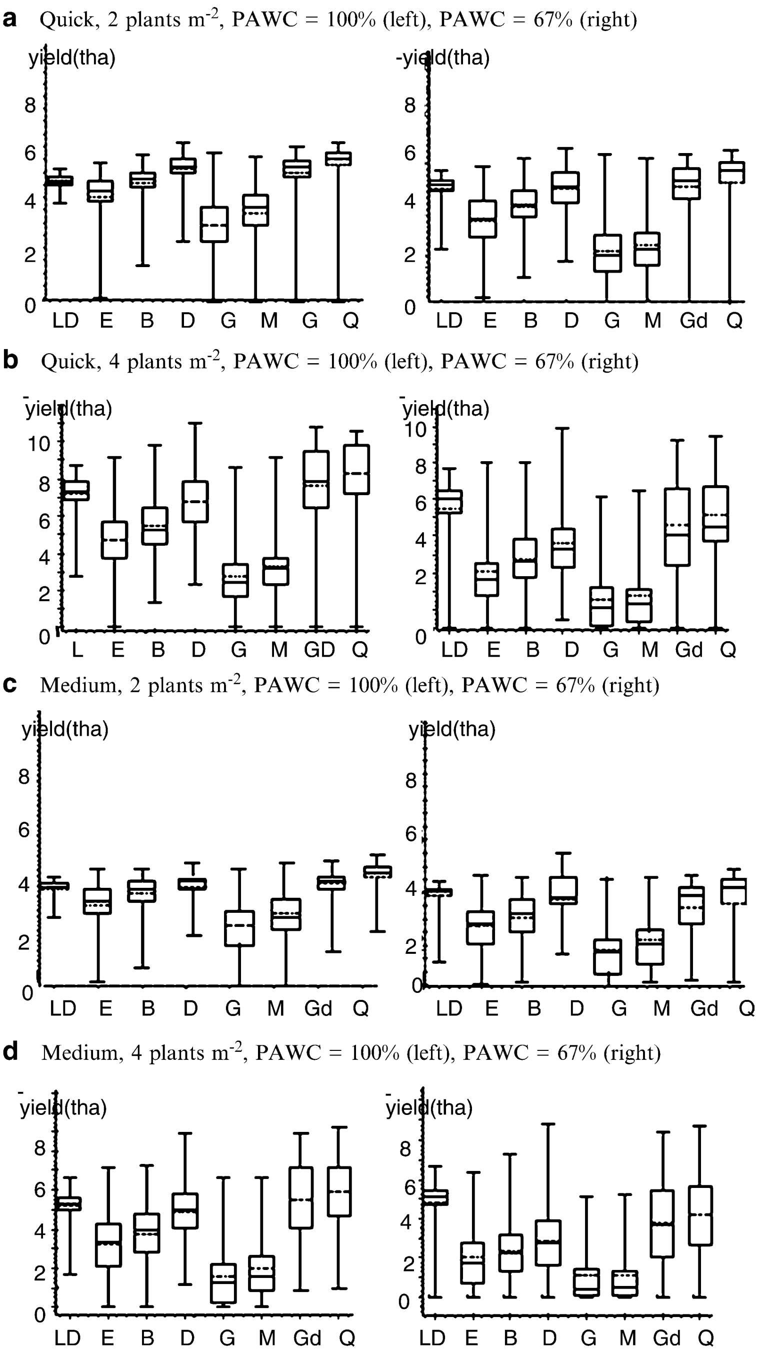

Fig. 25.6 Examples of predicted dry grain yield (kg/ha) of two maize cultivar types at two plant population densities on a full and partially full profile in representative soils at eight locations planted on 15th November. (Source: Birch et al. 2006)

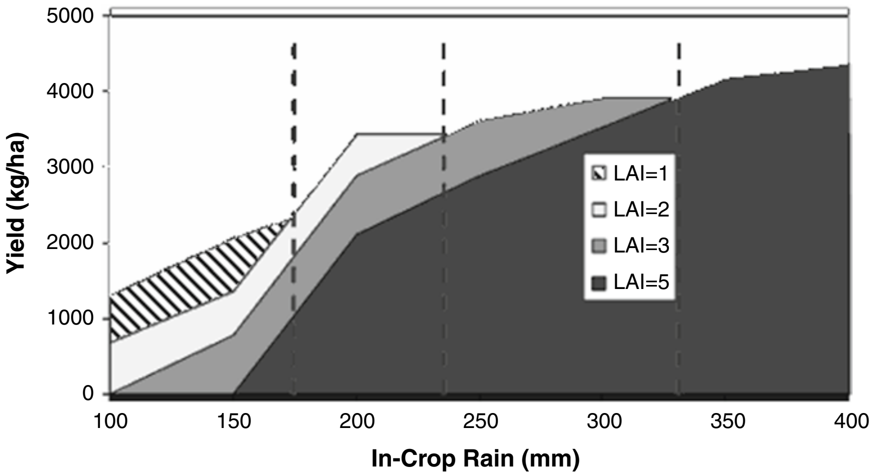

Fig. 25.7 Grain yield v. in-crop rainfall for a range of LAI targets for a simulated sorghum crop at Roma, planted at 50 000 plants/ha in December on a vertosol of 80 cm depth holding 100 mm of plant available water at planting . The vertical dashed lines identify rainfall levels at which yield for each LAI target is at its maximum and a higher LAI target is needed to achieve a greater yield. (Source: Hammer 2006b)

which the highest predicted yield for all options occurs. Target LAIs of 2 and 3 produce intermediate maximum yields that are reached at around 240 and 340 mm of in-crop rainfall. The intercepts on the Y axis represent predicted yield at 100 mm of in-crop rainfall, for crops planted on 100 mm of plant available water in the soil at planting. These predictions emphasise the importance of in-crop rainfall to crop production and show the interaction of target LAI (which can be managed by plant population density) and in crop rainfall.

Chapter 7 provides some additional guidance to use of models and likely future developments.

25.7 Animal Production in Association with Cropping

Though little use is made of ley pastures in the northern cropping areas shown in Fig. 25.1, (as discussed in Sect. 25.5), production of livestock, principally beef cattle, in association with cropping is widespread. Exceptions are the intensively cropped areas of the Darling Downs, Liverpool Plains and parts of north-western New South Wales. Many farms have substantial areas that are not cropped because of unsuitable soil or topography, but they are suitable for grazing. Commonly, livestock classes are matched to land capability; thus breeding cattle graze native pastures or less productive areas of naturalised or sown, non-native pastures (e.g. buffel grass[6]). Fattening or "backgrounding"[7] stock for feedlots, where greater growth rates of livestock are required, are usually conducted on more fertile land with forage crops or higher-quality pastures. Farmers regularly adjust these "trading stock" numbers in response to their current feed supply and expected seasonal conditions. Some producers have specialised into "trading" enterprises in association with the growing feedlot industry in the region. Sheep were once important in the region but only a few producers have cross-bred sheep flocks for prime lamb production on sown grasses or on rainfed lucerne.

The feedbase of mixed farms in the region can be diverse and may include native pastures, sown pastures that grow in winter or summer (e.g. non-native subtropical grasses, lucerne and annual medics), winter- or summer-grown forage crops (e.g. oats, lablab, forage sorghum[6]), abandoned crops, crop residues and conserved forage (hay or silage). Because of the dominance of summer rainfall, there is usually an excess of forage supply during summer and the main feed gap occurs in late winter and early spring. Hence, high-quality winter fodder, commonly provided by winter forage crops (e.g. oats) or pastures (medics and lucerne), is particularly valuable.

Annual forage crops are regularly integrated into cropping rotations within mixed crop and livestock enterprises. Oats grown in winter and forage sorghum in summer are most common, although forage varieties of wheat, barley and rape, forage or dual-purpose millets, and annual legumes such as lablab, cowpeas and purple vetch[6] are also common. While some of these provide benefits to the cropping system (e.g. nitrogen inputs from legumes, disease breaks), they are primarily grown as a high-quality feed source to fatten stock or to allow spelling of pastures. Hence, some producers have designated forage crop paddocks rather than integrate these crops with their grain cropping activities.

Using grain crops as a forage source is another way in which livestock are integrated with cropping activities. Crop residues are grazed (and sometimes baled for hay), most often during dry periods with low feed supply; however, this reduces soil surface protection and is now less common because of the benefits of stubble conservation. Sorghum crops are also allowed to re-grow for grazing after harvest, but this can reduce soil moisture available for subsequent crops (Whish and Bell 2008). Grain crops that are likely to fail or have failed due to seasonal conditions are used for forage or hay. This feed source can be valuable as the conditions that cause crop failure often result in a shortage of herbage for livestock. Bell and Hargreaves (2008) used APSIM simulations to explore how often a wheat crop may have more value for grazing than to continue to harvest and found that this can occur regularly in the northern, mixed crop-livestock areas, especially on soils with a lower PAWC (<150 mm). Grazing was more profitable in years of low yields and under average commodity prices. If expected grain yields are below 1.5–2.0 t/ha, grazing generally should more profitable. However, this is greatly influenced by the relative

[6] See Glossary for botanical name.

[7] See Glossary for definition.

commodity price of grain and livestock, and making a tactical in-season decision to graze crops is difficult with limited knowledge of final grain yields (see Chap. 37 for use of a DSS to help with this decision).

The use of ley legume pastures to provide nitrogen in cropping systems has been limited (as discussed previously), but longer-term phases of sown grass pastures are being increasingly used to rejuvenate soils that have become marginal for cropping. Grass-based pastures are the most effective means of improving soil organic matter and surface structure and fourfold increases in infiltration rates have been measured after 5 years of pasture (Bell et al. 1997). Grass-based ley pastures also offer substantial benefits for reducing runoff, erosion and deep drainage (Silburn et al. 2007).

While some producers happily integrate livestock with their cropping activities, there has been a trend towards greater segregation of these enterprises on different parts of the farm. With increasing awareness of vehicle soil compaction, many producers are also concerned about the potential for compaction by livestock of their cropping soils. Livestock can increase soil bulk density and soil strength, reduce porosity and infiltration rates, but these effects are much shallower (<10 cm depth) than from wheeled vehicles. In one study, Radford et al. (2008) found that livestock grazing stubbles under wet conditions reduced the yield of the following crop by 15%, but when livestock were only allowed on paddocks when the soil was dry there was no effect on soil properties or subsequent crop yields. The effects of livestock compaction on cracking vertosol soils are also short-lived after regular wetting and drying cycles at the soil surface.

There is a role for livestock in cropping systems in the northern agricultural region, but this varies according to farmer perceptions of the value of livestock (mainly beef cattle) in their systems. There may be greater emphasis placed on livestock if they became more valuable economically in relation to grain production, and if more productive and persistent perennial pasture legumes were available which had high feed value and which provided high levels of nitrogen to the soil to benefit crops. The importance of mixed farming for sustainable production in the region may then increase.

25.8 Conclusions

Rainfed farming systems in north-eastern Australia have had to adapt to a variety of resource limitations, predominantly water supply. The more northern areas have a wide potential planting window for summer crops (7 months) but this may be limited by inadequate water availability and high or low temperatures. In the more southern areas of this region the summer and winter planting windows overlap; however moisture is still a key limiting factor. In a climate that is highly variable, systems have been developed that permit cropping on either an opportunistic or planned basis, based mostly on strategies that conserve water in soils and then make the most efficient use of it. Such strategies include fallowing, adjusting plant population density and planting geometry and selection from a wide range of cultivars. If the grain crop failure seems unavoidable, the foliage may be grazed or baled for livestock to salvage plant material. Nitrogen, phosphorus and zinc are the main limiting nutrients. They are supplied by fertilisers, with some N also supplied by pulses in crop rotations. Research has indicated that there is, and has been, a net removal of soil nutrients by crops, and that this is unsustainable in the longer term.

Tools such as simulation and decision support systems are being used increasingly to develop production strategies in an environment that is inherently uncertain, and is expected to become more variable under climate change.

Cattle, and to a lesser extent sheep, make an important contribution to the farming systems of the region; however they are generally not integrated with crops through a pasture phase in rotations, as they often are in southern Australia. They graze on areas of farms with soils less suited to cropping, using native and improved pastures, and where suitable land is available, graze on sown annual cereal and legume species and crop residues, or they may be fed in feedlots.

An ongoing capacity to adapt, through adoption of new and advanced production practices, will be essential to the continued viability of agriculture in tropical and subtropical regions such as this with variable and sub-optimal rainfall.

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Chapter 26
Diversity and Evolution of Rainfed Farming Systems in Southern Australia

John A. Kirkegaard, Mark B. Peoples, John F. Angus, and Murray J. Unkovich

Abstract Rainfed farming systems in southern Australia have changed during recent decades from a traditional mixed crop–livestock system towards more intensive cropping. New technologies and greater economies of scale have increased productivity and have been accompanied by the adoption of more environmentally sustainable land management systems. Despite intensification of cropping, medium-term farm business profits vary less with the proportion of the area cropped than with the management skill of individual farmers. Many consultants believe that trends toward higher cropping intensity on mixed farms may have weakened recently as a result of prolonged drought, herbicide-resistant weeds, higher crop input costs, and higher prices for livestock products. These adjustments demonstrate the benefits of the reversible integration of mixed crop–livestock systems. Optimism for the future of broadacre farming, re-ignited in 2008 by high world grain prices and increasing demand for meat, is tempered by concerns over rising energy and input costs, the possible impacts of climate change, and slowing productivity trends. Case studies in this chapter illustrate the development of mixed farming systems in contrasting regions: (1) the equiseasonal rainfall area of southern New South Wales with clay loam soils, and (2) the winter-dominant rainfall area of the northern sand plain of Western Australia.

Keywords Mixed farming • Intensive cropping • Productivity • Sustainability

26.1 Introduction

This chapter focuses on the mixed farming areas of southern Australia lying south of latitude 32°S. We do not address the approximately three million hectares (M ha) of permanent pasture land in the high rainfall zone, or the 300 M ha of the arid

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_26,

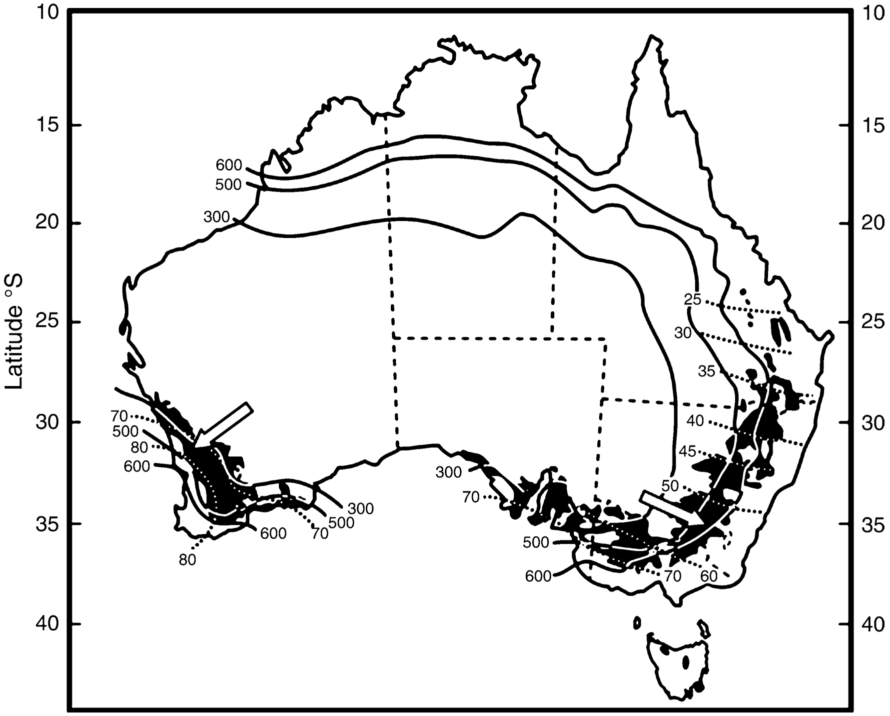

Fig. 26.1 The distribution of broadacre crop production in Australia (Angus and Good 2004 with permission of Crop Science Society of America). The southern mixed farming zones discussed in this chapter are those areas in south-eastern and Western Australia which receive 300–600 mm rainfall annually (*as shown by solid isohyets*), with >50% falling during winter months (*as indicated by the dotted lines*). Regions considered in more detail (Sect. 26.6) are indicated by arrows

inland pastoral zone. Around 80% of the 19–22 Mt grain produced each year in Australia between 2001 and 2006 came from southern Australia. There are estimated to be 39,500 broadacre[1] farms in the Wheat–Sheep Zone (ABARE 2006). These have mainly winter-dominant rainfall in the south and west, grading to summer-dominant in the north-east (Dark shading in Fig. 26.1). Until the 1980s, farms in this area were mainly mixed, producing mostly wool, typically from self-replacing Merino flocks, and wheat.[2] Since then, the diversity of grain and livestock enterprises has expanded with differences increasing between regions as well as between individual enterprises within regions. Thus mixed farming operations may involve not only wool production but also dual-purpose flocks, prime lamb, and beef production as well as livestock trading and agistment. The diversity of grain cropping has also expanded since the 1980s to include a range of pulse and oilseed crops and more conserved forage integrated into the cropping sequence.

[1] See Glossary.

[2] See Glossary for botanical names of crops.

Regional diversity in the enterprise mix varies widely, and while the national average cropping intensity (i.e. percent of farm area used for cropping) is around 35%, it ranges from 54% in the northern grains belt of Western Australia (WA) to 19% in central New South Wales (NSW) (Connell and Hooper 2002). Even greater diversity exists among individual farms, and most mixed farming regions contain farms that specialise in cropping, and those that produce livestock exclusively. Nevertheless most broadacre farms in southern Australia retain some mix of crops and livestock. As such, they have greater flexibility to alter or diversify their enterprise mix compared to other regions of Australia which tend to focus on specific products (see also Chaps. 11 and 25).

The enterprise mix and management operations that have developed in southern Australia are determined by a complex mix of biophysical resources (climate and soils), technical, economic and social factors, and the personal preferences and aspirations of individual landholders. This chapter examines how these factors influence diversity of system enterprises and operation in the mixed farming zone stretching some 3,000 km in length. Further, in the early part of the twenty-first century, it is important to assess the environmental sustainability of agricultural production systems with respect to climate change, energy requirements, soil degradation, agrichemical use and animal welfare.

The ley-farming system of repeated cycles of cropping rotated with annual legume-based pastures, once considered a model of sustainability (Puckridge and French 1983), has now been linked to high leaching losses of N and accelerated rates of soil acidification in the higher-rainfall areas (Ridley et al. 2004). However, the sustainability of both intensive cropping and intensive livestock enterprises that have replaced annual leys in some areas also require closer consideration.

In the following sections, we provide an assessment of mixed farming systems in southern Australia, focusing on the economic, environmental and social changes which have occurred during the last 20–30 years. We use research data, industry statistics and information from agricultural consultant client groups and individual farmer case studies to highlight recent trends in farm structure and operation, and likely future directions. Two contrasting areas, the equiseasonal rainfall region of southern NSW and the winter rainfall region in the northern sandplains of WA, are used to highlight differences in adaptation which result from varying the biophysical resource base.

26.2 The International Context

26.2.1 The World-Wide Impetus for Separation and Intensification of Cropping and Livestock Production

The separation and intensification of cropping and livestock production have been under way since the middle of the twentieth century in, for example, western Europe and the prairies of north America. This swing to separate intensive cropping and intensive livestock systems, which have almost totally replaced mixed farming, has occurred partly because of the economic efficiency of specialisation. In the developed world, the separation of cropping and livestock had been previously restricted by the need to recycle nutrients, particularly nitrogen (N), from animals to crops. This limitation was removed in the mid-twentieth century with the widespread availability of N fertiliser produced from cheap natural gas and other fossil fuels. Fertiliser, which was an insignificant source of N in the mid-twentieth century, now supplies more N input to crops than manure plus mineralisation of soil organic matter and decomposing legume residues (Smil 2000). The price of N fertiliser also decreased in real terms during the second half of the twentieth century.

An increased use of fossil fuel on farms has been accompanied by the increasing size of machinery for cropping, enabling economies of scale and reduced labour costs. Virtually all cropping operations can be mechanised and many of the costs are "per hectare" rather than "per tonne", so that relative costs tend to fall with increasing yield. Fewer economies of scale are available with grazing animals because operations such as drenching and shearing require labour on a "per head" basis. Other aspects of productivity growth show no clear differences between cropping and grazing industries. Breeding for more productive plants and animals have both been effective and the increased efficacy of herbicides, fungicides and insecticides for crops is matched by similar improvements in chemicals for parasite control and vaccines for disease in grazing animals.

26.2.2 The Situation in Southern Australia

There are explanations for the less pronounced trend towards specialised crop and animal production in southern Australia compared to elsewhere in the world. The climate is benign for grazing animals because it is not necessary to provide shelter during the mild winter. Furthermore, less feeding of conserved fodder is needed in the dry summer because dry forage and crop residues retain their quality in the field. Historically, there have been comparative advantages of keeping livestock for the export of animal products such as wool and meat because their high value could support the cost of freight along sea lanes to European customers. Grain traditionally lacked this advantage, although the situation has changed with the growing markets in the nearby Asia-Pacific region and the decreasing real cost of bulk freight. Another marketing advantage for Australian animal products has been the absence of Foot and Mouth disease[3] and bovine spongiform encephalopathy.

Since most of the production from southern Australian agriculture has been exported, prices received by farmers for commodities have typically been set by world markets. Until the 1980s, the main commodities produced by mixed farms were wool and wheat, in enterprises well suited to the environment. This combination provided income stability for farmers because low prices for one were often offset

[3] See Glossary for explanation.

by high prices for the other. Some price stability was also obtained from barley, beef and sheep meat, but their contribution to total income was relatively minor and local. Southern Australian farmers needed the income diversification provided by the sheep–wheat combination as they received virtually no price support or other forms of income maintenance from government.

Grazing animals on crop farms also provide income from non-arable areas where hills, rocky ground, thin infertile soils, or areas prone to water-logging or frost, are unsuitable for cropping. On arable lands, livestock graze phased pastures, forage crops, stubble, and failed grain crops.

26.3 Mixed Farming Systems in Southern Australia – An Overview of Industry Trends

26.3.1 A Brief History

After an initial decline in soil fertility from clearing and cropping in the early part of the twentieth century, the introduction of pasture legumes – subterranean clover (*Trifolium subterraneum)* on acid soils, annual medics (*Medicago* spp.) on alkaline soils – and related impacts of applications of superphosphate on pasture productivity resulted in substantial improvements in soil N fertility for cropping (Perry 1992). The ley farming system that developed (Donald and Williams 1954) has remained a key feature of rainfed agriculture in southern Australian since the 1950s, with advantages for both profitability and sustainability (Puckridge and French 1983; Tow and Schulz 1991). Historically, mixed farming operations provided opportunities not only to capitalise on potential synergies and complementarities between relatively stable crop and livestock enterprises (as detailed by Wolfe – Chap. 11), but also to change the enterprise mix reversibly in response to the relative short-term profitability of the main commodities. However, farmers faced increasing costs and progressively declining terms of trade from the 1950s[4] until the late 1980s so that the only practical solution was to improve productivity, reduce inefficiencies of operation and focus on more profitable enterprises. Since the early 1990s, there is some evidence that terms of trade for agricultural industries may have stabilised (Mullen 2007).

26.3.2 Industry Production and Profitability Trends

During the 1990s, changing commodity prices, farm profitability and seasonal conditions brought a significant shift in the mix of agricultural production which resulted in fewer livestock and increased grain production (Fig. 26.2). Despite the

[4]See also Chap. 12.

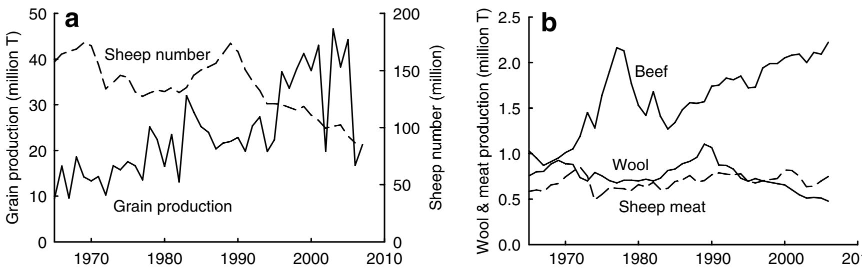

Fig. 26.2 Changes in Australian grain and livestock industries, 1965–2007 (ABARE 2008). Grain is the sum of wheat, coarse grain, oilseed and pulses. Wool is expressed on a greasy basis and meat represents carcass weight of beef and sheep, where sheep meat is the sum of lamb, mutton and an estimate for live-sheep exports, based on a 20 kg carcass weight. The animal production and numbers are from the high-rainfall and pastoral zones as well as the sheep-cereal zone

general advantages of grazing industries in southern Australia mentioned earlier, their productivity and profitability had not kept pace with that of crops. Between 1980 and 2006, Australian grain production doubled, beef production rose by about one half to regain peak levels of the late 1970s, and sheep meat production increased by one third. While wool production peaked during a period of high price in the late 1980s it has since fallen to half. The production data in Fig. 26.2 show more seasonal variability in crops than in animal enterprises, reflecting the impact of late frosts and drought on grain yield, in contrast to the buffering in livestock productivity through the use of standing pasture, conserved fodder such as hay and silage, or supplementary feeding with grain.

A major feature of Fig. 26.2 is the dramatic decline in sheep numbers and wool production since about 1990. The shift from wool to cropping was most dramatic in the wheat–sheep zone where average farm wool output declined by 13% per year during the period, and most farms earned more income from non-agricultural sources than from wool (ABARE 2008). The increased emphasis on cropping was driven by the greater profit from cropping than from sheep or beef cattle production (Fig. 26.3). The relatively poor economic performance of livestock resulted in a reduction in the profitability of mixed enterprises compared to sole cropping (Fig. 26.3). A key element was that productivity increases through this period were low for sheep and beef cattle, but higher for grains. A focus for the grains industry was how better to manage its resource base, particularly in the light of soil degradation and the increasing incidence of herbicide resistance across weed species.

Since 1990, as grains profitability has increased relative to livestock (particularly wool), the number of grain-producing farms has fallen by one third (45,000–30,000) but average farm size has increased from 1,700 ha to just below 2,500 ha (2.1% per annum) (Fig. 26.4). At the same time, crop area per farm increased by 3.6% per annum, associated with an increase in areas sown to pulses and oilseeds and a decline in total stocking rate of the non-cropped part of the farm from about 2.0 to 1.5 sheep equivalents per ha (calculated from Fig. 26.4 and assuming cattle are equivalent to eight sheep). Another emerging trend has been an increase in

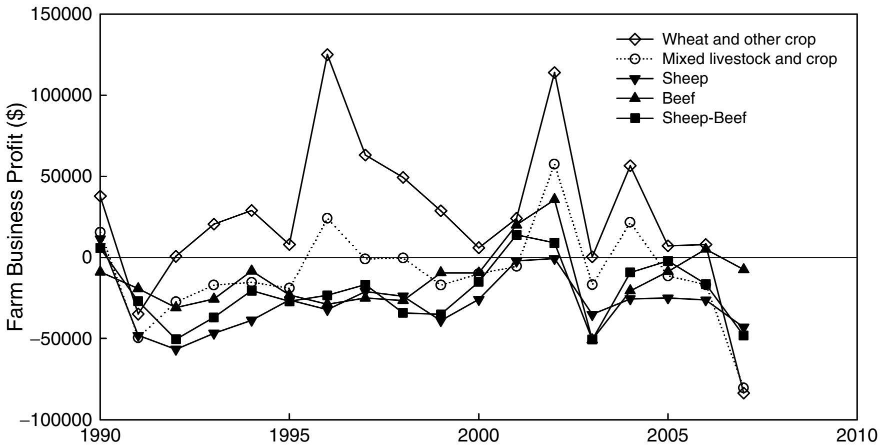

Fig. 26.3 Australian Farm business profit 1990/1991–2006/2007 (Based on data from ABARE 2008). Average of all farms in the individual industry

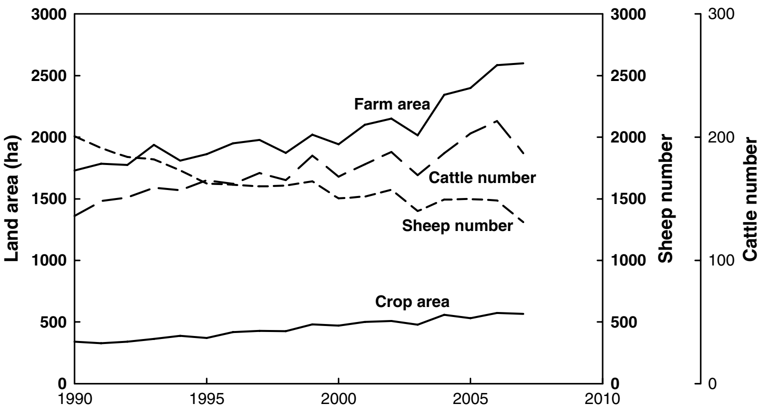

Fig. 26.4 Changes in land area, crop area and livestock numbers per farm in the wheat-sheep belt 1990–2007 (ABARE 2008)

production of hay and silage. Increasing animal production from feedlots and dairies depends largely on the supply of grain and conserved fodder from rainfed farms. Since intensive animal production is reported together with extensive production in statistical data, it is likely that the decrease in animal production on mixed farms may be greater than appears in Figs. 26.2 and 26.4.

As rural industries occupy 75% of the Australian landscape, governments and communities increasingly expect them to produce high-quality, competitive agricultural commodities without degrading the natural resource base and with good levels of animal welfare. A range of potentially undesirable impacts of farming on the environment have been identified (e.g. see Table 26.1). Researchers and farmers are responding to these issues by adaptive management or by adopting new technologies to address the problems once they arise (Table 26.1).

Table 26.1 Examples of environmental problems identified with farming practices in the rainfed farming systems of southern Australia, and strategies introduced to address them

Issue	Emergence	Examples of remedial changes	Reference
Soil erosion	Since 1930s	Reduced fallowing, improved pastures, contour banks, reduced tillage, stubble retention, strategic de-stocking, and drought lots	Cornish and Pratley (1987)
Soil acidification	1970s	Acid-tolerant plants Lime applied to cropped soil	Hajkowicz and Young (2005)
Soil structural decline	1980	No-till, stubble retention Controlled traffic Rotational grazing Gypsum application	Pratley and Robertson (1998)
Secondary salinity	1990	Perennial pastures, shrubs and trees Mosaic farming[5] Engineering works e.g. interceptor drains	Stirzaker et al. (2000)
Pesticides	1990	Minimise herbicide resistance in weeds Block farming[5] to minimise chemical drift Drum collection schemes (drumMuster)	Pratley and Robertson (1998)
Biodiversity	2000	Reduced clearing of native vegetation Fencing remnant native vegetation	Stoneham et al. (2002)
River health	>2000	Excluding livestock from riparian zones Salt interception schemes Environmental flows and water buy-backs Limits on farm-dam capacity	MDB Report
Climate change	2005	Reduced clearing of native vegetation Carbon sequestration in trees and soil Possible carbon trading	Garnaut (2008)
Animal welfare	2007	Mulesing phase-out	AWI (2008)

[5] See Glossary.

Despite the impact of drought across major cropping areas from 2002 until the time of writing in 2008, overall prospects for agriculture in southern Australia in the medium term are positive, provided more normal seasonal conditions return. One reason for this is that growing demand, driven by relatively low world grain stocks, is projected to underpin favourable prices. Low grain stocks in 2008 were largely a result of a series of unfavourable growing seasons in different regions of the world, and of government incentives in the USA and EU leading to the use of grain for biofuel production. The combination of continued growth in agricultural productivity and a slowing in the decline in terms of trade may mean Australia's ability to compete on world markets could improve (Mullen 2007). Productivity and financial viability also influence environmental management as low profits limit investment in the technologies or practices shown in Table 26.1 to protect the resource base of agriculture.

26.4 Farming System Evolution Through Technology and Innovation

Several technological innovations, discussed in this Section, have been adopted broadly across mixed farming systems of southern Australia during the last 20–30 years (Fig. 26.5). These have contributed to gains in total factor productivity (TFP), a measure of the ratio of marketable outputs to marketable inputs (Kokic et al. 2006), and positive environmental outcomes. In some cases, the innovations are specific to particular enterprises, but most create benefits which flow through the whole farming system.

Awareness of the individual issues and background research often preceded wider adoption by decades, partly because on-farm benefits were only achieved by the synergies of integrated, easily adopted management packages. An example is the increase in wheat yields during the 1990s which flowed from the combined impacts of (1) broadleaf break crops such as canola on the control of cereal root disease, (2) tactical N fertiliser management (on newly responsive, disease-free wheat crops grown after canola), (3) liming (made profitable by responsive break crops), and (4) more timely no-till sowing of crops into retained stubble (facilitated by non-selective herbicides) (Fig. 26.5). Both cereal root diseases and acid soils had been identified and understood as limiting factors in crop production for decades, but the availability of profitable break crops underpinned a synergy of farming system change.

Many of the major innovations in plant, animal and soil management adopted in southern Australia since the 1980s have improved both productivity and the efficiency of input use (water, fertiliser, labour) so that individual enterprise profitability stayed ahead of the declining terms of trade. Often these innovations also contributed to alleviating the environmental concerns outlined in Table 26.1. In the following sections, these innovations are discussed in relation to how they have facilitated changes in the farming system.

SYSTEMS ISSUES		SYSTEMS INNOVATIONS: SOIL	CROP/PASTURE		LIVESTOCK
1980s	EROSION ACIDITY SOIL STRUCTURE	Reduced tillage Lime, P Stubble retention	Pasture leys Acid tolerant plants Selective herbicides	GENETIC IMPROVEMENT	Managing stocking rate Rotational grazing Parasite control
1990s	ROOT DISEASE SALINITY WATER-USE-EFFICIENCY	Tactical N management No-till	Break crops Manage phase changes Perennials		New anthelmintics Objective breeding EBVs Feedbase management
2000s	SUBSOIL CONSTRAINTS INPUT EFFICIENCEY BIODIVERSITY	Controlled traffic Precision agriculture	Dual-purpose crops Short-term pastures Remnant vegetation management		Pregnancy scanning Drought feediots Fencing remnants and riparian zones
2010s	CLIMATE CHANGE ANIMAL WELFARE	Soil carbon management	Biofuel options		Control methane emissions Mulesing alternatives

Fig. 26.5 A summary of farming systems issues and the technical innovations in soil, plant and animal science that have helped address them in productive mixed farming systems. Genetic improvements in crop and pasture plants and in livestock have continued in parallel with innovations in plant and animal management. System improvements have arisen from packages of these technologies being adopted and adapted to local regions

We do not include the impacts of increasing farm size (see Fig. 26.4), mechanisation, automation and the advent of more rapid communication and data acquisition through facsimiles (fax), computers and, more recently, the internet to obtain weather forecasts and marketing information (See Chap. 7). We acknowledge the important role of these technical innovations during a period when labour costs and timeliness have been important influences on farm productivity, but we now focus more on innovations in crop, pasture, soil and livestock management which have improved system productivity and sustainability.

26.4.1 Genetics for Improved Plant and Animal Performance

Improvements in the disease-resistance, yield and quality of crop and pasture species have contributed significantly to increased productivity of mixed farming systems during the last 20–30 years (Fig. 26.5). Conventional breeding of wheat and other cereals has delivered a steady yield improvement of around 0.5% per year since crop production began in southern Australia in the late 1800s, with some periods of up to 1% following release of the semi-dwarf varieties (Fischer 2009). Initially the yield increase was associated with phenological adaptation to ensure optimum flowering time, lodging resistance and increases in harvest index of the crop. Disease-resistance (in particular against yellow or stripe rust) and grain quality requirements significantly compromise capacity to make genetic gain for yield potential. These have received continued attention in breeding programs; however, improved grain yield under limited water supply remains a target. The development and continued improvement of a range of alternative legume and oilseed crops and pastures has also involved significant breeding effort.[6] These efforts have often involved major quality improvements (e.g. reduced erucic acid and glucosinolate content to convert rapeseed to canola) or the need to overcome catastrophic disease and pest outbreaks such as aphids in lucerne (Downes 1980), blackleg (*Leptosphaeria maculans*) in canola (Cowling 2007) and ascochyta (*Ascochyta rabiei*) in chickpea (Nasir et al. 2000). In pasture legume and grass species,[7] improvements in tolerance to soil acidity, waterlogging and diseases have contributed significantly to the overall improvement in winter forage production of new varieties, which is a key profit driver in animal enterprises. New breeding technologies including molecular markers and improved statistical methods have provided more reliable and rapid selection, more targeted genetic gain and new genetic diversity. Benefits from genetic modification have come much more slowly than initially predicted because of public concerns about these technologies and consequent State government moratoria.

The genetic improvements in crop and pasture species have parallels in animal breeding. The principles of population genetics for farm animals were largely developed by the 1980s but were not widely adopted at the time by the stud industry. Since then, groups of producers and some studs have adopted objective breeding strategies such as Estimated Breeding Values (EBVs), (for sheep now available as Australian Sheep Breeding Values – ASBVs) and a range of associated tools. These have generated significant improvements, most clearly within the lamb meat industry, which has been transformed by the adoption of these approaches (Banks 2002). EBVs describe the value of each animal's genes, calculated using information from performance of individual animals and its relatives. In all, EBVs are now available for over 45 traits, including growth, carcass composition, wool weight and quality, reproduction and disease traits, at a range of ages. Australian Sheep Breeding Values (ASBVs) have been developed to ensure that there is a common national language for genetic breeding values that are used in the Australian sheep industry. Benefits which have been achieved in the meat industries are beginning to flow into the wool industry where there appears to be a relatively untapped source of productivity improvement (Massy 2007).

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[6] See http://www.csiro.au/org/OilseedsLegumesOverview.html

[7] http://www.csiro.au/science/ps108.html,http://www.wool.com.au/Pastures/Pasture_selection_and_plant_breeding/page__2021.aspx

26.4.2 Improvements in Plant and Animal Nutrition

Low soil pH can significantly limit crop and pasture performance. Naturally acidic soils (pH <5.0 $CaCl_2$) are common in the mixed farming zone in south-eastern and WA (Scott et al. 2007). Acidification rates are accelerated by the use of legumes and the subsequent leaching of nitrate, along with associated cations, by the removal of plant products and by the use of acidifying fertilisers (Helyar et al. 1997). Acidity of surface soils can be readily addressed by the application of lime, but its application to acid soils was limited during the 1980s because the main cereal (wheat) and pasture legume (subterranean clover) were relatively tolerant to acid soils. Despite the problem of "sub-clover decline", thought to be related to acid soils, and the sensitivity of other pasture species such as lucerne to acidity, livestock enterprise income rarely justified the expense of lime application. It was the expansion of the more acid-sensitive crop canola during the 1990s that stimulated a major increase in lime application to farms in southern Australia, providing opportunities to include other acid-sensitive species in the farming system. Lime application to the surface does not ameliorate deeper soil layers which can continue to acidify. Sub-surface acidity remains a concern as deep placement of lime is problematic and currently uneconomic. On alkaline soils in low-rainfall southern Australia, where acidity was not an issue, ley farming systems based on annual *Medicago* species predominate as they are well adapted to the combination of alkaline soils and winter-dominant rainfall.

Most of the specific nutrient deficiencies and toxicities affecting animal and plant production were resolved during the mid to late twentieth century. The more recent focus has been on better matching supply with demand to improve nutrient use efficiency. In crop production, more efficient use of N fertiliser now involves more careful N budgeting. This includes pre-season soil testing for available N, in-crop assessments and later top-dressing (Angus 2001). As N fertiliser costs rise, more effective capture and efficient use of both biologically fixed-N and fertiliser N will be needed.

In pasture production, the focus has been on phosphorus (P) fertiliser with the development of a 1-step P-Buffer index (Burkitt et al. 2002) leading to much better determination of P supply in perennial pastures (Moody 2007). It is now also recognised that the productivity of native pasture can be improved by fertiliser application (Garden et al. 2003). Until recently, there has been less emphasis on applying P fertiliser to crops, except for application of fluid P fertilisers on highly P-fixing alkaline soils in South Australia (Holloway et al. 2001). Experimental responses to the deep placement of nutrients on duplex soils have also been impressive, but systems developed for deep delivery to date have been too expensive (Adcock et al. 2007).

Innovations in livestock nutrition have included targeted supplementary feeding to boost ovulation rates, increase staple strength and reduced fibre diameter in wool. In addition livestock finishing, mineral supplements, and supplementary feeding during droughts have been improved. In many cases, supplementary feeding systems and management of the overall feed-base have been assisted by computer-based animal nutrition programs within grazing decision support tools such as GRAZFEED and GRAZPLAN (Donnelly et al. 2002). More recently programs such as "Pastures from Space" are being used by livestock managers to remotely assess pasture availability and better manage feed supplies (CSIRO 2008).

Dual-purpose, semi-winter or obligate-winter cereals – sown early and grazed during the winter feed gap, prior to grain production – have been used for some time in mixed farming operations in the 500–700 mm rainfall zones of southern Australia (Dann et al. 1983). The development of milling-quality, dual-purpose wheat varieties has caused a rapid expansion of dual-purpose wheat since 2000 (Virgona et al. 2006). These cereals have higher winter growth rates than pasture grasses and legumes, and provide high-quality feed. They also provide an opportunity to spell winter pastures, especially during the recovery after winter spray-topping[8] for weed control. Management of the timing and intensity of grazing allows recovery without significant grain yield penalty. The profitability of dual-purpose crops can be higher than grain-only crops, provided an appropriate animal enterprise is used (Virgona et al. 2006). Whole-farm benefits are moderated by the frequency of early planting opportunities, and also by the need to remove perennial pasture earlier to establish the crop, to move stock elsewhere during the establishment period and to maintain or purchase livestock to capitalise on the additional winter forage. Recent outbreaks of wheat streak mosaic virus have also reduced the safe early sowing opportunities for wheat although lower-value oat and triticale options are less affected. Recent research has also shown that winter and long-season canola varieties may have potential for dual-purpose (graze/grain) use while also acting as a break crop for weed and disease control in mixed farming systems (Kirkegaard et al. 2008b).

26.4.3 Disease Control – Break Crops and Animal Health

Before the 1980s, cereal root diseases including Take-all[9] were ubiquitous in mixed farming systems across southern Australia. These systems comprised mainly cereals in rotation with pasture phases, which along with legumes, contain grasses that are hosts to cereal diseases. Prior to selective grass herbicides, grassy weed hosts of take-all growing within small areas of non-host rotation crops such as oats, oilseeds and grain legumes also perpetuated the disease within the farming system. The development and rapid expansion of lupin[10] as a break crop in WA during the 1980s, and subsequently canola throughout southern Australia, significantly reduced the impact of these diseases, providing average yield benefits of 20% to following cereals (Kirkegaard et al. 2008a).

[8] See Glossary for explanation.

[9] *Gaeumannomyces graminis*.

[10] See Glossary for botanical name.

The break crops also provided benefits to the N economy of the farming system – legume break crops by contributions of 40–60 kg/ha of symbiotically-fixed nitrogen, and legume and oilseed break crops by the increased efficiency and responsiveness of the disease-free cereal crop to N fertiliser. Such break crops also provided opportunities for better grass weed control, and the freedom of their residues from cereal disease inoculum allowed surface residue retention for the practice of conservation agriculture. The lime applied to canola benefited acid-sensitive perennial pasture species such as lucerne. In southern NSW, the combination of canola break crops, liming, responsiveness to tactical N fertiliser and earlier sowing afforded by conservation cropping, combined to almost double average wheat yields during the 1990s (Angus 2001). When these crops were combined with 3–4 year phases of legume-based perennial pastures (now more productive due to liming), the resulting "phase-farming system" was one of the most profitable and sustainable systems to emerge during the 1990s.

Parallel success flowed from disease control in mixed farming systems on the lighter-textured alkaline soils of the South Australian and Victorian Mallee regions. This arose from the development of cereal cyst nematode (CCN)-resistant cereals, grass-cleaned[11] medic-based pastures, *Pratylenchus*-tolerant break-crops and the use of no-till with stubble retention (Coventry et al. 1998); *Rhizoctonia* root rot remains an important disease under these systems.

Significant improvements in animal productivity have also arisen from innovations in animal health. Strategic control programs for internal parasites, arising from research conducted in the 1970s, was implemented during the 1980s. Summer drenching in southern regions increased flock and per head productivity and reduced drenching frequency (to less than once every 6 weeks). This translated into much more efficient use of labour. New macrocyclic lactones were highly effective drenches (Lyons et al. 1989), and became available just as major resistance problems to existing products were becoming serious on many farms. New methods for control of external parasites include pour-on lice control and the highly effective insect growth hormone (IGR group) for control of blowflies, reducing losses from flystrike. In terms of the reproductive health of animals, pregnancy scanning allowed more directed management of pregnant or dry ewes and improved the efficiency of feed and flock management.

26.4.4 Herbicides and Herbicide-Tolerant Crops

Many selective herbicides using an array of modes of action have become available during the last 20–30 years (see Chap. 8). These have facilitated the adoption of conservation cropping systems (see next section) and underpinned the intensification of cropping in many areas. Despite the development of herbicide-resistance, selective herbicides and herbicide-tolerant crops have improved yields immensely

[11] See Glossary.

through reductions in weed competition, hosts of root disease, and losses of pre-season stored water and mineral N to weeds. These systems have also provided flexibility in the choice of crop and pasture sequences previously impractical due to weed control constraints.

The widespread adoption of triazine-tolerant canola varieties heralded the era of herbicide-tolerant crops and facilitated the expansion of canola into areas where it previously could not be grown because of wild radish (*Raphanus sativus*) infestation. The suite of herbicide-tolerant crops has since expanded to other modes, the latest and most contentious of which is glyphosate (Round-up®)-resistance. Moratoria on the sowing of genetically-modified (GM) glyphosate-resistant canola cultivars have been lifted in some Australian states in spite of concerns about the development of "superweeds", the difficulty of segregating GM from non-GM varieties and the loss of some export markets. A sound stewardship program is required to avoid widespread development of glyphosate-resistant weed species (as has occurred in the USA) while capturing the benefits of this new tool in weed management (see Chaps. 8 and 31).

26.4.5 Conservation Agriculture, Zone Management and Precision Agriculture

Significant adoption of direct-drilling (no-till) and other conservation agriculture (CA) techniques did not start until the 1980s with the advent of suitable herbicides, machinery and region-specific extension packages (Cornish and Pratley 1987). In many cases, adoption by growers was driven as much by cost savings (labour, fuel and machinery) and improved timeliness of planting operations as by potential reductions in soil erosion. The general progression of the technology has been from reduced tillage (number of passes) to no-till (no cultivation prior to sowing), to minimal surface-soil disturbance at sowing using narrow points (zero-till), and retention of as much residue on the surface as possible. Various machinery modifications (wider tine spacing, disc openers, deeper sowing points, separate fertiliser placement tubes) for specific soil conditions have improved the precision of seed placement (see Chap. 39).

Further improvements in input efficiency and soil protection have been promoted recently through controlled traffic farming (CTF). In this, machinery is confined to permanent tracks, which can be guided by global positioning systems (GPS) with 2 cm accuracy, allowing crops to be sown between rows of a previous crop and reducing re-infection of cereals by stubble-borne crop diseases such as crown rot (*Fusarium pseudograminearum*) (See also Chap. 34).

On mixed farms in southern Australia, there were also benefits from CA through extended grazing during the autumn (no-till fallows), increased availability of stubble for grazing (not burnt), firmer soil to reduce potential trampling damage by livestock, as well as the longer-term improvement to soil structure and fertility. However, the compatibility of no-till, CTF cropping with grazing animals has been questioned due to potential impact of animals on soil structure. Ironically, the increased cropping intensity and herbicide use under a no-till, CTF regime can accelerate the development of herbicide resistance in weeds. This often requires either cultivation or a return to a pasture phase for adequate control.

Differential management of contrasting zones within variable paddocks according to the soil type, or to other positional characteristics influencing productivity (frost, pH, soil fertility, soil depth, salinity), offers opportunities to improve input efficiency and to maximise profitability from large heterogeneous paddocks. Inputs can be reduced or abandoned on consistently unresponsive zones and optimised on responsive zones. Yield monitors routinely fitted to harvesters provide growers with information on the yield variability across paddocks and can be complemented with other remote or mobile sensing tools. These monitor biomass and/or N status of crops during the growing season or soil properties such as salt concentrations using electromagnetic induction (EM) meters. These technologies, collectively referred to as "precision agriculture" (PA), can lead to benefits of up to $50/ha/year in broadacre cropping systems although this has been variable (Robertson et al. 2009, Chaps. 4, 34 and 39).

During the late 1980s and 1990s, raised-bed farming was developed in high-rainfall areas (>550 mm) of the southern and western regions of the mixed farming zone to reduce the impact of winter water-logging on crops and pastures (Roth et al. 2005). These principles, widely used in irrigated agriculture, have been adapted since the 1990s to generate a successful and highly productive system on land otherwise restricted by frequent winter inundation (some 80,000 ha in southern Australia and 35,000 ha in WA). The system is generally suitable for land with 0.2–1.5% slope. The beds effectively form a field drainage tool and, by their nature, control traffic movements and improve soil structure where traffic is absent. Risk of crop failure is reduced, crop yields are increased by 10–40% and the system is highly profitable – with increases in farm income of $180/ha/year – despite the initial costs of installation (Roth et al. 2005). Mixed farming systems incorporating raised beds are possible as long as grazing is managed to avoid excessive damage to the beds in wet conditions and beds are designed to avoid animals being cast.[12] However, pasture performance and persistence on the beds has been poor, especially regeneration in dry autumn months.

26.4.6 Annual and Perennial Phased Pastures and a Possible Role for Woody Perennials

Declining economic returns from grazing enterprises during the 1980s and 1990s (Fig. 26.3) led to reduced expenditure on pasture leys, and often an extension of the cropping phase. In some cases, this led to a continuous cropping sequence of cereals and broadleaf crops, using herbicides and more fertiliser N.

[12] See Glossary.

Without careful nutrient, pest and grazing management, the legume content of pastures declined. Grasses and broadleaf weeds dominated, reducing potential N fixation, disease-break benefits and feed value of the pastures. However, a refocus on the benefits of a pasture phase to subsequent crops has generated renewed interest in pasture management. Management practices included winter "cleaning" of pastures using grass-selective herbicides in the year before cropping, improved P nutrition, liming and control of pests such as red-legged mite (*Halotydeus destructor*). These measures substantially improved the input of fixed N by pasture legumes, increasing soil mineral N by 100–200 kg N/ha/year and increasing grain yield from following crops by 30–50% (Peoples et al. 1998; Harris et al. 2002). Rotational effects of pastures can persist for 2–3 years into the cropping phase.

Despite the many benefits of the ley farming system, a mismatch has sometimes occurred between the timing of rainfall and the water requirements of the annual crops and pastures causing an insidious increase in deep drainage and secondary salinity (Passioura and Ridley 1998). This issue emerged right across southern Australia, though most dramatically in catchments in WA where the permeable sandy soils and strongly winter-dominant rainfall led to the most rapid rise in saline water tables (Dunin 2002). This problem has been minimised by inclusion in the system of perennial plant species, such as lucerne, which can utilise deeply stored water (Angus et al. 2001; Ridley et al. 2001; Ward et al. 2001; Fillery and Poulter 2006). Lucerne may not only reduce deep drainage but may also provide a larger and more consistent (year-round) supply of high-quality forage than annual clovers and fix considerably more N (Peoples et al. 1998). Depending upon the timing of its removal before cropping, lucerne can supply much of the soil mineral N for following crops (Angus et al. 2000).

Perennial grass species, including phalaris and cocksfoot, and dicotyledonous plants such as chicory, have been proposed as alternatives to lucerne on soils which are acid or prone to waterlogging (e.g. Sandral et al. 2006), but these are also not suited to all environments (Fillery and Poulter 2006). Phase-farming with suitably adapted perennial pastures may thus provide adequate control of deep drainage in areas with annual rainfall less than 600 mm.

In higher rainfall areas, other approaches might be required (Passioura and Ridley 1998). "Pasture cropping", a system involving planting of winter crops into permanent, winter-dormant native grass pastures or lucerne swards, may provide a strategy to retain the water-use characteristics of the perennial throughout a sequence of annual crops. To date, this has not been widely adopted (Harris et al. 2007), and it is restricted to areas receiving year-round rainfall (see Fig. 26.1). The use of trees and other woody species may be required to achieve the required reduction in groundwater recharge in higher rainfall areas (greater than 600 mm) and systems of block planting, tree belts, alley cropping, and woodlots have been investigated (e.g. Lefroy et al. 2001; Stirzaker et al. 2002). Other suggestions are patches and corridors of planted native vegetation, managed remnant vegetation or riparian strips with limited or no grazing by livestock. The concept of "mosaic" farming proposes a positioning of this perennial vegetation to provide a mosaic with productive crops and pastures in the landscape in an effort to capture a range of ecosystem services such as water capture, deep drainage reduction, riparian zone protection, refuges for beneficial bird or insect species for pest control, and zones with high biodiversity value. At present, mosaic farming is probably limited by a lack of profitable perennial species (Brennan et al. 2004), but is the focus of on-going research.

26.4.7 Benchmarks of Performance

The widespread use of benchmarks of farm productivity and economic performance has been a hallmark of the last 20 years in agriculture. Benchmarks represent productivity or economic targets considered to be close to the achievable limit for particular scenarios against which farm performance can be compared (see also Chap. 27). The water-use efficiency (WUE)/Potential Yield benchmark for cereals published by French and Schultz (1984) provided a valuable tool to assess crop performance under variable rainfall (see Chap. 1). It provided a stimulus for researchers and growers to diagnose and address yield-limiting factors. Several industry-wide surveys have since used the benchmark to compare regional crop performance and to target research investment (Hamblin and Kyneur 1993; Beeston et al. 2005). The concept has also been modified to include economic (e.g. $/ha/mm rainfall) and business health indicators (Beever and McCarthy 2004).

With similar purposes, structured paddock monitoring programs such as TopCrop and CropCheck encourage growers to monitor and record crop performance at specific stages throughout the season (e.g. records of plant density, tillers/m^2, flowering dates). These programs have provided opportunities to extend packages of recommended best practice to growers, while anonymous comparisons of performance within local grower groups have provided insights for improvement. Sustainability indicators have also been developed and added to productivity and financial performance indicators for use in industry-wide surveys to guide research and development (See Chap. 27; Connell and Hooper 2002).

The extensive use of performance indicators within the grains industry has no obvious parallel in the livestock sector where levied funds are directed more to product marketing and promotion than to production research. Individual consultant groups which specialise in livestock-dominated industries are the exception (e.g. McEachern et al. 2007), where stocking rate benchmarks such as DSE[13]/ha/100 mm and $/DSE are applied. Computer-based crop simulation models (e.g. APSIM) (Keating et al. 2003) and animal–pasture simulation (e.g. GRAZPLAN) (Donnelly 2002) have been developed to allow paddock-specific simulations to be conducted to predict outcomes of particular management strategies.

[13] Dry Sheep Equivalent – see Glossary for explanation.

26.5 Factors Influencing System Structure and Function – Perspectives from Agricultural Consultants

Sections 26.3 and 26.4 have dealt with the evolution of southern Australian mixed farming systems at the industry level. This conceals the considerable variation in operation, productivity and profitably occurring amongst individual farms. To try to understand the causes of this variation, we interviewed ten leading agricultural consultants across southern Australia and examined recent published reviews of client data. Such consultants operate regionally and often serve 50 or more clients. Their observations can provide insights into farm systems not gained in other ways. Figure 26.6 summarises factors influencing the composition of cropping and livestock enterprises on farms, and some of the differences between specialist crop and livestock enterprises which are discussed in more detail below.

26.5.1 Biophysical Factors

The type of land and its suitability for cropping or livestock enterprises is a fundamental determinant of land use including the overall enterprise mix and the types of animal enterprises and crop or pasture rotations possible on farms. Many farms have a proportion of land unsuitable for cropping (steep, frost-prone, water-logged, infertile) and offering more opportunity for profit from grazing (Fig. 26.6). Increasingly these areas are also being targeted as potential "set-aside" land for re-vegetation or biodiversity value on farms. In southern Australia, farms within the higher rainfall zones (>500 mm) will often also comprise hilly or undulating landscapes with significant areas of non-arable land, or land with considerable erosion risk, a greater proportion of which is usually devoted to livestock enterprises.

On flatter land, generally further inland and with lower rainfall (less than 400 mm), a greater proportion of farms are arable and higher proportions of farms are cropped. The frequency of drought and rainfall reliability also influence decisions to maintain enterprise diversity on farms; for example, the consultants generally reported that the serious drought affecting much of eastern Australia in the early part of the twenty-first century has slowed the trend toward more cropping. This is a consequence of significant economic losses incurred in high-input cropping operations reliant on more drought-sensitive broadleaf break crops for adequate disease and weed control. These break crops generate larger losses than well-managed pastures in dry seasons.

26.5.2 Technical Factors

Most consultants agreed that the requirements for weed management, especially of herbicide-resistant weeds, have contributed to the slowdown or reversal of continuous cropping in some areas. Even on continuous cropping farms where much of

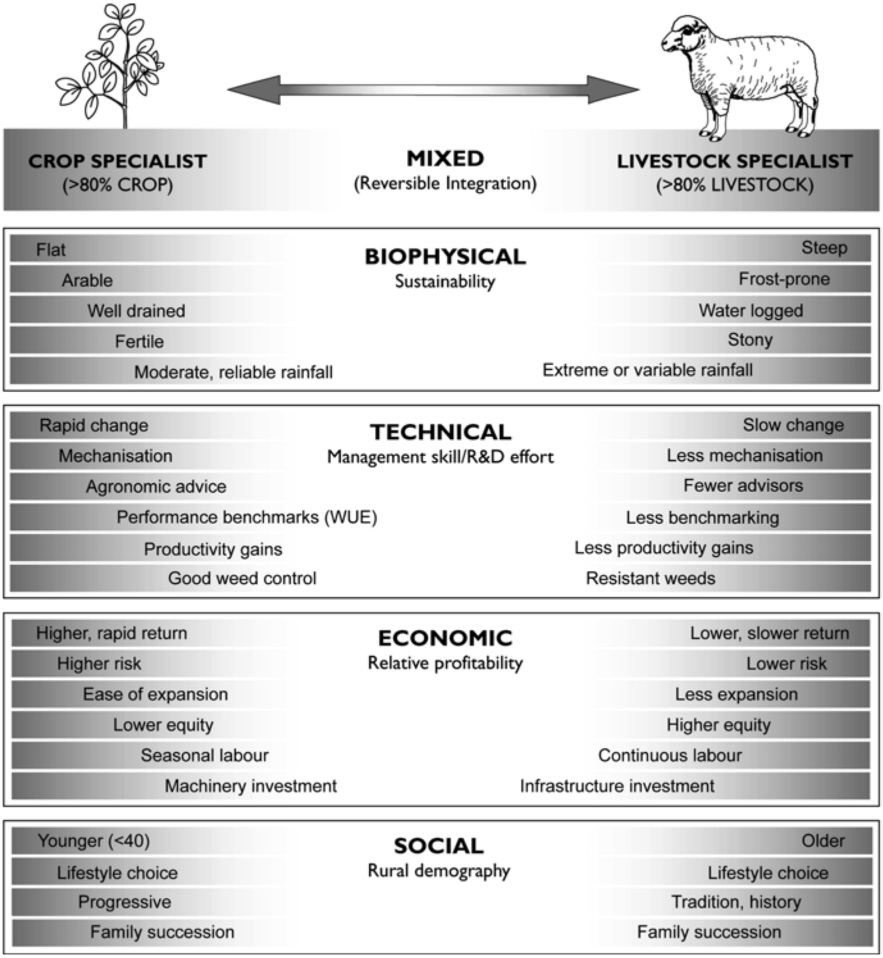

Fig. 26.6 Factors nominated by ten agricultural consultants as influencing the mix of livestock and crops on mixed farms. Some factors of specific importance for crop and livestock specialists are shown under each category while important issues of relevance to individual managers irrespective of the crop:livestock mix are shown in the centre. Potentially irreversible specialty in either cropping or livestock may arise when the relevant infrastructure (e.g. livestock, fences, water troughs) are no longer maintained, relevant skilled labour is unavailable, or there are economic imperatives

the infrastructure for livestock is gone, a break in cropping for grain is generally required to control weeds. Such a break could involve production of hay, green manure or pasture. On such farms, pastures are now treated more like a crop, and livestock are often bought in to capitalise on opportunities arising from additional forage production. Where fences may have been removed, hay or stubble straw can be cut and sold off-farm. Farmers are also encouraged to maintain diversity of enterprises in farm systems to reduce the risks to crop production from crop diseases.

These include threats from increasingly virulent strains of stripe rust of wheat (*Puccinia striiformis*), a new strain of wheat leaf rust (*Puccinia graminis*), *Ascochyta* in chickpeas and wheat streak mosaic virus in early-sown dual-purpose cereal crops.

Grains industry access to consultants and advice is not often matched in livestock enterprises. Cropping has had the edge in utilising performance indicators (e.g. WUE benchmarks) to identify limitations to profitability and promote adoption of innovations such as break crops, no-till, integrated weed management, fertiliser budgets and liming requirements. Agronomists employed by input suppliers provide an increasing amount of advice about cropping, particularly on topics related to agrichemicals, but provide less information about pasture and livestock, which generally require lower inputs. Livestock benchmarks are often focussed on "per head" measures (e.g. fleece weight/head, lambing percentage, sale weights) which may correlate poorly with "per ha" profitability. Independent consultants provide more advice on strategic topics such as crop and pasture sequences, stocking rates and lambing times. Some independent advisers specialise on either crops or livestock industries, but the more experienced cover integrated systems.

Farmers who specialise in sheep can make big profit gains with good management, improved pasture cultivars, good animal nutrition, marketing and trading, efficient cell/strip grazing, higher twinning percentages, feed-lotting and confinement. An example was given of a young farmer increasing lambing by 40% in two consecutive years after attending a course on livestock nutrition. Unfortunately, good crop managers are often poor livestock producers. For instance, some consultants suggest that there is a negative correlation between the proportion of the farm cropped, and stocking rate (as the driver of animal enterprise profitability) on the remainder. This can reduce whole-farm profitability. The extent to which a focus on one enterprise can come at the expense of another enterprise cannot be overlooked, and these trade-offs are discussed in more detail in Chap. 11. However, the lack of any clear relationship between the enterprise proportions and overall farm profitability on individual farms within regions (see Fig. 26.7a) suggests that much of the variation in farm profitability is driven more by manager skill than enterprise mix.

26.5.3 Economic Factors of the Enterprise Mix

The higher profitability for cropping than for livestock production persisted from the wool price crash in the 1970s until the severe drought of 2006/2007. This has fostered a long-term shift to higher proportions of cropping on farms. Consultants also suggested that the move to cropping was favoured by the ease of expansion, livestock labour shortages (made worse by the mining boom), a dislike by some farmers for wool marketing, capital investment concerns, and occupational health and safety issues. Often the significant investment made in new machinery for expanded cropping forces many farmers to remain in high cropping enterprises (i.e. an irreversible specialisation, Fig. 26.6), even though the lower equity and higher gearing of some cropping enterprises exposes them to significant risk in a

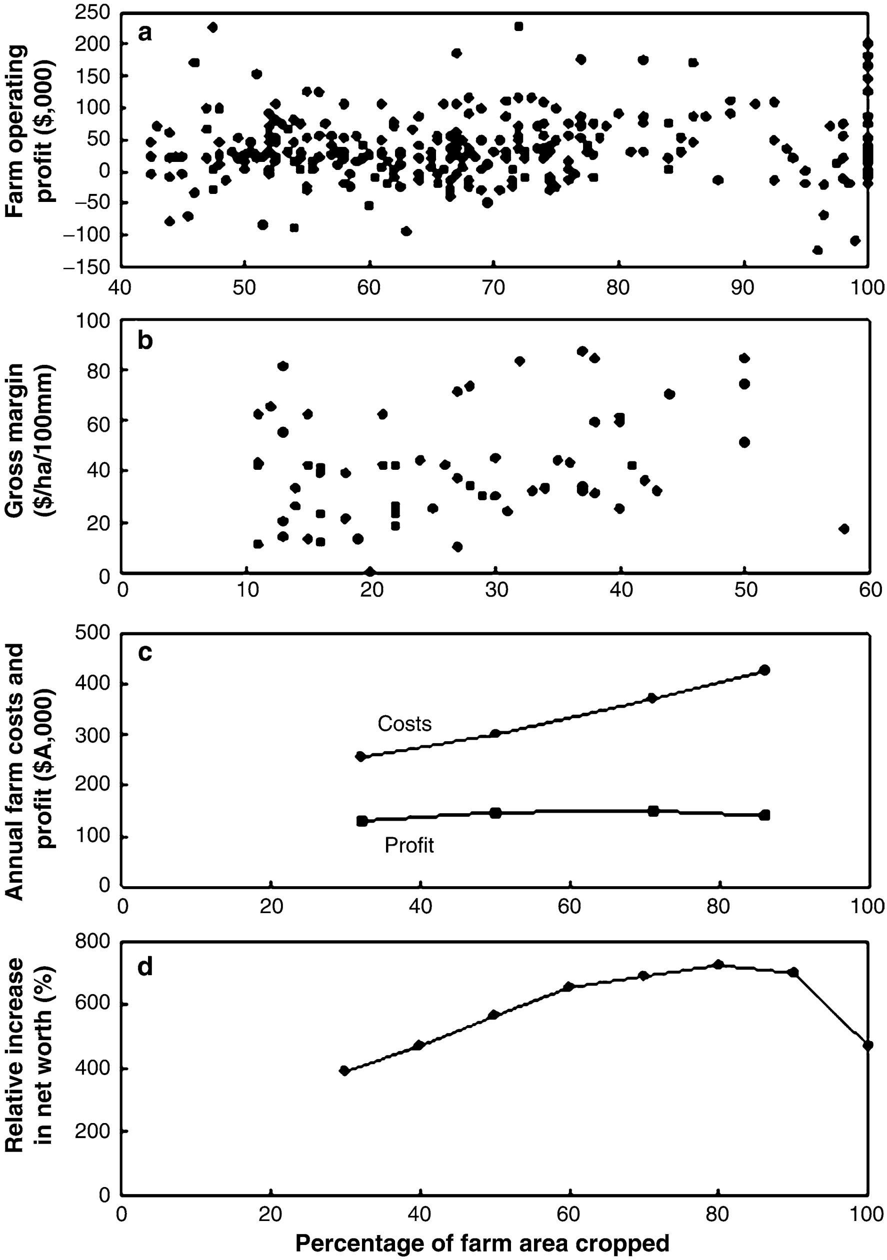

Fig. 26.7 Financial performance of mixed crop–livestock farms in relation to the percentage of cropped area from four regional consultant surveys throughout southern Australia (**a**) Average operating profit over 5 years for crop-dominated farms in Western Australia (Sands and McCarthy 2007); (**b**) Gross margin per unit of rainfall for livestock-dominant farms in south-eastern Australia, mostly in the slopes areas of NSW (McEachern et al. 2007); (**c**) Mean annual costs and profit for mixed farms in a 350 mm rainfall area of the Eyre Peninsula, SA (Hunt and Lynch 2007); (**d**) Mean increase in net worth (between 1995 and 2005) for farms in the south-west slopes of NSW (Sykes 2007)

series of low-rainfall years. Many medium-sized businesses may at first try to intensify into more cropping, but because sufficient economies of scale may not be available to them, they will instead look to diversify in mixed farming.

The recent trends towards rising costs of fuel, fertiliser and harvesting may curb the increase in intensity of cropping, especially in lower-rainfall areas. Some consultants consider that many good crop producers are already operating near economic potential, given the available technology, and that further improvements in productivity through increased inputs may be offset by the increased risk associated with those investments. However, significant gains in profitability remain possible through new research in both cropping and livestock and, in the case of livestock enterprises, through closer attention to profit drivers such as increased winter stocking rate.

A number of consultant groups throughout southern Australia have recently published surveys of economic data from clients to investigate the relative profitability of different farm enterprises and to consider the optimum enterprise mix (Fig. 26.7). While the surveys from different groups are difficult to compare due to regional differences in the mixture of enterprises and in how "crop specialists" are defined, a relatively consistent picture nevertheless emerges. In general, there is little variation in actual farm profitability across a wide range of enterprise mix (50–80% cropping). Outside these limits, the evidence from all regions represented in Fig. 26.7 suggests little benefit from further crop intensification (>90%) while pointing to opportunities for increased profitability from this at low cropping intensity (<50%).

In Western Australia, Sands and McCarthy (2007) found little impact of variations in the enterprise mix on 5-year farm operating profit among 292 clients (Fig. 26.7a), but questioned the continued intensification of cropping (>90%) in some areas in the face of increased input costs and herbicide resistance in weeds. A comparison of two closely-located farms showed how the farm with 66% of the area cropped and with good livestock management returned 5% on productive assets compared with 2.6% for the farm with 100% crop. This difference was largely caused by the lower returns from the legume and oilseed break crops in 100% cropping enterprises than from well-managed pastures in the mixed farm.

McEachern et al. (2007) surveyed 135 mixed (greater than 15% income from crops) and grazing farm businesses throughout south-eastern Australia. They found that the 9-year average gross margin was higher for mixed farms ($210,000) than for grazing farms ($140,000), even after normalising for rainfall ($/ha/100 mm) (Fig. 26.7b). While gross margins and operating profits provide somewhat different measures of financial performance, the key point for both the crop-dominated and livestock-dominated enterprises was that there was more variation in the economic performance between individual producers than between different enterprise mixes (Fig. 26.7a, b).

In the Eyre Peninsula of South Australia, a study by Hunt and Lynch (2007) showed that as cropping increased above 85%, farm profit declined because well-run livestock operations had similar gross margins to break crops, but plant and machinery depreciation and input costs were much higher under intensive cropping (Fig. 26.7c).

On the south-west slopes of New South Wales, Sykes (2007) reported a significant mean increase in the area cropped by clients during the 1990s (from 40% to 62%), and found that the largest increases in net worth (Fig. 26.7d) came from enterprises which adopted the best cropping technology, cropped 80–90% of land and expanded their total crop area by purchasing new land. In contrast, operating profit was highest for those who had raised productivity alone as larger borrowings and poor seasons penalised those who had purchased land. Increases in land prices have since limited the capacity to capture the same benefits from expansion. Although the data in Fig. 26.7d appear to be inconsistent with the surveys summarised in Figs. 26.7a, b and c that show no evidence of benefits from increased cropping intensity; the benefit to net worth from increased cropping in Fig. 26.7d is mostly from increased land values. While this was a real benefit to the farmers who bought land at the time, it does not disprove the results of the other three studies that show no benefit from increased cropping intensity in these surveys.

Experimental comparisons of the economics of such enterprise mixes are rare, but a study by the Birchip Cropping Group (BCG 2006) comparing continuous cropping systems and mixed farming systems supports the surveys in showing little benefit from high cropping intensity. The experiment conducted in western Victoria from 2000 to 2006 showed that gross margins (gross income minus variable costs) for the system with 70% crop and high stocking rates on pasture ("hungry sheep") were a little higher than both fallow–cereal cropping with 60% crop ("fuel burner") and an opportunistic continuous cropping system with a high proportion of cereals and 80% crop ("reduced till") (Table 26.2). These three systems were much more profitable than the one with 100% cereals, oilseeds and pulses, with full stubble retention and minimum soil disturbance ("no-till"). This was due to the poor performance of the various break crops included in the "no-till" system. Lower annual rainfall during the experimental period (290 versus 347 mm long-term average) may have favoured the mixed systems. The economic analysis does not include possible changes in soil properties (e.g. C, N, physical structure) associated with the different management regimes.

In summary, it is clear that, despite the intensification of cropping in response to higher profitability revealed in the national statistics (Sect. 26.3), the medium-term farm business profits of individual enterprises vary less with the proportion of area cropped than with the management skill of individual farmers. Thus well-managed pastures with livestock in mixed farms may be as profitable as non-cereal break crops in some intensive cropping systems.

Table 26.2 Gross margin of four farming systems averaged from 2000 to 2006 from an experiment conducted by the Birchip Cropping Group (BCG 2006)

Farming system	Gross margin ($A/ha)
Fuel burner	84.8
Hungry sheep	97.8
Reduced till	82.2
No till	36.5

26.5.4 Social Factors

Consultants generally agreed that, within the biophysical limits, personal preferences and social factors drive decisions about the enterprise mix, and the economics are often bent to fit the farmer's preference (see also Chap. 30). There is a widely held view that younger farmers (age under 40) are generally less interested in livestock, which often become the responsibility of older family members. The livestock enterprises on family farms then decline as the seniors age and their capacity to contribute labour declines. The average age of farmers within the grains industry in southern Australia was around 50 in 2001 (Connell and Hooper 2002) and is increasing, which may be a factor in the declining numbers of sheep, especially for wool production.

The increasing influence of the environmental movement and the emphasis given to perennials in the farming system were mentioned as drivers for retention of a pasture area and, as a consequence, of the livestock enterprise. Consultants also believed that although there is an increase in corporate ownership, farms will primarily remain family-owned, but will get bigger. Diversification is also reflected in an increasing proportion of total income earned off-farm (e.g. from residential property, contract work).

Data and experience from practising agricultural consultants across southern Australia illustrate that decisions around enterprise mix and management on individual farms are influenced by factors beyond the economic performance of individual sectors or commodities and the presumed complementarities between crops and livestock.

Importantly, the data reveal considerable scope for improved productivity and profitability of individual farms that is linked to improved management across a wide range of different cropping intensities. The interplay of these factors are best exemplified using case studies of individual farms as the many combinations of circumstances suggested in Fig. 26.6 are difficult to capture without specific examples. In Sect. 26.6, we focus on more detailed discussion of the farming systems within two contrasting regions, and provide case studies to illustrate how mixed and specialist farmers in both regions have adapted to the changes in the industry (Sect. 26.2), the technical innovations (Sect. 26.4), and other factors (Sect. 26.5) during the last few decades.

26.6 Regional and Enterprise Diversity

In this section, we move from broader industry considerations across the southern rainfed farming zone, to focus on two specific regions – the southern slopes of New South Wales (NSW) and the northern sandplains of Western Australia (WA), as shown by arrows in Fig. 26.1. Table 26.3 summarises enterprise data for the two regions and compares farms in the average and the highest and lowest quartiles of

Table 26.3 Performance indicators for the grains industry in two regions from 1998/1999 to 2000/2001 (Connell and Hooper 2002)

	Ranked by rate of return on capital		
	Average	Top 25%	Bottom 25%
NSW Slopes			
Total effective area (ha)	1,010	1,077	417
Cropping intensity (% area sown to crop)	33	45	21
Broadleaf crop (% of total crop)	32	31	28
Direct drill (% of crop)	42	46	0
Landcare (membership %)	60	15	91
Age (years)	53	44	69
Farm income ($)	317,569	429,094	145,543
Farm surplus ($ income–operating costs)	126,934	211,214	31,363
Net off-farm income ($)	18,514	26,840	4,448
Disposable income per family ($)	65,845	116,445	16,220
Rate of return (%)	+3.8	+10.9	–4.7
Northern WA			
Total effective area (ha)	3,251	2,846	2,153
Cropping intensity (% area sown to crop)	54	63	50
Broadleaf crop (% of total crop)	29	29	39
Direct drill (% of crop)	55	10	85
Landcare (membership %)	87	100	89
Age (years)	54	50	60
Farm income ($)	621,975	707,451	575,675
Farm surplus ($ income–operating costs)	168,874	281,117	24,382
Net off-farm income ($)	13,538	16,492	20,757
Disposable income per family ($)	43,079	134,945	–53,951
Rate of return (%)	+0.7	+6.4	–4.1

rate of return on capital. The northern WA region has, on average, larger farms, a greater cropping intensity, more direct-drilling and higher Landcare membership than the NSW farms, but the two regions had similar proportions of broadleaf crops (canola and pulses) and average age of farmers. Despite the WA farms generating on average twice the farm income of the NSW farms, their average disposable income and rate of return was much lower. This was due to the higher costs and overheads of the WA farm businesses.

Within the NSW region, the poorer performing farms (lower rate of return on capital) were smaller and had much lower farm income than the best performing farms. This was in contrast to northern WA, where differences in farm size and income were far less dramatic between the performance classes. In both regions, the operators of poor-performing farms were on average more than 10 years older than those on the best performing farms, which may have had a significant influence on both their motivation and capacity to generate high income. There is no consistent relationship between the productivity and the sustainability indicators of Landcare membership and use of direct drilling. In NSW, the top performing farms had low Landcare membership but relatively high practice of direct drilling, whereas in WA they had higher Landcare membership but very low adoption of direct-drilling. Clearly care must be taken in interpreting the links between productivity and sustainability indicators at broad survey scale.

Much is known about components of farming systems, but there is far less appreciation of how to harmonise those components for optimal “whole” farm performance, maximum sustainable profit and ease of management, especially at the interface between livestock production and cropping. There are also few “whole-farm” decision support tools or means to track whole-farm performance which recognise that each farmer’s economic, family and risk positions are also different. Below, we present case studies for the regions described in Table 26.3 to illustrate the changes in enterprise mix that have occurred in the past two decades. They illustrate the interplay of the above factors on farms which have either moved towards continuous cropping or have retained a significant livestock enterprise in the farming system.

26.6.1 Northern Sandplains of Western Australia

The northern sandplain has a gently undulating landscape, and the predominant soils are mildly acidic sands (Rudosols[14]) and sand-over–clays (duplex soils such as Sodosols). Both soil types are erosion-prone, have low water-holding capacity, and can be non-wetting. The Rudosols are mostly deep, allowing annual crop roots to reach a depth of 2–3 m (Hamblin and Hamblin 1985; Unkovich et al. 1994). The climate is semi-arid with winter-dominant rainfall and a mean growing-season rainfall (May–Oct) of 314 mm.

Much of the area was developed for cropping in the 1950s and, by the early twenty-first century, wheat made up 70% of the crop area, lupin up to 20%, with the remainder sown to barley, oats, triticale, field pea and faba bean. Livestock are principally self-replacing Merino sheep. The lupin industry of the northern sandplain region of WA was a major development (Delane et al. 1989). This crop provided a profitable alternative to subterranean clover-based pasture as a means of increasing soil N for following cereals (Unkovich et al. 1994). Early sowing, the key to maximising yields of wheat and lupin (French and D’Antuono 2003) depends on the timing of the autumn break.

About 50% of wheat has been grown in rotation with lupin and the other 50% in rotation with self-regenerating annual pastures containing subterranean clover on light soils or annual medics on heavier soils. Income from livestock enterprises varies with the intensity of stocking, but typically only accounts for 15% of farm income in the region, with export wheat providing more than 50%. Wheat yields average around 2.2 t/ha and are the mainstay of agriculture in this region.

[14]This chapter uses the Australian Soil Classification see http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm.

The relative importance of the different enterprises has changed with their profitability. In the mid-1950s, about 50% of farm area was allocated to self-regenerating annual pastures. Livestock enterprises decreased in the 1970s and 1980s, but recovered briefly in the late 1980s with improved wool prices. The lower wool prices since then have led to a period of more intensive cropping using the profitable lupin–wheat sequence. From 2001 to 2006, the total area of lupin in WA halved to 0.5 M ha, the lowest since 1986. This dramatic change was precipitated mainly by the widespread emergence of herbicide-resistant weeds, particularly annual ryegrass and wild radish, following repeated use of selective herbicides in the conservation cropping systems (Allen and Llewellyn 2003; Flower and Braslin 2006). Strategies to reduce these weed problems included "crop topping" (in-crop suppression of weed seed set by herbicides), and a range of machinery operations and grazing methods. Nevertheless, growers are forced to use more expensive herbicides, which the returns from lupin crops cannot sustain. A second pressure on lupin was the arrival of the anthracnose fungus in 1996. Despite containment, sowing lupin requires the additional expense of fungicide treatment, further eroding margins.

Triazine-tolerant canola increased in importance during the late 1990s to assist in weed management in the region, but its potential has been limited by late autumn rainfall breaks and short growing seasons. The release of glyphosate-tolerant canola may provide further weed control options.

Machinery innovations include deep ripping to remove compacted layers, controlled traffic and sowing rows using GPS guidance (tramlining). The financial benefits have been variable, ranging from –$27 to +$54/ha, and arise predominately from input efficiencies from reduced overlap in operations including herbicide and fertiliser application (Robertson et al. 2008).

Conflicts between livestock and cropping enterprises emerge as fallow weeds are eliminated, cropping intensity increases, and stubble is retained for erosion protection. These changes result in less feed resources for livestock, particularly over late summer and autumn. However, because of the low and variable rainfall in this environment, most growers will probably maintain some stock for income diversity and lower risk. Soil erosion caused by overgrazing of meager stubble remains a risk on sandy soils. Serradella (*Ornithopus compressus*), a promising annual pasture legume introduced in the 1990s, has been adopted by some growers.

26.6.1.1 Case Study – Ian Blayney, Mixed Farmer

Location: Geraldton district, WA
Mean Annual Rainfall: 385 mm, winter-dominant
Soils: fertile red soil river flats 10%; fertile yellow sandplains 25%; deep white infertile sands 50%; stony ridges 10%; native bush, rough hills, river frontage 5%

Enterprise description in 1990: Farm area was 3,000 ha, 75:25 crop:livestock ratio on the arable 75% of the farm area, with wheat and lupin crops concentrated on the better soils. The livestock were a self-replacing Merino flock at 3 DSE/ha (over the whole farm), grazing stubble and subterranean clover pastures on the better soils. Pastures on the poorer soils were WA blue lupin (*Lupinus cosentinii*) or serradella. Wind erosion was a significant problem.

Major changes since 1990: Ian increased farm size to 3,900 ha with the purchase of 500 ha of new land in 1997 and 400 ha in 1999. He upgraded cropping plant by purchasing second-hand machinery, and thereby conserved funds to invest in land. He continued to develop stock fences and water points for the livestock enterprise.

Between 2000 and 2005, cropped area expanded from 1,000 to 2,400 ha but contracted to 2,000 ha in 2007 when poorer soils were returned to pasture. Since 2000, he has purchased larger-scale cropping machinery to cover the ground quickly and improve timeliness of operations. He applied lime across the farm and spray-topped pastures to reduce herbicide-resistant ryegrass. He attempted to introduce serradellas to the farm but found it difficult to produce and harvest seed.

Ian has reduced cropping since 2006 by concentrating cropping effort on better paddocks to achieve higher yield and profit, and increasing sheep numbers on the other areas. However, the 2006/2007 drought reduced the flock to one third of the pre-2006 numbers, so crop area has returned to 2,400 ha for the 3–4 years needed to breed sheep replacements. The reasons for retaining livestock within the system include: (1) history and personal interest (they represent a lifetime work); (2) diversified additional income streams from wool and stock sales, particularly from poorer soils where crops struggle; (3) reduced capital in machinery and lower operating costs, spreading the workload across the year; and (4) management of herbicide resistance in ryegrass.

Future: Climate change has become a big worry, especially after the dry 2006 and 2007 seasons. If these become typical, Ian doubts the future long-term viability of the farm with the current enterprises. Potential improvements in productivity for this mixed farm may come from improved pasture management and new pasture species on poorer soils. Ian attended courses, run by Australian Wool Innovation, that suggested that the profitability driver for livestock was stocking rate, but he found that increasing stocking rates following this advice was disastrous in 2006. Ian considered that GM crops may help manage herbicide resistance in future.

26.6.1.2 Case Study – Brian and Tracy McAlpine, Specialist Cropping

Location: 20 km west of Maya, northern wheatbelt WA
Mean Annual Rainfall: 340 mm, winter-dominant
Soils: Yellow tamma-tussock sandplain (organic matter 0.2%); pockets of gravel, red clay, Salmon gum loams.

Enterprise description in 1990: 4,000 arable ha with 70:30 cropping livestock ratio. Wheat was the main crop (50% of farm area with average yields of 1.4 t/ha) with an increasing use of lupins (20%) in a very profitable wheat–lupin rotation. Crops were spread evenly around the farm for sheep grazing of stubble in summer. Sheep were run for wool and meat production on poor pastures made up of capeweed, annual ryegrass and wild radish[15] (DSE < 1).

Major changes since 1990: Wheat production methods changed from cultivation to no-till by 1993 but this led to increased weeds. These were managed by intensive cropping with lupins and then triazine-tolerant canola. An interest in long-term soil health also encouraged a move to continuous cropping due to the structural damage caused to the soil by livestock and the perceived potential to increase soil organic matter under continuous crop, no-till farming. In 1997, a gross margin analysis of paddock returns revealed low returns for sheep, and all stock were sold.

Sowing methods changed progressively from full cultivation to direct-drilling with wide points, then inverted T points, and finally to knife points. Deep ripping, green manure, potash and lime addition were all used to lift soil fertility and crop yields. Controlled traffic was introduced in 2005 as information on benefits became available.

The farm area expanded with purchase of new land (937 ha in 1999; 1,466 ha in 2002; 1,836 ha in 2006). By 2005, the area under crop peaked at 6,900 ha under wheat, barley, oats, lupin and canola. Lupin and canola crops failed in the droughts of 2006 and 2007, and although it was thought that herbicide resistance could be managed, good profits from these crops were required to achieve it. The lack of rain caused a trend back to livestock, but decisions about the need to diversify into livestock were also driven by herbicide resistance and emerging salinity problems in the region which required incorporation of deep-rooted perennial pasture species into the system.

In 2006, after considering other livestock diversification options, Brian and Tracy decided to introduce a “back-grounding” cattle enterprise. This involved agistment of cattle for around 6 months (winter/spring) from surrounding pastoral stations, with payment based on liveweight gain during the period. Back-grounding agistment involves no upfront purchase costs, no animal husbandry requirements and no summer feeding requirements. This is in contrast to the significant labour requirement of sheep enterprises at a time of limited labour supply during a regional mining boom. Since the sale of all farm livestock in 1997, the farm did not have sufficient infrastructure for cattle and so before cattle arrived for agistment, 500 ha of arable land with intractable weed problems was partitioned into 100 ha paddocks using electric fences and troughed water. Oat fodder crops as well as annual pastures provide cattle feed. In 2008, 93% of the farm was cropped and 7% was available for back-grounding cattle, actual proportions depending on the season and feed availability.

Future: Brian and Tracy see “backgrounding” as a feasible on-going part of farm diversification, implemented strategically in variable seasons. In the cropping system,

[15] See Glossary for botanical names.

they are concerned about the future of controlled traffic, as it restricts machinery purchase (scale and axle stress) to keep to the width, the “tramlines” are becoming eroded by rainfall, and crop residue is concentrated in the same spots. They will continue to seek improvements and modifications to add further efficiencies to the system while protecting the resource base.

26.6.2 Southern NSW Slopes and Plains

This mixed farming area comprises hills in the east grading to plains in the west. Soils in the east consist of loamy topsoil grading into clay at depth (Kandosols). Soils on the plains are generally Chromosols and Sodosols,[16] with loamy topsoil and a distinct texture contrast at 10–20 cm to a clay or clay loam. Sodosols, which include some areas of saline subsoils, can limit rooting depth and water-holding capacity. Annual rainfall, evenly distributed through the year, varies from more than 650 mm on the upper slopes where the elevation is 500–600 m above sea level to less than 400 mm on the plains where the elevation is around 100 m (asl). The area has been cropped for more than 100 years.

Until the 1980s, the area grew mainly cereals in rotation with annual grass–subterranean clover pastures and fallow, with some areas of early-sown oats for sheep. The area of lupins and field peas increased in the 1980s but has decreased since the late 1990s. Canola became a significant component of the system during the 1990s, always following an application of lime. Correction of the acidity by the lime allowed successful establishment of lucerne which has contributed greatly to the annual clover-based pasture production. Adoption of direct drilling and stubble retention has been much slower in this area than in most others, partly because erosion risk is lower on the highly permeable loam soils with the low rainfall intensity. The uniform (year-round) rainfall distribution also reduces the reliance of crops on stored moisture, and the productive legume-based pastures which are grown in phased rotation with crops contribute to the maintenance of organic matter. In addition, stubble loads in excess of 8 t/ha are common and present a significant obstacle to sowing equipment not specifically designed for stubble-retained cropping systems.

The undulating topography and areas of stony and acid soils in the east have served to maintain mixed farming systems. On the plains to the west, the low enthusiasm for continuous cropping has delayed the emergence of serious herbicide resistance in ryegrass, and wild radish is less prevalent. Adoption of controlled traffic has generated interest, but is slow because it may be incompatible with livestock.

[16]This chapter uses the Australian Soil Classification (Isbell 2002) or http://www.clw.csiro.au/aclep/asc_re_on_line/soilbgro.htm.

The use of canola, with increased lime addition, reduces cereal root diseases. Tactical N fertiliser application to responsive cereal crops produced significant improvements in average crop yield throughout the 1990s (Angus 2001). Root-disease control through spray-topping and winter-cleaning of pastures to remove grass hosts also allowed growers to capitalise on higher returns for high-protein cereals sown immediately after legume-based pastures. Highly productive pastures and dual-purpose crops support higher average winter stocking rates, leading to profitable livestock enterprises. The general trend toward higher cropping intensity observed nationally is also evident within the region in keeping with the trends in net farm worth (Fig. 26.7d).

26.6.2.1 Case Study – Hart Brothers, Mixed Farmers

Location: Junee Reefs, 50 km north of Wagga Wagga, NSW southern plains
Mean Annual Rainfall: 525 mm, uniformly distributed through the year
Soils: Red Kandosols, pH 4.2–4.8, C 0.85%, N 0.09%.

Enterprise description in 1990: The farm comprised 1,000 ha, with a 50:50 cropping:livestock ratio. Major crops were wheat (mean yield 4–4.5 t/ha) and canola (mean yield 1.8–2.0 t/ha) with smaller areas of lupins and field pea; medium wool is produced from a self-replacing Merino sheep flock. Lucerne–clover pastures was sown with wheat or canola in the last year of the cropping phase and removed using herbicides in the spring prior to cropping. The pastures were rotationally grazed on a 4-field system and supported 15–20 DSE/ha with hay and silage production in spring when rainfall was favourable. Rotations were typically 3 years of pasture followed by 3 years of crop. The farm business was managed by two brothers – Bernard, who specialised in cropping, and Adrian in livestock.

Major changes since 1990: Farm size increased from 1,000 ha in 1990 to around 2,500 ha in 2006, by purchase and lease. The partnership between the brothers was dissolved to allow succession. Leased blocks now form two compact operations in districts 50 km apart; most leased land is suitable for continuous cropping. The disadvantages of leasing are the additional complexities of financial management and of achieving a reasonable return on the investment over the lease cost.

A move to two sheep flocks, a self-replacing Merino flock and a cross-breed flock for prime lamb production, during 1990–2000 was reversed when the cross-breed flock was considered unprofitable and dispersed; the Merino ewes were joined to terminal rams for prime lamb production. Chicory was added to the lucerne-clover pasture mix in the early 2000s to help control “red gut” in lambs.[17] Lucerne survived well in the droughts during 2000–2006 but the clover consistently failed and, since 2003, pastures have been established in winter without a cover crop.

[17] See Glossary.

Crop performance has been benchmarked using the water use efficiency (WUE) system of French and Schultz based on effective April–October rainfall.[18] Between 1998 and 2005, the mean values of transpiration efficiency were estimated to be 17 kg grain/ha/mm (range 10–23) compared with the accepted benchmark of 20 kg grain/ha/mm.

Through most of the 1990s, a system based on a 50:50 crop:pasture ratio worked well but, in 1998, falling livestock gross margins prompted a move to 80:20 until 2002 when drought increased cropping costs and improved livestock returns caused a change to the current ratio of 65:35. The most profitable system occurred between 1992 and 2002 when pasture spring growth was either grazed and sprayed out prior to cropping, or cut for silage or hay. This gave excellent long-term (over 3 years) weed control and residual N benefits from the lucerne to the crops.

Whilst many total cropping enterprises have achieved cash flow by offsetting sales with delayed payments and stored grain, the Harts have found that cash flow from livestock has been steady except during the 2006/2007 drought. On the other hand, livestock rarely develop cash flows big enough to trade out of a drought whereas cropping may do so, given average world prices. Nonetheless, each enterprise is examined critically each year. When the crop gross margins are low because of low yields, it is difficult to cut costs in the face of unknown future rainfall. Livestock, on the other hand, are more flexible as the product is bred on farm and marketed at an approximately known price per kg. Further, the cost of maintaining stock in difficult seasons can be easily calculated. Investment costs tend to be about equal per ha of land use – about $500/ha for both stock and cropping machinery. In comparison, investment by continuous croppers tends to be higher at around $800 per ha (due to machinery overheads), or they have a heavy reliance on contractors.

Future: The Harts may well reduce the size and structure of their animal enterprises as family labour becomes less available, and relative prices shift across seasons, but they are still likely to retain some animal enterprises within their enterprise mix.

26.6.2.2 Case Study – Di and Warwick Holding, Specialist Croppers

Location: Yerong Creek, 40 km south of Wagga Wagga
Mean Annual Rainfall: 525 mm uniformly distributed through the year
Soils: Red Chromosols and Sodosols, pH 4.4–4.9, total C 1.3–1.9%

Enterprise description in 1990: The 300 ha family farm was 100% arable but with a 60:40 cropping:livestock ratio. The main crops were wheat, lupin, canola, triticale. First-cross ewes for prime lambs were grazed on subterranean clover–annual ryegrass or lucerne–clover pastures; there was a 40-sow piggery. The farm business

[18] Note that this location has significant summer rainfall. Moisture in the soil at planting needs to be taken into account in the calculation.

was managed by Warwick's father, but was too small to support the next generation. Warwick earned off-farm income from contract spraying and haymaking and by leasing land to run sheep.

Major changes since 1990: Warwick and Di began a program of expansion through buying land, leasing and share farming from 1995 and, by 2008, had expanded to 1,260 ha with 100% cropping of wheat, canola and faba beans, all using controlled traffic. The change from mixed cropping to continuous cropping was made because of personal preference for crops, the heavy workload required to keep sheep, the higher economic returns from crops than for sheep, and the damaging compaction of the surface soil by sheep. The transition to increasingly profitable and sustainable sole cropping occurred as follows:

Initial expansion of farming area and change to 100% cropping (1995–2002): Farming area was expanded in 1995 by leasing 260 ha for merino wethers (wool only), on condition that one third was cropped, and by share farming 160 ha. The latter was increased to 280 ha in 1998. A 40 ha "home block" was purchased.

All sheep were sold in 1998, and the proportion of the leased block under crop was increased to 70%. The other 30% was a poorly structured soil and remained under Phalaris pasture.

Two tractors, a boom spray and a second-hand airseeder were purchased during this period.

Advances towards Conservation Farming (*2002–2003*): The total area cropped was now 1,100 ha, including more canola with increased application of lime and gypsum. Crop failure in the drought was a watershed in terms of thinking about a change in soil management to conserve soil moisture.

Purchase of a new airseeder with narrow points on 22 cm spacing and a prickle-chain allowed direct-drilling for all crops including canola and all crop operations were now done "up and back" using global positioning system (GPS) guidance. Cutting and baling stubble led to less burning. Crop choice was based on disease and weed control with 2–3 year forward planning rather than chasing high prices at sowing.

Precision farming (*2004–2006*): In 2004, Di and Warwick purchased a harvester with a 10 cm GPS and began yield mapping, elevation mapping and improved accuracy of operations.

They were concerned that soil compaction remained a problem. Attendance at a Controlled Traffic Farming (CTF) Conference was a watershed and provided impetus for further modifications. In 2006, they adopted 12 m CTF on permanent wheel tracks with wheel centres spaced 3 m apart; and they installed 2 cm autosteer for all operations. The sowing tine spacing was widened from 22 to 30 cm and individual press wheels were added. They moved to block farming so that each leased farm was under the same crop for purposes of logistics, disease control and ease of management.

Continued "fine tuning" of previous developments, with diversification (*2007–2009*): By 2007, sulphonyl urea herbicides were no longer used on cereals because of their impact on canola. Stubble burning has been confined to tactical weed control.

Inter-row planting was introduced for cereals following cereals to reduce root disease. Income is supplemented with off-farm activities including contract planting, spraying, harvesting, windrowing, baling, spreading urea and running a communication business. Warwick and Di consider sheep are too much work, unprofitable and antagonistic rather than complementary to the crop enterprise, especially through surface soil compaction. However, on land they do not own they can still profit from sheep, without having to own them.

In 2008, they purchased 220 ha that was previously share-farmed.

By 2009, they were farming 305 ha of their own land, 910 ha leased, 320 ha share-farmed, 1,350 ha contract farming, all on controlled traffic.

Future: Their long-term goal to buy more land has been delayed by a series of droughts. Rising input costs are a greater concern than climate change which they believe they can adapt to. Their next innovation will be to have a grain-chaser bin which follows the harvester to unload grain on 12 m spacing permanent tracks. Another innovation will be to modify the harvester to direct chaff onto permanent wheel tracks, to allow spraying of any weeds which emerge, and to get a header straw spreader to distribute straw across 12 m.

26.6.3 Case-Study Summary

These case studies reinforce the data which point to a drift away from mixed farming to more intensive cropping in southern Australia. They illustrate how many of the technical innovations outlined in Sect. 26.4 have been adopted on-farm. They also highlight the importance of personal preference as well as family circumstances in enterprise selection and management, and the impacts of sudden changes on individual farms when land or large equipment items are purchased or livestock are sold. These changes were sometimes the result of long-term planning but sometimes triggered by changes in prices, droughts, or new family circumstances.

26.7 Conclusions and Future Issues

In recent decades, the rainfed farming systems of southern Australia have remained among those sectors of the Australian economy with the highest total factor productivity (a measure of production per unit input) (Kokic et al. 2006). This was achieved after a relentless decline in terms of trade, exposure to volatile global markets and the usual climatic variability. This achievement was underpinned by technical innovations to improve productivity and efficiency, adjustments to enterprise structure – primarily increased scale – and increased intensity and diversity of the cropping enterprises on mixed farms. Some of the cropping innovations (broadleaf break crops and tactical N fertiliser application) have led to more productive but more variable systems. Other technical innovations (e.g. lime application, no-till techniques, precision agriculture, increased use of perennial pastures) have not only increased productivity but also simultaneously reduced (but by no means eliminated) the risk of various forms of land degradation within the agricultural regions. At the same time, awareness of the broader issues of biodiversity, river health and climate change within the rural community is high.

However, as demonstrated by the consultant reviews and farmer case studies, the industry-wide trends outlined in Sects. 26.3 and 26.4 mask a great diversity of individual farm enterprise response to these external drivers for change. The evolution of that diversity exemplifies the value of the reversible integration of crop and livestock enterprises in southern Australia.

The predicted increase in world demand by 2030 for cereals (50%) and meat (80%) (World Bank 2007) provides optimism for the future of farming through high demand and prices. However, further changes in farming system will be influenced by continued volatility of global export markets, decisions on enterprise mix and management on individual farms, increases in energy-related input costs, a reduced labour force, increased scrutiny of the environmental and ethical credentials of production systems, and, with the projected climate change, increasingly warmer, drier and more variable seasons.

In the future we anticipate some existing trends to continue, such as fewer, larger farms with increased intensity and diversity of crops, more meat and less wool production, and increased off-farm investment. The following are also expected to occur:

- Farms will largely remain owner-occupied but there will be more contracting and use of advisory services (i.e. separation of ownership and management) and increases in equity rather than debt financing.
- Farms will be more closely integrated into marketing systems linked to value markets and improved efficiency of post farm-gate handling.
- Farmers will be more accountable and improve their environmental management (and perhaps be rewarded for these improvements).
- On-farm innovations in both crop and livestock production systems will focus on improved precision, with energy and labour efficiency, including the use of intelligent machinery with remote and electronic management.
- Projected climate change scenarios and higher energy prices may affect grazing enterprises less than cropping enterprises because of their lower energy use and greater stability under drought. This may cause a swing back towards more grazing, but new technology will inevitably be required to assist all enterprises adapt to climate change.
- Australian rainfed farming will have to benchmark its performance against its competitors in the export markets in relation to the possibility of greater vulnerability to climate change but lower dependency on external energy.
- In marginal areas, resilient cropping systems will require strategies to improve the capture and efficient use of water with careful attention to timeliness (e.g. safer approaches to fallowing, soil and residue management, and new

varieties with appropriate phasic development, higher water use efficiency and deeper water extraction).

- Systems will be needed to adapt broadleaf crops better into a changed climate so as to preserve the break crop advantages for cereals. At the same time, a drift of cropping into the higher, more reliable rainfall areas may be inevitable, where they will need to be integrated with existing livestock-dominated enterprises, and non-agricultural land uses.

Fine-tuning these adjustments to integrate enterprises on mixed farms may be limited initially by the lesser technological advance in the grazing industries compared to that in cropping. For example, production and utilisation of pasture will need to be improved. Improved integration of crop and livestock is also needed to underpin the future of mixed farming. Other necessary innovations will include increasing economies of scale and reducing labour-intensive operations.

Acknowledgments The authors would like to acknowledge contributions from agricultural consultants (Tim Condon, John Francis, Ed Hunt, Bill Long, Allan Mayfield, Matt McCallum, David Sackett, John Sykes, Alan Umbers, Geoff Wray) and growers (Ian Blayney, Bernard Hart, Warwick and Di Holding, Brian and Tracey McAlpine) for providing data, experience and useful discussions for this Chapter.

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Part III
Evaluation and Improvement of Rainfed Farming Systems

Part III chapters delve deeper into some aspects of the structure, operation and management of rainfed farming systems to show how they may be improved.

Chapter 27 deals with the imperative to monitor and evaluate the farm system and its components before the process of improvement; this also features in other chapters throughout the book. Examples of improvement of diverse farming systems include the:

- integration of research and management to achieve sustained crop yield improvements over a wide geographic area
- introduction of a new profitable crop (soybeans), together with associated marketing infrastructure, to produce a successful new farming system
- improvement in decision-making in mixed farming systems in times of drought through an understanding of the social character of, and social influences on, decision making by farmers
- widespread improvement in crop yields through the combination of advanced weed management technology and superior management
- change in the structure, components and management of the farm system to best suit changed environmental characteristics and marketing requirements
- introduction of a new and improved farm system (Conservation Agriculture) in a low-productivity, developing economy to improve productivity and sustainability
- achievement of greater efficiency and productivity through the advanced technologies of Conservation Agriculture and Precision Agriculture, requiring technical skill and superior management
- improvement of rainfed farming systems through adopting effective risk management.

Chapter 27
Using Monitoring and Evaluation for Continuous Improvement of Rainfed Farming Systems

Eloise Seymour and Roger Wickes

Abstract Monitoring and evaluation are essential components involved in managing rainfed farming systems and surrounding catchments in a sustainable way. Keeping track of changes, trends and farm inputs and outputs ensures that farm managers can make adjustments to the farming system with a view to continuous improvement. The continuous improvement of rainfed farming systems includes the monitoring and evaluation of the farm biophysical resources, business elements and human elements. A number of planning approaches are available that incorporate monitoring and evaluation into farm management. These include on-farm monitoring tools, simple target-setting, environmental self-assessment checklists and property management planning. These basic planning frameworks allow for monitoring and evaluation relating to the property and extending into surrounding catchments. Market-driven monitoring and evaluation processes such as Quality Assurance and Environmental Management Systems (EMS) are more complex and formal processes that are required by some industries and markets in developed countries.

Keywords Sustainability • Monitoring • Management action targets • Resource condition targets • Continuous improvement • Property planning • Self assessment check lists

27.1 Introduction

Rainfed farming systems are limited by rainfall and reliant on best use of resources (environmental, social and economic) within the constraints of local conditions. Flexibility and learning from past management decisions – learning by doing – is the basis for being able to farm these areas to their full potential whilst sustaining

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_27,

the resource base (particularly soil and genetic resources). Such adaptive management relies on monitoring and evaluation of the farming system by keeping track of changes, trends, farm inputs and outputs, and assessing success or failure of past actions/decisions. This monitoring allows the manager to make beneficial adjustments to the farming system – and leads to the concept of "**continuous improvement**". Central to continuous improvement of the farming system is the notion of *sustainability*.

As outlined in various other chapters of this book, there are many facets to a farming system which interact as part of the whole. In order to achieve continuous improvement, all of these elements should be considered in a monitoring and evaluation context, including:

- The **biophysical** elements relating to production (e.g. crops, pastures, soil, climate, physical inputs and outputs) and the environmental aspects of the property (e.g. area of remnant vegetation, riparian areas, soil condition, groundcover, nutrients entering waterways).
- The elements relating to **enterprise/business** management, such as business planning, staff management, adherence to industry requirements (e.g. Quality Assurance), setting business indicators, monitoring of gross margins and return on capital.
- The **people** elements, such as personal goals, succession planning, capacity-building of staff.

Maintaining the resource base in the farming system is vital for rainfed agriculture in both developed and developing countries. Further to this, consideration of how the activities occurring within the farming system impinge on the catchment (or watershed) around it is important for environmental sustainability beyond the farm – a factor of increasing community concern.

Strategic planning frameworks such as property management planning have a useful role for monitoring and evaluation in any rainfed farming system. Such approaches involve setting goals and targets (environmental, business and personal goals), implementing these goals, assessing the success of implementation and then using that information as a basis for review and improvement (Anon 1995). Included in the planning process is the formulation of resource condition targets (i.e. changes in the condition of the physical resources of the farm) and management actions (i.e. actions taken by the farmers that are expected to improve resource use) and simple indicators to measure progress (see Chap. 12 for more on this topic). Monitoring and evaluation are an important consideration when new concepts, technologies or innovations are introduced into the farming system.

While basic planning approaches can be applied to any rainfed farming system, more complex approaches may be required in developed countries where the demand for "clean and green" farm produce is increasing (See also Chap. 13). Supplying farm products that meet food safety, product quality and environmental requirements is part of the farming system in developed countries. As such, farm businesses are exposed to a plethora of approaches, tools, schemes and industry requirements – which can create confusion.

This chapter aims to provide a relatively simple overview across a number of key areas and approaches for monitoring and evaluation of rainfed farming systems. It begins with an exploration of the concept of sustainability and the role of on-farm monitoring to achieve sustainable rainfed farming systems. The impact of farming activities on catchment (or watershed) sustainability is also discussed. The development of on-farm targets and management actions are an important feature of monitoring and evaluation processes and are discussed in Sect. 27.3. Section 27.4 outlines a range of less formal monitoring and planning approaches that can be applied across all rainfed farming systems. The market-driven approaches, discussed in Sect. 27.5, are most relevant to the farming systems used in developed countries.

27.2 "Sustainability" of Rainfed Farming Systems

Sustainability is a term based on a variety of concepts and is given a range of meanings. Stoneham et al. (2003) defined sustainability in terms of ensuring that future generations have access to the same level of natural resource quality that is available to the current generation (which they called "strong sustainability"). The often-quoted Brundtland Report (WCED 1987) also focused on meeting the "needs of the present without compromising the ability of future generations to meet their own needs".

A sustainable farming system is said to be able to maintain itself biologically, economically and socially. It can refer to the level of management (inputs) required to maintain the farming system's outputs (Pearson 2007; Pearson and Ison 1997). By "economic sustainability" we mean the ability of a farm to produce crops and livestock whilst enabling future generations to generate wealth from the same resource (Stoneham et al. 2003). Agricultural systems that provide sufficient profitability and quality of life are also important elements of economic sustainability. Environmental sustainability is concerned with maintaining biological and physical assets (plant, animal and soil) for future generations (Stoneham et al. 2003). Finally, "social sustainability" considers the role of agriculture as part of the community and of the process by which society provides for the well being of people in an equitable way (Stoneham et al. 2003; Yencken and Wilkinson 2000).

Sustainability (environmental, economic and social) is the ultimate goal for any farming system. Maintaining both productive and environmental sustainability is complex, but it is crucial. Society is becoming increasingly concerned about the environmental sustainability of agriculture.

27.2.1 Indicators for Sustainability in Farming Systems

The decade of the 1990s saw a proliferation of indicators developed to measure society's progress towards environmental sustainability. Such indicators can be defined as key attributes that can be reported on (Schwenke et al. 2003) and then used to guide decision-making to improve sustainability. Sustainability indicators can also be very useful to help monitor and manage the sustainability of farming systems.

In Australia, as in many other countries, there is a commitment by government to State of the Environment (SoE reporting). Environmental indicators developed by the OECD (Organisation for Economic Cooperation and Development) allow the environmental sustainability of different countries to be compared. Sustainability indicators can measure changes not only in the environment but also in social, cultural and economic systems (Zhen and Routray 2003).

In Australia, ANZECC (1998) developed guidelines for the development of indicators to ensure that they would be:

- relevant to management or policy needs.
- useful for tracking trends at a range of scales.
- scientifically robust.
- cost effective.
- able to be monitored regularly.

Similar principles could also apply for the development of on-farm indicators to maintain farming system sustainability. The requirements for an environmentally sustainable farming system have been proposed by many. One example developed for the Australian grains industry (Ridley et al. 2003), suggested sustainable farming systems should feature:

1. Minimal leakage of water and nutrients (leakage can occur when excess water and nutrients unused by plants are leached below the root zone to contribute to salinity or soil acidification or escape to groundwater)
2. Negligible soil erosion from wind or water.
3. No persistent toxicities (such as soil acidity, heavy metal contamination, pesticide residues)
4. Control of pests, diseases and weeds (that threaten sustainability)
5. Retention of biodiversity in surrounding areas.
6. Sufficient profitability and quality of life for people.

These elements apply to both within the farm itself and also to off-farm or catchment/watershed impacts.

On the other hand, there has been a different emphasis in developing countries. There, sustainable agriculture has been defined by Zhen and Routray (2003) as being based on the imperative of maintaining food production, preserving the resource base, increasing land use efficiency, balancing use of external inputs and profitable and efficient production.

The suggested features of sustainable farming systems have been used to develop on-farm indicators and monitoring. However, the types of indicators that government agencies monitor are not likely to be useful to farmers (Pannell and Glenn 2000). Farmers are more likely to monitor aspects of the environment that guide their own farm management rather than broader environmental indicators (Carruthers and Tinning 2003).

Table 27.1 Comparison of on-farm indicators and indicators for SoE reporting

On-farm indicators for a grain enterprise[a]	Indicators used for state of the environment reporting[b]
Crop production: Crop yield/ha/year, Water Use Efficiency (WUE), gross margin/ha/mm of water	Land use and management: Area of land under best management practice, potential for erosion.
Soil: pH, EC, organic matter, microbial biomass, soil cover, rooting depth	Dryland salinity: Rising water-tables, area affected by dryland salinity
Stream: turbidity, intact riparian vegetation, water quality	Water quantity and hydrology: Extent of perennial vegetation cover by catchment
Biodiversity: ecosystem diversity	Biodiversity: Distribution of introduced species, extent and condition of native vegetation, area re-vegetated

[a]Dalal et al. 1999
[b]Australian and New Zealand Conservation Council 1998

Schwenke et al. (2003) suggest that indicators should be such that they are easily and reliably interpreted against scientific thresholds and be suited to local conditions. The monitoring of such indicators then proceeds to inform management goals and actions.

Dalal et al. (1999) developed a range of indicators for grain growers in Queensland, Australia. Table 27.1 outlines these indicators and compares them with the ANZECC[2] indicators used for State of the Environment reporting.

The SoE indicators listed here have both on-farm and off-farm applicability. Furthermore, on-farm indicators cover both production and environmental aspects of farm management. For example, water use efficiency (WUE) indicators, such as gross margin/ha/mm of water, provides useful information both for maximising crop production and for estimating water loss to localised or regional groundwater systems. These indicators can lead to improvements in sustainability, both on and off the farm, by providing feedback on how the management actions are contributing to a more sustainable use of the resources.

Indicators not only apply to the environmental aspect of the farming business but also to monitor farm business health. An Australian farm business program known as FAST (Farming and Sustainable Technology) developed a suite of business health indicators. FAST includes indicators for: income, assets, income drivers (such as rainfall), input costs (debt, machinery), non-farm income and resource use (land productivity, labour, return on capital) (Wylie et al. 1999).

27.2.2 Sustainability Indicators and Issues of Scale

Agroecosystems operate at a number of scales ranging from the paddock, through to the farm, catchment and region. Farming boundaries are usually linear and do not recognise the complex natural boundaries of systems operating in a catchment.

Table 27.2 The different scales for sustainability indicators[a]

Scale	Issues	Sustainability indicator examples
National	Access to key services	Distance to regional centres
State	Health of river basins	Trends in water quality
Region	Health of rural environments	Land affected by salinity (%)
Catchment	Meeting water quality targets	Trends in water quality
Farm	Optimising farm returns	Disposable income per family
Paddock	Yield performance	$ water use efficiency

[a]Based on Schwenke et al. (2003, p. 209)

Consequently, many farms are affected by processes operating outside their property, while the management actions on a property could have an impact on neighbouring farms and then further down catchments or river systems.

Indicators that may be monitored by farmers can be measured and reported at various scales (Schwenke et al. 2003). The most commonly used farm indicators are those which affect profitability or farm efficiency such as yields, stocking rates, soil test information (Reid and Ridley 2007). These indicators might differ from the information that catchment agencies report on (Ridley et al. 2007). Nevertheless, Schwenke et al. (2003) provide a useful table for summarising sustainability indicators at different scales (Table 27.2).

Farmers may cooperate at the catchment scale to monitor resource condition (for example, water quality, soil erosion), or to monitor the effect at the catchment level of sustainable management actions on their own farms (such as addressing water erosion, controlling pests and weeds and fertiliser budgeting), or to develop shared projects (such as biodiversity corridors and fencing off remnant vegetation). Often these management actions align with regional catchment or watershed plans, and the offering of incentives or funding to assist the farmers in these management actions – the basis of Integrated Catchment Management.

Integrated Catchment Management (ICM) or regional-scale approaches are used in many parts of the world (Ewing 2003). ICM involves regional bodies working in partnership with the community to plan environmental activities, set priorities and targets and monitor progress towards the targets (Pannell et al. 2007). These are known as Resource Condition Targets (RCTs), under which sit a suite of Management Action Targets (MATs). Targets and management actions can be set for the farm, with the more altruistic farmers aligning them to contribute to regional targets and actions. For example, a regional agency may set a target of reducing mean annual nitrogen load to streams by 40%. Reaching this target will then require a series of MATs such as constructing 100 km of stream fencing and creating buffer zones on stream frontages. Landholders are often able to access incentives to help them establish such buffer zones, and thus reduce the amount of nutrients entering the streams. This target can be measured by monitoring levels of nitrogen in the stream.

27.3 Resource Condition Targets and Management Actions

Resource condition monitoring is often conducted by state or regional government agencies to provide information about the state of the environment and various economic and social issues. In a farming system, resource condition can be monitored by setting indicators that, with minimal effort, will provide the farmer with early signs of change, risks and trends in the resource; and show strengths and weaknesses in their farm management (Dore 1997). Various environmental, economic and social indicators can be developed to measure progress towards farm targets through management actions. Examples of such indicators are outlined in the following sections.

27.3.1 Biophysical Resource Condition Targets and Associated Management Actions

A biophysical resource condition target may be within the context of a farm or within the catchment. Again, the issue of scale is an important consideration; the most useful indicators are those which make sense at all scales – field, whole farm and catchment.. A survey conducted by Ridley et al. (2007) found that some land condition indicators are more useful for aggregation than others. The useful ones include measures of soil cover, perennial vegetation cover and native vegetation cover.

A good example of a biophysical target within a cropping enterprise is the management of farm resources to optimize crop production efficiency. In rainfed farming, the most significant variable determining crop yield is usually rainfall and, while rainfall cannot be controlled through management, its efficient use can. Consequently, the leading indicator is Water Use Efficiency (WUE), which can be estimated at the paddock/farm/regional level, though particularly useful at the paddock and farm level (see also Chap. 1). It is widely used and adaptable to a wide range of climates and soils (Sadras and Angus 2006). Many of the farming techniques (or management actions) discussed in Chaps. 4, 5 and Chapters in Part II of this book, and summarized in Table 27.3 below should increase the efficiency of water used by the crop.

A management action is simply a plan or practice that the farm manager may put into place in order to meet a certain target. In the case of WUE, the overall target may be to “Maximise crop yields by utilising available resources efficiently”, that is to approach the potential yield (French and Schultz 1984 and Day et al. 1990). The WUE value is the indicator that is monitored. Then there are a series of management actions that can be put into place to meet the target.

Table 27.3 WUE and link to farm targets and management actions

Biophysical target	To maximise crop yields by utilising the available resources efficiently.
Indicator	Water Use Efficiency of the crop (WUE).
Management actions	*Soil fertility*: Do soil tests to assess soil nutrient status. Apply fertilisers and ameliorants accordingly.
	Time of sowing: Aim to sow as close to optimal time as possible.
	Soil-borne disease: Develop and implement paddock rotation plan to reduce disease and improve soil fertility.
	Varieties: Aim to sow the best-performing varieties for the climate and soil.
	Control weeds: Aim to eliminate competition from weeds.
	Soil erosion: Determine groundcover and period of vulnerability to erosion and apply stubble retention and direct drilling.
	Control pests and disease: Carry out tests for soil-borne and leaf disease and apply appropriate control methods.

27.3.2 Economic and Business Targets and Associated Management Actions

The FAST target of return on capital provides a useful indication of how a business is performing. It takes into account all the costs and income in the business, including the allowance for the owner/ manager which, on farms, is often overlooked. The management actions that increase physical yield do contribute to the return on capital. However, these may come at high cash or capital cost if the farming technology and system used require high levels of inputs, capital investment and risk. If the overall indicator of return on capital is not meeting the owner's expectations, each part of the business should be analysed. An alternative indicator that could be considered is return on equity, particularly if the business has other significant investors specifically interested in the return on investment.

The definitions that are usually used are:

- Return on labour, management and capital = Income minus cash expenses and depreciation
- Return on capital = Return on labour, capital and management minus owner's allowance
- Return on equity = Return on capital minus interest

Table 27.4 provides an example of the target, indicator and management actions that may be put in place to achieve that target.

27.3.3 Personal Goals and Associated Management Actions

Business and personal goals are important in shaping the business, and will often influence the level of innovation and risk that the business is prepared to take. For example, obtaining a high income may be critical where a business is supporting a

Table 27.4 Return on capital and links to farm targets and management actions

Biophysical target	To maximise farm return on capital invested.
Indicator	Return on capital.
Management actions	*Use Purchasing* power and negotiation to reduce costs. *Match Capital purchases* of plant and equipment to enterprise needs. *Manage Cash flow* to reduce call on loan funds. *Market* produce to maximise return and minimise risk. *Reduce Seasonal risk* by using insurance (fire/frost) and preparing for drought (bonds/deposits).

Table 27.5 Personal goals and links to farm targets and management actions

Biophysical target	Assess personal needs and take action towards achieving personal goals of farm family members and staff.
Indicator	Achievement of personal goals of farming family and staff
Management actions	*Training needs*: Undertake an audit of the current skill levels of staff, assess the business needs and identify training required to meet the business needs. *Succession planning*: Develop future aspirations for members of the farming team or family and build them into the business plan. *Worker OH&S and Welfare*: Assess the risks on the farm and develop policies and investment to make it a safe and healthy work environment.

young family. To make that income, the business owners may be more open to change and adoption of new techniques. Table 27.5 provides an example of the management actions that could be used.

27.4 Frameworks Used for Planning, Monitoring and Evaluation of Farming Systems

This section provides an overview of some of the frameworks available for farm planning, monitoring and evaluation. The approaches include on-farm monitoring tools, property management planning and self-assessment. They are useful for any rainfed farming system and can be adapted to suit local conditions. They also allow for the monitoring of both production and environmental indicators, goals and targets.

27.4.1 On-Farm Monitoring

> We can't steer accurately if we don't know where we are (Meadows 1998).

A useful definition of monitoring is:

> The periodic re-measurement of appropriate parameters to determine the effects of particular management strategies or policies, and the response of systems to change in the wider environment (Bosch et al. 1996).

Reasons why farmers might want to monitor their farming system include:

- to assess performance and aid decision making – from the day-to-day tactical decisions (for example, when to spray or harvest) through to more long-term strategies (for example, change crop variety).
- to monitor progress towards short-term and long-term business goals
- to reveal where changes in farm management need to occur – as part of adaptive management (for example, changing tillage to improve soil structure)
- to ensure that optimum use is made of soil nutrients and water by using soil and tissue tests and nutrient budgeting.

For rainfed farming systems in more developed parts of the world, monitoring may also be done for the following reasons:

- to report to agencies on environmental improvements (e.g. accountability for incentives provided by an agency to a business)
- to meet the requirements of a Quality Assurance (QA) scheme (see Sect. 27.5.1 below)
- to demonstrate environmental performance – increasingly driven by markets and/or communities.

Farmers mostly monitor for production purposes as this provides a direct benefit. In southern Africa, farming systems are opportunistic in nature and require sound nutrient management practices. Some nutrient balance monitoring studies have been conducted at the field, farm and regional scales. Monitoring is vital in these low-nutrient soils to ensure that the farming system can best use available soil nutrients and soil water, with optimum use of fertilisers (Dougill et al. 2002).

Monitoring of purely environmental issues usually only occurs out of interest or if there is some sort of incentive for the farmer (Pannell and Glenn 2000). A study of a group of Australian landholders in the state of Victoria (Reid and Ridley 2007) found that some farmers monitor for production purposes, but few for environmental purposes. Those who do monitor for production prefer environmental monitoring tools that lead to production outcomes and that do not require them to spend large amounts of time monitoring and record keeping (Ridley et al. 2003).

On-farm monitoring tools come in a range of formats and vary in their sophistication. They can take the form of simple "back of the envelope" calculations, risk assessment tools, instructions for direct measurement or may involve sophisticated computer modeling (see Chaps. 7 and 37). Regardless of their format they generally have the same underlying purpose, to:

- present a scientific or complex topic in a simpler and more practical way for farmers
- provide ways to measure a certain aspect of production and/or the environment
- increase awareness of environmental and/or production issues
- provide interpretation of what those measurements mean and the implications for management

Monitoring tools designed specifically for farmers should be:

- low cost for farmers to use
- practical, locally relevant and simple
- make intuitive sense
- have a benefit – farmers are unlikely to monitor the environment for its own sake so production benefits should be incorporated.

The following example (Example 1) is taken from a monitoring tool which was developed for grain growers in south-eastern Australia (winter rainfall-dominant areas) (Ridley et al. 2003). It provides farmers with a series of calculations to assess whether their farms are minimising water leaching losses from the property into underground storage and thereby reducing the risk of ground water induced dryland salinity. This example instructs farmers how to calculate the perenniality of their farming system on the assumption that perennial vegetation uses most water, and has both production and environmental benefits.

27.4.1.1 Example 1: Dryland Salinity Tool for the Australian Grains Industry

Perennial plants use water throughout the year but especially over the summer period, and this results in drier soils at the autumn break, the time when most leakage to groundwater occurs. A farmer can work towards a goal of increasing perenniality for environmental improvement within and beyond the farm, using the following steps:

1. Define the plant type and area of each in each field.
2. Add up the areas of each plant type.
3. Determine the perenniality rating of each plant type by referring to Table 27.6.
4. Calculate the perenniality of the farm by calculating the perenniality of each area of the farm sown to the different plant types, summing them and expressing the total as a percentage of the total farm area.

Table 27.6 Perenniality rating for various plant types

Plant type	Perenniality rating
Average annual crops or pastures	0
Crops or annual pastures with high levels of dry matter	0.1
Trees (either planted or remnants)	1
Lucerne-based pasture (at least 5 plants/m^2)	0.9
Perennial grass pasture (at least 5 plants/m^2)	0.5
Native grass pasture	0.5
First crop following lucerne pasture	0.7
Second crop following lucerne pasture	0.5
Third crop following lucerne pasture	0.2
Fourth and subsequent crops following lucerne	0
Irrigated pastures	0

27.4.2 Property Management Planning

Property Management Planning (PMP) (Anon 1995) programs (as they are called in Australia) have a number of variations; these are known as environmental whole farm plans in New Zealand and Canada and whole farm plans in the United Kingdom (Manderson et al. 2007). However, they share a common strategic planning approach, and have all been used as extension tools to encourage planning and monitoring of various aspects of farm businesses (including the business itself, the natural resources of the farm, finances and the people).

PMP programs usually involve the whole family business team in a series of interactive workshops to produce a whole farm plan for the business (Anon 1995). Property management plans often contain a farm description, assessment of the available resources, assessment of the enterprise, identification of important risks or issues, evaluation of land use, development of actions, and a review or follow-up program (Manderson et al. 2007). Maps and aerial photography are often used.

The development of a methodology to monitor and evaluate the progress towards defined goals is an important component of the process. Various indicators may be monitored as part of a PMP, or any farm monitoring approach, and these are used to inform future actions on the farm. In a cropping enterprise, the farmer may monitor water use efficiency, protein percentage of the grain, and crop disease status. Soil attributes such as sodicity, acidification, availability of various nutrients, organic carbon levels and soil structure may be monitored. Finally, various environmental attributes may be applicable at the farm and catchment scale; these include groundcover, percentage of perennial plants, nutrient leakage calculations, stream turbidity and water table measurements.

The monitoring and evaluation component of a PMP needs to be developed to suit each farming system, the available time to undertake monitoring and specific industry requirements; a calendar of when to monitor certain indicators is a useful aid. Effective record-keeping is a crucial component of any monitoring program.

The business may choose to adopt a more sophisticated framework, such as an EMS or Quality Assurance scheme, for marketing or accreditation purposes. Monitoring and evaluation frameworks that can be adopted are discussed below.

27.4.3 Self-Assessment Checklists

Self-Assessment checklists (also known as “guides” and “benchmarking tools”) have been produced by rainfed agricultural industries as a useful way of presenting environmental and production indicators for producers. They are often based on current “best practice” for various aspects of farm management, and may also incorporate regulatory requirements. The check lists help farmers to work towards sustainability; they can be used as a “stand-alone” process or as an introduction to something else, such as an Environmental Management System (EMS) or Property Management Planning.

A common format includes a series of questions where farmers can rate their own performance across a number of farm management areas. They can be based on scoring systems or any indication of whether the current farm practice "meets current best practice". These checklists enable landholders to assess where they are performing well and those areas needing improvement. Self-assessment checklists are used mainly for the benefit of the producers themselves but some processes compare farmers with each other and provide the landholder with a "report card", as in the LEAF process (Linking Environment And Farming) in the UK[1]. Self-Assessment checklists can be a useful (but optional) part of EMS, particularly in the Environmental Review stage where the business/farm needs to assess its own environmental performance. Self-assessment is a useful "warm-up" to the more formal parts of an EMS (Ridley et al. 2003).

In the United States, a successful environmental program – Farm*A*Syst – has been running for the past decade. Self-assessment is a common component of the program and allows farmers to assess their current environmental performance. An example from the Tex*A*Syst self-assessment is given in Table 27.7. In undertaking this exercise, farmers rate their current practices according to a series of statements. In the soil and fertiliser management examples provided below, farmers choose the statement that best describes their current practice. The categories vary according to environmental risk.

Table 27.7 A cropping self-assessment questionnaire where a choice is made from condition levels as in this example in the Tex*A*Syst program in the US (http://waterhome.brc.tamus.edu/farmasyst/crops.htmpl)

Problem or need	Rank 4 (low)	Rank 3 | (low – moderate)	Rank 2 (moderate – high)	Rank 1 (high)
Soil structure	Open. The soil is very crumbly with lots of pore space.	Mostly open. The soil is crumbly with good pore space.	Slightly dense. The soil breaks into clods. Pores are less visible.	Dense. The soil breaks into large clods with very little pore space.
	No sign of crusting or compaction.	No sign of crusting or compaction.	Soil sometimes crusts. Some compaction.	Crusting and compaction are evident.
Soil testing	Cropland fields have been tested annually.	Cropland fields tested every 3 years.	Cropland fields tested every 4–6 years.	No soil testing in the last 7 years.
Time and placement of fertiliser	All N is applied in the spring. A small amount at planting and the remainder is applied at side-dress time.	All N is applied in the spring. Most of the N is applied pre-plant but a small amount is applied at planting.	Some N is applied in the fall. The remainder is applied in spring. Some use of N stabiliser is used in fall.	All N except a small amount applied in the fall. Only starter N is spring applied.

[1] http://www.leafuk.org/leaf/producers/audit.asp.

Other examples of self-assessment approaches include the Ontario Environmental Farm Plan (EFP) which is a voluntary, educational program based on environmental sustainability for Canadian agriculture. Farmers have to use it to access incentives for on-ground environmental works (OFEC 1996).[2] The Michigan Agricultural Environmental Assurance Program, Crop*A*Syst[3], is based on risk management, and is designed to assess the risk of cropping practices affecting groundwater and surface water resources (see also Chap. 20, Sect. 5.3).

27.5 Market-Driven Farm Planning, Monitoring and Evaluation Approaches

The previous section outlined the less-formal, on-farm approaches that can be used for planning, monitoring and evaluation across a range of aspects of the farm business. In some cases, more formal systems for monitoring and evaluation will be needed – particularly if they are required in order to enter a new market or maintain market access. These approaches include a variety of Quality Assurance systems (many agricultural industries and markets have their own versions) and Environmental Management Systems (EMS). These systems are discussed in this section.

27.5.1 On-Farm Quality Assurance (QA) Systems

Many Quality Assurance (QA) systems relate to agricultural production. They have some common features in that they are usually based on Codes of Practice developed for a particular industry or market to ensure that the product meets food safety, product quality and consistency standards. The farmers need to be able to demonstrate compliance with a Code of Practice to sell their product to a certain market. To demonstrate compliance requires them to plan, monitor and evaluate their farm practices, keep good records and pass an audit.

Some commonly-used QA schemes are the Australian On-Farm QA Schemes: Cattlecare™ and Flockcare™[4] and Graincare™[5]. These are prescriptive schemes which set out criteria that the business needs to meet in order to become certified. They need only to meet the standard without the need for continuous improvement (such as an EMS requires). The Australian On-Farm QA schemes require the business to: (1) check their own farm against the specified criteria; (2) make improvements to meet the criteria; (3) keep good quality records; (4) conduct an internal audit;

[2] http://www.omafra.gov.on.ca/english/environment/efp/efp.htm

[3] http://www.maeap.org

[4] http://www.ausmeat.com

[5] http://www.graincare.com.au

(5) proceed with any necessary corrective actions; and (6) organise for an external audit to be done (Seymour et al. 2007).

Another type of QA scheme is referred to as "HACCP-compliant" or "HACCP-based". Hazard Analysis Critical Control Point (HACCP) is an internationally-recognised standard for identifying and managing food safety risks (see http://www.haccp.com.au). It requires the farm business to conduct a process involving : (1) identification and analysis of hazards and control points; (2) development of control mechanisms; (3) monitoring; (4) record keeping; (5) carrying out corrective and preventative actions; and (6) putting verification procedures into place (Seymour et al. 2007). A major difference with HACCP-based schemes (compared with CA) is that farm managers have to identify their own hazards, control points and control measures (with assistance from outside parties if needed), rather than follow a stated Code of Practice. EUREPGAP is such a scheme and is currently most relevant to the horticultural industries that would like to enter European markets[6]. The Safe Quality Food (SQF1000) is another example and is relevant to the grains and livestock industries, also[7] Environmental Management Systems (EMS).

Consumers, mostly in the developed world, are questioning the environmental performance of agriculture. The terms "clean and green" are frequently used for marketing purposes; "Clean" refers to the claim that food products are free of pesticides and chemical residues, whereas "green" refers to food that is produced in an environmentally sustainable way. Whilst many developed countries can demonstrate "clean" food through Quality Assurance (QA) systems, many are poorly prepared to justify any "green" claims. EMS can be used to prove such credentials, as well as enabling farmers to be pro-active in environmental management instead of waiting for increased environmental regulation and imposed international scrutiny.

In terms of the role for EMS for monitoring and evaluation of rainfed farming systems, EMS offers an effective way to monitor and integrate sustainability indicators into a complete management system. It can also incorporate the less-formal approaches to monitoring and evaluation such as monitoring tools, self-assessment and whole farm planning, as well as any other specific industry requirements such as Quality Assurance and Occupational Health and Safety (OH&S) issues (Seymour et al. 2007).

27.5.1.1 What is an Environmental Management System (EMS)?

EMS is a formalised, structured approach to help farmers assess, document, improve and monitor their environmental performance (Morelli 1999; Carruthers and Murray 1999). It is based on continuous improvement through a "plan-do-check-review" cycle.

[6] http://www.eurep.org.

[7] http://www.sqfi.com.

EMS is based on the International Standard, ISO14001 and is quickly becoming the dominant EMS model throughout the world (Altham and Guerin 1999; Morelli 1999).

27.5.1.2 What Is Driving EMS in Agriculture?

In many parts of the world, particularly in the US, UK and Europe, the trends for environmental accountability are continuing. Overseas, retailers are reacting to pressure for clean and green products; this trend is most apparent in Europe and Japan and is being led by large supermarket chains. Consumers in the more developed countries are now questioning the environmental sustainability of farming systems in addition to having food safety concerns. With international food safety scares such as BSE (Bovine Spongiform Encephalopathy), food safety is high on the political agenda. EMS also has the potential to be an effective tool for government to meet natural resource management outcomes that relate to public-good issues (such as biodiversity) and to ensure sustainable agricultural production.

In Australia, EMS started in the cotton industry, which wanted to improve its public image, through the Cotton Best Management Practice program. It is almost certain that EMS will become part of everyday operation in industries under closer public scrutiny (e.g. cotton, seafood/fishing, forestry, rice, intensive animal industries). However, in rainfed agriculture, the use of EMS will increase only if the market demands it. Nevertheless, it is a useful approach for monitoring and evaluation, and has the benefits of improved business management, production efficiencies, improved environmental outcomes on farms and improved public perception (Seymour et al. 2007).

EMS, in the true sense, is compliant with the ISO14001 process. Given that market and community drivers are relatively weak in the broadacre industries, a number of industries have developed their own interpretations of EMS (but have still called it "EMS"). Although not a complete EMS, these approaches are seen as good preparation for EMS or as ways to demonstrate environmental responsibility to the community.

EMS in Action

In Australia, EMS has been trialed in a number of rainfed and irrigated agricultural industries, and with rainfed pastoral producers in western Queensland. As the ISO14001 EMS process was deemed to be too complex, the model was simplified to a 7-step process so that more producers might be motivated to undertake EMS (Sallur et al. 2007). The process was delivered to 53 producers over a series of group learning days. The program took producers through the topics of risk assessment, objective and target setting, implementation and monitoring. Based on feedback from producers, a simple and relevant EMS was developed for the pastoral industry, although a number of the steps were not to certification standard (Sallur et al. 2007). The conclusion was that there was little motivation for farmers to undertake EMS activities after the project had ended because of the lack of tangible benefits for producers. However, the process of learning about EMS was felt to be a useful "trigger" for environmental improvement (Sallur et al. 2007).

27.5.1.3 Where Do on-Farm Monitoring and Evaluation Fit into the EMS Process?

If monitoring is connected to a system of continuous improvement or adaptive management, such as EMS, it can become a valuable and integral part of farm management. Monitoring fits into the EMS cycle at a number of points in the "plan-do-check-improve" cycle:

Planning	Performance objectives and targets are set (which are monitored later in the process). This means the objectives need to be practical and measurable, in order to be effectively monitored. Various indicators for monitoring are included with each proposed management action.
Implementation	Roles and duties for monitoring are identified. EMS documentation and document control should identify where monitoring records are kept and how the data will be used to inform management decisions. Operational procedures are developed to outline the techniques for monitoring to ensure all staff use consistent approaches.
Monitoring	A monitoring program is developed, implemented and assessed. Both production and environmental indicators are monitored. This will highlight where the EMS has been successful and identify any issues needing corrective action and improvement.
Review	The effectiveness of the monitoring program is evaluated. This is also a good opportunity to assess how measurable the targets and objectives are. Preventative, corrective and remedial actions are taken if required.

When developing indicators, it is important to set a range of threshold points within which the resource should be managed to avoid irreparable damage. Such measurements and indicators should be built into the monitoring and evaluation program of the business. Tools such as Property Management Planning and EMS are useful for this purpose as they allow for planning and review within a flexible framework.

27.6 Conclusion

This chapter has set out the role of monitoring on a farm and explains the many monitoring frameworks that are available for various purposes. Farmers are prepared to monitor aspects of the business that are of an advantage to them, but the monitoring program needs to be simple and cost-effective.

When new technology is available to be introduced into a farm business, it will only be added if it can enhance the goals of a business. Simple monitoring indicators can show the impact of introducing a new management action on a business. Indicators can also help to highlight the components of a business that are not performing, and lead to assessment of the contributing management actions. Consequently, the extension of any new farming practice must be promoted in the context of its impact on the total business goals including those of economic, environmental and personal aspects.

All farm businesses operate in a catchment and external factors may be influencing the farm. Many catchment organisations have goals and aspirations of sustainable management, and these should be included in business planning and monitoring frameworks.

Some monitoring frameworks are promoted by groups with specific interests, and many of them cover only part of the business – such as marketing monitoring frameworks for quality assurance. As consumers become more concerned about the environmental performance of agriculture, environmental factors will gain in importance, leading to a higher use of marketing approaches such as Environmental Monitoring Systems. Other industries, particularly the smaller ones, are already including some environmental measures where there is a market advantage. However, where bulk products such as grains are produced, there is currently little market recognition of environmental issues.

Monitoring is an important component of any business as it provides feedback regarding the whole business or components of that business. Without that feedback, management change and performance cannot be properly assessed. To achieve improved performance from rainfed farming systems, an appropriate monitoring and evaluation system should be an essential part of the business. Monitoring and evaluation should also be included in extension programs that promote new techniques to modify the rainfed farming system.

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Chapter 28
More from Less – Improvements in Precipitation Use Efficiency in Western Australian Wheat Production

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Abstract Wheat is the principal crop in the Western Australian rainfed farming system. Over the past 25 years, yields have doubled while rainfall has declined, resulting in a greater than doubling of the rainfall use efficiency or Precipitation Use Efficiency (PUE). This has enabled producers to maintain economic viability. The increased PUE has arisen from a number of agronomic and genetic advances. The use of herbicides and rotations to control weeds, in association with minimum tillage, has enabled earlier planting and improved use of seasonal rainfall. Increased use of fertiliser, especially nitrogen, and legume-based rotations has also resulted in increased yields and PUE. Drainage to reduce waterlogging has benefited yields and PUE, especially in high-rainfall environments and on duplex (texture-contrast) soils. Early planting has required the development of wheat cultivars with a range of flowering times and early vigour. Other characteristics that assist in achieving high yields and high PUE in a Mediterranean-type climate with terminal drought are deep roots, osmotic adjustment, transpiration efficiency and greater assimilate redistribution. The synergistic interaction between breeders and agronomists to identify the interactions between genotype and environment and management (G × E × M) has resulted in the adoption by producers of cultivars and management practices that have led to advances in yield and PUE.

Keywords Wheat • Precipitation use efficiency • Rainfall use efficiency • Water use efficiency • Agronomic advances • Genetic advances • Genotype by environment by management (G × E × M) interaction

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_28,

28.1 Introduction

The rainfed farming system of south-west Western Australia is based around the production of wheat[1]; this requires inputs of technology and management to maintain a high level of productivity and sustainability. Between 2000 and 2005, wheat yields in the region have averaged 1.8 t/ha from 4.6 million planted hectares (AWB 2007) with Western Australia producing 35% of Australia's total production of 20.6 million tonnes (AWB 2007). Ninety-five percent of the wheat produced in the state is exported.

Rainfall in the Mediterranean-type climate of this south-west region is limited (300–700 mm annually) and, as wheat is produced without supplemental irrigation, efficient use of this rainfall is necessary to maintain profitability of the farming system.

Over the 1980s and 1990s, productivity of rainfed broadacre farming systems in the region increased at an annual rate of 3.5% driven mainly by the high productivity of the wheat-based system; this maintained positive farm incomes as farmers' terms of trade declined (Kingwell and Pannell 2005). High profitability has also enabled farmers to invest in sustainable practices such as minimum tillage, tramlines (Controlled Traffic - CT) to minimise soil compaction, improved maintenance of remnant vegetation and the introduction of perennials to minimise secondary salinity (Turner and Ward 2002). Over the past century, there have been continual efforts to maintain and improve wheat yields and PUE through a range of means that include plant breeding and agronomic management.

Australian wheat yields from initial clearing in 1865 decreased over the first 60 years as the initial fertility declined (Donald 1965) but then increased with the introduction of superphosphate fertiliser, better adapted cultivars, soil water conservation by fallowing, and the introduction of the Ley Farming System using the self-regenerating annual pasture legume, subterranean clover (Dunne and Shier 1934). Analysis to 2000 suggests that yields of wheat increased in bursts as new technologies were introduced (Angus 2001). The most recent rapid increase in wheat yields in Western Australia started in 1982 and continued unabated until 2000 (Stephens 2002) (Fig. 28.1). Since then, yields have been too variable to determine whether they are still increasing linearly or beginning to level out (Fig. 28.1). Up to 1982, yield increases in Western Australia were 7 kg/ha/year, thereafter 42 kg/ha/year. As this higher rate of yield increase occurred over a period when annual rainfall decreased significantly by 15–20% (Indian Ocean Climate Initiative 2002), rainfall use efficiency or (using the more general term) Precipitation Use Efficiency (PUE) must have increased significantly over the two decades. In this chapter the reasons for the increase in yield and PUE of wheat in south-west Western Australia are examined.

The Mediterranean-type climate in south-west Western Australia has cool wet winters and hot dry summers (Turner 1992, 2004a). Annual rainfall in the region

[1] Botanical names of crops may be found in the Glossary.

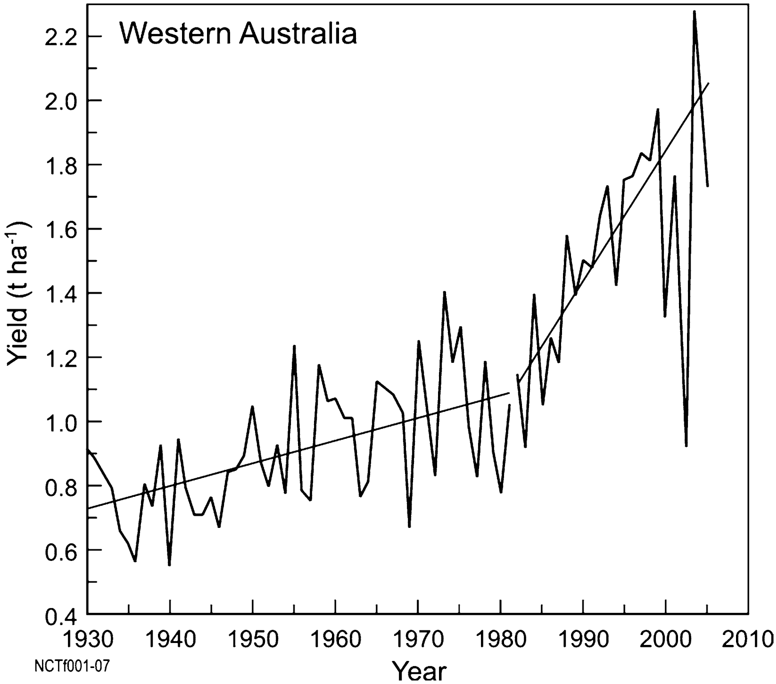

Fig. 28.1 The average annual yields of wheat in Western Australia from 1930 to 2005 (Extended from Stephens 2002, with data from AWB 2007)

where wheat is grown varies from 300 to 700 mm, while growing-season rainfall varies from 200 to 500 mm. Because increases in temperature and vapour pressure deficit coincide with decreasing rainfall in spring (September–November), soil water availability decreases markedly and leads to terminal drought as the crop fills its grain. Spring wheat is grown in the winter after planting on the opening rains in autumn/early winter (April–June), flowering occurs in early spring (September) and harvest in late spring or early summer (November–December) (Turner 2004b). About 20% of the soils are deep (more than 0.6 m) coarse-textured sands with low water-holding capacity; 60% are duplex soils with shallow (0.1–0.5 m) sandy surface soil of low water-holding capacity overlying a clay subsoil that deters root penetration; and 20% are clay loams with good drainage and high water-holding capacity (Turner 1992; Tennant et al. 1992). Thus, wheat in Western Australia is grown mostly on soils with poor water-holding capacity and on current ('in crop') rainfall. The crop must use this incoming rainfall efficiently to maximise yield. In water-limited environments, yield is a function of water use by the crop, the efficiency of conversion of water to biomass by the crop (transpiration efficiency), and the conversion of biomass to grain (harvest index[2]) (Passioura 1977). The greater

[2] See Glossary.

the water used in transpiration by the crop rather than evaporation from the soil, the greater the yield. As management practices can increase yield without increasing overall water use, by increasing crop transpiration at the expense of soil evaporation (Turner 1997), many increases in PUE arise from increases in yield. The maximum PUE for wheat in the water-limited Mediterranean-type environment of South Australia is 20 kg/ha/mm after water loss by soil evaporation is taken into account (French and Schultz 1984a), but many producers do not achieve this PUE for a number of agronomic reasons (French and Schultz 1984a, b). However, both management (agronomic) and genetic advances are responsible for the increases in the yield and PUE in wheat in Western Australia.

28.2 Agronomic Advances for Wheat Improvement

A range of agronomic advances are responsible for improved wheat production and PUE in Western Australia WA (Table 28.1).

28.2.1 Early Planting

Probably the greatest increase in PUE comes from earlier planting. Any delay in planting after the first opportunity – the "break of season" – reduces yield of modern cultivars by up to 30 kg/ha/day (Anderson and Smith 1990; Anderson 1992). With older planting techniques, 25 mm of rain needed to accumulate over the previous 10 days for planting to begin (Asseng et al. 2001) but, with modern techniques, planting is feasible on 10 mm of rain accumulated after mid-April. Early planting allows more growth under the higher temperatures of late autumn, and results in earlier ground cover, a higher proportion of water being used for plant transpiration, rather than for soil evaporation and ultimately higher yields and a greater PUE. The planting date in south-west WA advanced by 15–20 days between the 1970s and the end of the 1980s (Stephens and Lyons 1998). To ensure maximum growth after the first rains, some farmers on the coarse-textured sandy-surfaced soils in WA sow their wheat into dry soil before the rain; one farmer starts planting on 15 April every year, whether the rains have started or not (G O'Brien 2003 personal communication). Early planting may give rise to three risks: (1) weeds – good weed control is essential

Table 28.1 Agronomic and genetic advances for increasing yields and precipitation use efficiency in water-limited environments (Turner and Asseng 2005)

Agronomic advances	Genetic advances
Early planting	Phenological adaptation
Weed control	Early vigour
Nutritional management	Deep roots
Tillage	Osmotic adjustment
Rotation	Transpiration efficiency
Waterlogging	Assimilate redistribution

to gain a benefit, (2) wheat flowering in a high frost-risk period, resulting in severe losses in frost-prone areas, (3) lack of follow-up rain, so that the young seedlings are subjected to moisture stress. Although young wheat seedlings can tolerate considerable drought, their development is delayed during the period of zero growth, and phenological development is later than expected from chronological time or thermal time (day degrees) (Armstrong et al. 1996).

28.2.2 Weed Control

Weeds are critical competitors for limited water supplies. Traditionally, weeds were controlled by cultivation after they emerged on the 'break-of-season' rains. While this may still be done if rain in March or early April stimulates an early flush of weeds, pre-emergent herbicides mean that farmers do not need to wait for the weeds to emerge in order to control them. A pre-emergent herbicide is sprayed at the time of sowing, even if the wheat is dry planted, allowing sowing to occur about 2 weeks earlier (Anderson et al. 2005). Weeds are also important transmitters of diseases, such as 'Take-all' (*Gaeumannomyces graminis* var. *tritici*) (MacNish 1980) and rusts, which can reduce PUE and yield. Farmers therefore begin to reduce grass weeds in the previous crop to limit the incidence of such diseases (Anderson et al. 2005). Weed and disease incidence can also be minimised by the use of rotations (see below).

28.2.3 Nutrition

The introduction of superphosphate was a major factor in reversing the decline in yields over the first 60 years after land clearing (Donald 1965), while the use of nitrogen fertiliser increased wheat yields in South Australia to near the maximum PUE of 20 kg/ha/mm (French and Schultz 1984a, b). Turner (1997) re-analysed data by Shepherd et al. (1987) in Syria to show that increasing fertiliser use (in this case phosphate fertiliser) could double yields of barley with little or no increase in water use, thereby doubling PUE. Simulation analysis by Asseng et al. (2001) showed that this increase in PUE arose from higher biomass with higher nitrogen, but this higher biomass had little effect on total crop evapotranspiration due to a reduction in soil evaporation by the increased ground cover. The influence of the increased nitrogen on grain yield varied depending on the soil and on rainfall distribution. The higher biomass increased pre-anthesis water use which, on fine-textured soils and seasons with limited spring rainfall, decreased the water available to the crop after anthesis and reduced harvest index (HI). Nevertheless, the decrease in HI was insufficient to reduce the PUE for grain yield (Asseng et al. 2001). Regular testing of soil nutrition has resulted in farmers tailoring their fertiliser application, including microelements, to expected yields based on average or predicted rainfall.

Superphosphate applied to pastures in the ley farming system has ensured a bank of available phosphate and there is less need for superphosphate. In contrast, the rate of nitrogen used on wheat in WA has doubled in the period since wheat yields began to increase in the early 1980s. In the high-rainfall zones of south-west WA, higher levels of nitrogen fertiliser are still required to achieve the high yields achievable on the growing-season rainfall (Zhang et al. 2006).

28.2.4 Tillage

Developments in tillage practice have enabled more timely sowing of wheat. Most wheat in WA is now sown in a one-pass operation in which a furrow is opened, fertiliser dropped into the base of the furrow, followed by the seed and then the surface is sprayed with pre-emergence herbicide. The rapid and early sowing of wheat helps to maximise PUE while the use of narrow points minimises the disturbance of the soil and subsequent moisture loss by evaporation (Anderson et al. 2005).

28.2.5 Rotations

Rotation of other crops and pastures with wheat has been widely adopted to control pests and diseases, to increase the soil organic matter, to provide nitrogen through legume fixation and to diversify cropping to minimise risk. Early rotation trials in WA showed that legume-based pastures increased total soil nitrogen and this benefited the subsequent wheat crop. After successive wheat crops, total soil nitrogen and yields decrease (Dunne and Shier 1934; Rowland et al. 1988; Perry 1992; Turner and Asseng 2005). The decrease may be minimised by the use of nitrogen fertiliser, but farmers use less nitrogen fertiliser following a legume crop or pasture than after another cereal or oilseed crop, and farmers who grow high-protein durum wheat usually precede it with a legume crop such as field pea, lentil or chickpea (Miyan and Anderson 2003).

Rotation with broadleafed crops such as canola or leguminous crops such as lupin or field pea also allows control of grass weeds through the use of grass-selective herbicides. (McLeod et al. 1993; Anderson et al. 2005). The increasing incidence of herbicide-resistant weeds, particularly annual ryegrass, has resulted in the use of pastures to reduce the population of ryegrass seeds in the seedbank by either grazing or by spray-topping, i.e. spraying the pasture with a broad-spectrum herbicide such as glyphosate at flowering to sterilise the seed and increase palatability for grazing stock (Leury et al. 1999). The persistence of ryegrass seeds in the soil for several years (Steadman et al. 2004) has resulted in the introduction of 'phase farming' whereby several years of leguminous pasture are alternated with several years of crop (Reeves and Ewing 1993); herbicide-resistant ryegrass is controlled by grazing and cutting for hay. This has led to the introduction of new pasture legume species that can be readily harvested for seed to suit this phase farming concept (Nichols et al. 2007).

28.2.6 Waterlogging

The duplex or texture-contrast soils of WA are subject to transient waterlogging in winter, particularly in the high-rainfall zone (McFarlane and Cox 1992; Zhang et al. 2004, 2006). Waterlogging at the tillering stage can halve the number of fertile tillers and hence halve wheat yields, resulting in a halving of the PUE (Zhang et al. 2004). Draining the soil can decrease the incidence of waterlogging (McFarlane and Cox 1992), as can the presence of tree belts in association with interceptor drains (Turner and Ward 2002; White et al. 2002).

28.3 Genetic Advances for Wheat Improvement

The genetic mechanisms that confer an advantage in terms of yield have been termed drought-resistance traits (Turner 1979, 2003). As these usually increase yields without increasing water use, this will result in an increase in PUE. Table 28.1 lists a number of genetic mechanisms that putatively increase PUE in water-limited environments such as WA.

28.3.1 Phenological Adaptation

Modern cultivars have patterns of earlier water use than older historical cultivars in which this was delayed and poorly aligned with rainfall (Siddique et al. 1990: Turner 2004b). Wheat breeders now select cultivars of wheat with a water-use pattern that better matches the rainfall pattern of the Mediterranean-type climate, and farmers now keep seed of a selection of cultivars for different sowing dates. For early sowing, cultivars with a later flowering date minimise the risk of frost damage, whereas a shorter time to flowering is required for later sowing. This has led to the development of a model 'FLOWER' and a frost-risk guide (Perry et al. 1987; Loss et al. 1990) for farmers to select the most suitable cultivar for the sowing opportunity and the region.

28.3.2 Early Vigour

On sandy soils with low water-holding capacity, early vigour is an important trait to gain high yields of wheat in the short-season Mediterranean-type climate of WA (Turner and Nicolas 1998; Botwright et al. 2002; Turner and Asseng 2005). This early vigour (and specific leaf area – a surrogate for early vigour) can be selected at the seedling stage when differences due to seed size are no longer evident (Turner and Nicolas 1998; Rebetzke and Richards 1999; Rebetzke et al. 2004). The higher yields in the vigorous lines were associated with earlier ground cover, greater biomass at anthesis, deeper rooting and greater seasonal water use (Turner and Nicolas 1998; Turner and Asseng 2005). Simulation analysis showed that the benefit from the early vigour trait required nitrogen application, particularly in the higher rainfall regions of the wheat belt (400 mm growing-season rainfall) and can increase yields by 10–15% (Asseng et al. 2003). However, this is no benefit on fine-textured soils where high leaf areas and the consequent greater water use before anthesis restrict water availability during grain filling (Asseng et al. 2003). Early vigour has been an objective of breeders in Canberra (south-eastern Australia) (Rebetzke and Richards 1999), and new 'high-vigor' lines are being evaluated.

28.3.3 Osmotic Adjustment

The active accumulation of solutes in plants as water deficits develop is termed osmotic adjustment (Turner and Jones 1980) or osmoregulation (Morgan 1984), and this maintains plant physiological activity as soil water availability decreases (Turner and Jones 1980). In wheat, osmotic adjustment is under the control of a single gene or major gene (Morgan et al. 1986; Morgan 2000) and is associated with yield increases of up to 10% in water-limited environments in eastern Australia (Morgan 2000; Richards 2006). Breeding and selection for high osmotic adjustment in bread wheat led to the release of a cultivar, 'Mulgara', for the low-rainfall regions of northern New South Wales, but it is not well adapted to the shorter growing season of WA. The successful development of a cultivar with high osmotic adjustment demonstrates that it is a trait worth pursuing in wheat-breeding programs for the low-rainfall environments of WA.

28.3.4 Deep Roots

Although early vigour and osmotic adjustment are associated with deeper rooting characteristics and greater water extraction (Turner and Nicolas 1998; Morgan and Condon 1986), there has been little direct selection for deeper rooting characteristics in wheat because of the difficulty of screening for root traits (O'Toole and Bland 1987). Simulation analysis shows that deeper roots (faster root penetration) can increase wheat yields by up to 20% on the deep sandy soils in the medium- to high-rainfall regions (300–400 mm growing-season rainfall) of the WA wheat belt; and by 10% in the low-rainfall region (230 mm growing-season rainfall) (Asseng et al. 2002). Simulation also shows that deeper roots capture more nitrogen in the soil profile before it moves out of the root zone. Thus, yield increases would be higher on sandy, coarse-textured soils (subject to greater leaching) than on the fine-textured clay soils (Asseng et al. 2002). The greater rooting density associated with the 'high-vigor' lines also captures more nitrogen (Liao et al. 2004, 2006). The 'synthetic' wheat lines developed at the International Maize and Wheat Improvement

Center (CIMMYT) in Mexico have more vigorous root systems that contribute to their higher yield in water-limited environments (van Ginkel and Ogbonnaya 2007).

28.3.5 Transpiration Efficiency

The demonstration that transpiration efficiency (TE, see Chap. 1) is under genetic control in wheat (Farquhar and Richards 1984) has led to an active breeding program for high transpiration efficiency in wheat for low-rainfall environments (Condon et al. 2002, 2004; Richards et al. 2002; Richards 2006). Two cultivars with high (TE), 'Drysdale' and 'Rees', have been released for the low-rainfall, subtropical, summer-rainfall dominant regions of northern New South Wales and southern Queensland (Richards 2006). High TE in wheat is primarily the result of lowered stomatal conductance with consequent slower rates of photosynthesis and growth (Condon et al. 2004). This may be detrimental on the sandy soils of WA where early vigour provides a yield advantage. In the low-rainfall environments of WA, the cultivars with high (TE) are no better than locally-developed cultivars when grown on fine-textured soils (Condon et al. 2004); however, simulation suggests that they may give a yield advantage on sandy, coarse-textured soils provided nitrogen fertiliser is applied (Asseng et al. 2002).

28.3.6 Assimilate Redistribution

Assimilate storage in stems of wheat and its redistribution to the grain after anthesis benefits yields on sandy soils in the water-limited environment of WA (Nicolas and Turner 1993). Simulation suggests that assimilate redistribution increases yields by 12% in moderately water-limited environments and years (Asseng and van Herwaarden 2003). However, it gives no benefit in high-rainfall environments because adequate assimilate is produced during grain filling; nor in very low rainfall environments where there are insufficient assimilates for stem storage. As there is genetic variation in this attribute (Nicolas and Turner 1993), breeding programs have been initiated to increase assimilate storage and redistribution in wheat.

28.3.7 Interaction Between Breeding, Environment and Management

While the agronomic and genetic factors influencing the yield increases in wheat in south-west Western Australia have been dealt with separately in this chapter, it is the interaction of breeding and agronomy for a specific environment that has resulted in the yield increases achieved over the last two decades (Anderson et al. 2005; Turner and Asseng 2005). While breeders have focused on developing cultivars for specific environments of WA and highlighted the genotype by environment (G × E) interactions, the associated development of appropriate agronomic packages for the cultivars (sometimes in a rapidly changing agronomic environment) has achieved the yield benefits. For example, when a new cultivar of wheat is released in WA, information on time of sowing, planting density, nutritional requirements, frost risk and quality characteristics are also available (e.g. Garlinge 2005). It is therefore the utilisation of the appropriate genotype by environment by management (G ×E ×M) interaction that has given the greatest benefits. Because it is difficult to conduct experiments in a range of environments with a range of agronomic manipulations as cultivars change, simulation modeling is also used to help understand and identify the genetic traits and management practices required for particular environments (Asseng et al. 2001, 2002).

Two independent analyses of the rapid increase in yield over the past 25 years (Fig. 28.1) have suggested that about two-thirds of the yield increases have arisen from changes in management practices introduced by farmers and one-third from new cultivars (Turner and Asseng 2005; Anderson et al. 2005). While genetic advances have steadily increased yields for over a century (Perry and D'Antuono 1989), wheat breeders have had to introduce new genes to combat disease resistance simply to maintain yields and genes for quality characteristics demanded by changing market requirements. Nevertheless, the development of cultivars with a range of phenological developments has had a major impact on the yield and PUE of wheat in WA. These developments have enabled farmers to choose a cultivar to suit the timing of the break of season, adopt changes in agronomic management, particularly minimum tillage, use pre-emergence herbicides, pre-prepare the site for weed- and disease-free production and plant quickly after the break of season. The doubling of PUE and yield has enabled farmers to keep ahead of the cost-price squeeze (Turner and Asseng 2005; Kingwell and Pannell 2005), to remain profitable in a period of declining terms of trade and to have funds to develop management practices that will keep the industry sustainable in the long term.

Predictions of a warmer and drier climate in south-west WA as a result of climate change (CSIRO 2001) makes the development of drought-resistant cultivars of paramount importance for the drier eastern and northern regions of the wheat belt, but is likely to reduce the incidence of waterlogging in the western and southern high-rainfall zones. Wheat production in the state is therefore likely to remain high, but with the areas of primary production moving to the western and southern regions. Climate change will also impact on farming systems with the drying climate making secondary salinity from water excess a decreasing threat and the need to include perennials in the system less urgent. However, the increasing incidence of herbicide resistance will make it essential to manage farming systems using rotations that include pastures, hay production and phase farming. In the longer term, the development of genetically-modified, herbicide-tolerant and pest-resistant wheat will allow agronomic packages to be developed to increase the PUE and yield of wheat, by minimizing water loss through weeds, pests and diseases.

28.4 Conclusions

The improved yields and PUE by wheat farmers in Western Australia over the past 25 years, during which rainfall has decreased, can be attributed to both the better adaptation of cultivars to the environment and to the adoption of agronomic practices that have had a significant benefit to yields and to PUE. The G ×E ×M interactions that have led to 'more from less' also provide an example of the need for agronomists and breeders to work closely together to achieve benefits for farmers. The complex G ×E ×M combinations also provide a role for modelers in understanding and predicting the yield and PUE benefits from either management or genetic advances, or the combination of both.

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Chapter 29
Transforming Farming Systems: Expanding the Production of Soybeans in Ontario

A Study in Farming System Improvement

David J. Hume and Craig J. Pearson

Abstract Before 1975, the soybean (*Glycine max*) crop had been grown only in small areas in the southwestern corner of southern Ontario, which has the longest growing season and warmest conditions in Canada. As earlier-maturing soybean cultivars were developed, soybeans could be expanded into cooler areas. In this chapter, the expansion of soybeans to major crop status is recounted, including the background research and the extension efforts. Introduction of this new crop decreased the areas under cereals and corn, greatly decreased the use of fertiliser and pesticides and lowered grain drying costs. We suggest that the speed of adoption of this new cropping system was due to several factors, including thermal adaptation of the crop, a production system that used existing field equipment, elite rhizobia, enhanced economic returns and regionally focused plant breeding. The corn–soybean–wheat rotation has benefited efficiency of production (in terms of inputs of fertiliser, pesticides and tillage), environmental friendliness, and farm income. Even though the introduction of soybeans was deemed a positive change, it did not reverse long-term trends of declining farm profitability, polarisation of income, and loss of farms and farmers. Recent increases in field crop commodity prices may reverse the trend in declining farm profitability but not the other trends.

Keywords Soybean • Cultivars • Crop rotations • Crop management • Corn • Extension • Fertilisers • Inoculants • Pesticides • Planting • Harvesting equipment • Economics

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_29,

29.1 Introduction

Between 1976 and 1997 there was a rapid increase in the number of hectares of soybean in the Province of Ontario. The area under soybean increased over sixfold, from 153,000 to 937,000 ha (Ontario Soybean Growers 2004). Ontario is the southern-most province in Canada; and southern Ontario, between 42 and 45°N latitude, is the main soybean production area in the country.

In this chapter, we recount the transition to this new crop and describe the changes and benefits which soybeans brought to the cash crop rainfed farming system.

29.2 Background

Southern Ontario, in 1951 (Canadian Census 1951), had four major crops: hay and pasture, oats,[1] mixed grain (usually oats and barley planted together) and winter wheat. Between 1961 and 1971, the planting of corn (*Zea mays)* for grain expanded rapidly eastward in Southern Ontario (Joseph and Keddie 1981), increasing from 160,000 to 511,000 ha. This expansion had resulted from several factors, including earlier-maturing corn hybrids, the development of atrazine as an effective corn herbicide, improvements in planting and harvesting equipment, new developments in drying and storing of grain corn and substitution of grain corn for cereal grains in livestock rations (Ross and Crowley 1999). Efforts to extend information to growers through farmer meetings, on-farm field demonstrations and research station field days also sold the concept of changing cropping systems to include grain corn (White et al. 2007).

Southern Ontario is adjacent to Ohio and Michigan and the expansion of grain corn represented an adoption of U.S. Corn Belt (mid west) agricultural systems already in use. Much of the research in breeding, fertiliser application, harvesting equipment and grain drying had been conducted in the U.S.A., and was readily accessible. The major Ontario contributions included the breeding of earlier-maturing corn hybrids (Russell 1971) and the development of a system using atrazine for broadleaf weed control (White et al. 2007).

Most of Ontario's prime agricultural areas are glaciated soils developed over limestone bedrock. They range from neutral pH to slightly alkaline and from sands to clays. Most of the clay areas are sedimentary soils developed in the lakebeds formed after the last ice age about 10,000 years ago.

Southern Ontario lies among three of the Great Lakes and benefits from regular rainfall. Precipitation averages about 75 mm/month all year.

In Ontario, the length of the growing season for cropping has traditionally been measured in corn heat units (CHU) (Brown and Bootsma 1993) (for details see Agriculture and Agri-Food Canada 2006). CHU are highest in extreme southwestern Ontario and decrease with elevation away from the Great Lakes and with more northerly latitudes (Fig. 29.1a).

[1] See Glossary for botanical names of crops.

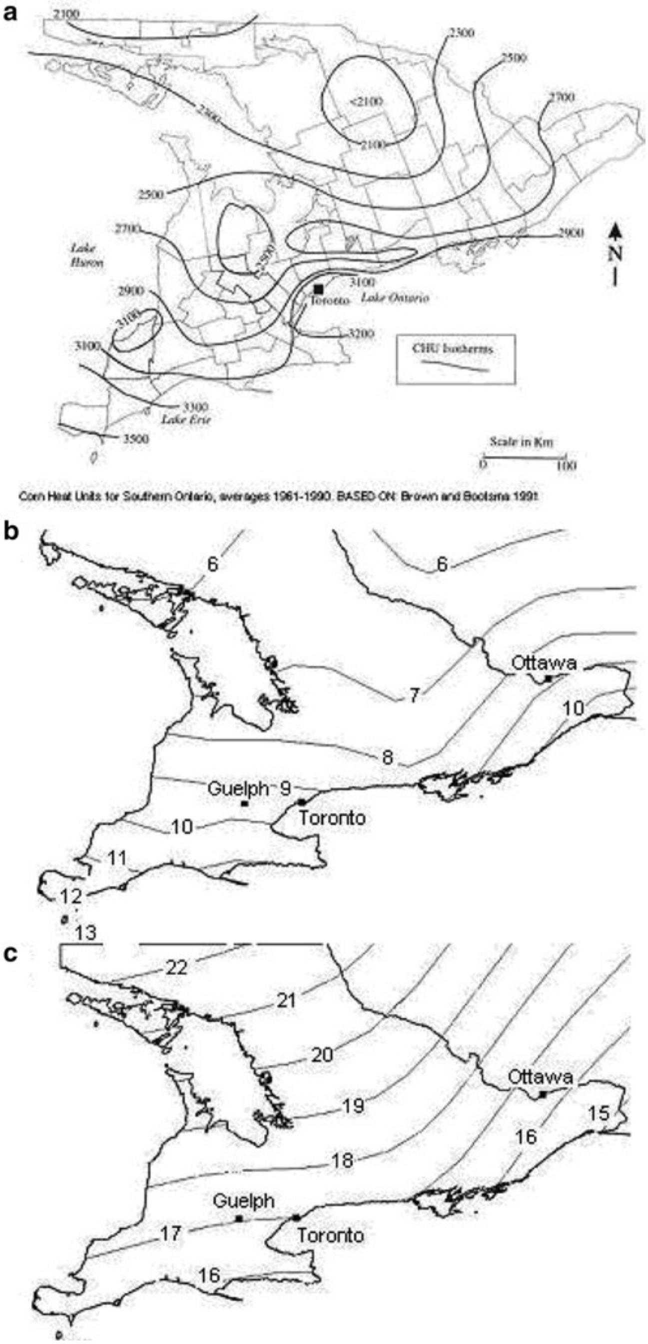

Fig. 29.1 Spatial variation in the potential for cropping in Ontario: (**a**) seasonal corn heat units (*CHU*), (**b**) and median seasonally-integrated growth index values (*MIGI*), both showing a rapid diminution of potential as one moves northeast; and (**c**) variability between years in the growth index (the variance of the median integrated seasonal growth index, (*MIGI*)) (Sources: (**a**) from 1961 to 1990, Brown and Bootsma 1993; (**b**, **c**) from 1961 to 2000, Pearson et al. 2008)

An alternative method of calculating the climatic potential for cropping, which is equally simple but more dynamic than CHU, is to calculate weekly Growth Index values, ranging from zero (no growth) to one (optimal) depending on temperature, soil water availability and solar radiation (Fitzpatrick and Nix 1970; Hutchinson 2002). The weekly growth index values can then be integrated across the growing season, which is bounded at both ends by low temperatures. Thus, the seasonally-integrated growth index, or over many years the median seasonally-integrated growth index (MIGI), can describe regional suitability for cropping, and the variance across years in this suitability. As with CHU, the growth index values, integrated over the growing season, are also highest in the extreme south-west (Fig. 29.1b). Further, the variation in growth index between years (calculated as variance about the median integrated growth index, or MIGI, over 40 years: Pearson et al. 2008) increases as one moves away from the south-west. Thus, as the potential for cropping decreases, so the reliability decreases (Fig. 29.1c).

For both corn and soybeans, genotypes adapted in northern Ohio or Illinois could be grown in the high heat unit areas near Windsor and production of both crops started in Ontario in that warm corner. For expansion to occur, however, it was necessary to breed earlier-maturing corn hybrids and, in later years, earlier-maturing soybean varieties. Further, this expansion required the breeding of varieties or genotypes which not only matured in lower heat units or growth index units but also were more tolerant of inter-year variability (Fig. 29.1c).

29.2.1 Soybean Introduction into New Areas

The expansion of the area of soybean production in Ontario is summarised in Fig. 29.2. Between 1960 and 2000, there was a 900% increase in area of soybean

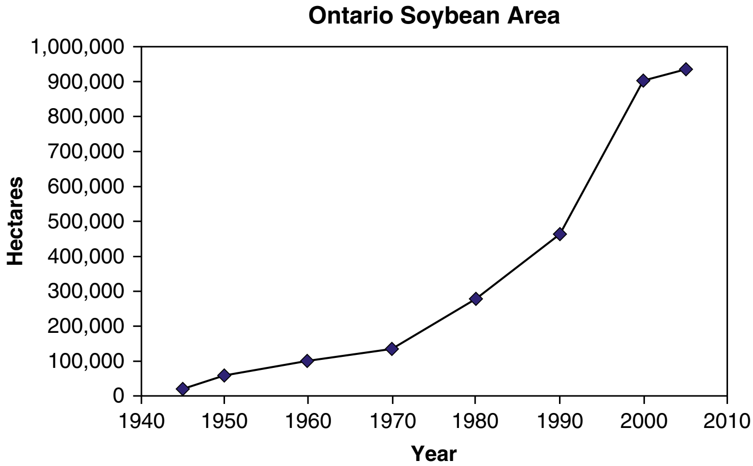

Fig. 29.2 Hectares of soybeans in Ontario from 1940 to 2005 (Sources: for 1943–2000, Ontario Soybean Growers 2004, and for 2005, Cumming 2006)

and, during that period, soybean average yields increased by 71% (White et al. 2007). There has been a gradual expansion, beginning in the 1940s, with no significant expansion between 1971 and 1976 but then an 85% increase between 1976 and 1981 (Keddie and Wandel 2001). This chapter explains some of the events between 1976 and 1978 that influenced the takeoff of soybeans in Ontario.

In the fall of 1977, Dr. Wallace Beversdorf and Dr. Dave Hume, who were both faculty members at the University of Guelph, approached the Ontario Soybean Growers Marketing Board (OSGMB) with a proposal and a request for some financial support. The proposal was that the researchers would work with the Ontario Soil and Crop Improvement Association (OSCIA) branches in each county north and east of London, Ontario (at the time, London was about as far east or north as soybean production went). The OSGMB directors, who all came from the existing corner of Ontario where soybeans were being grown, had the foresight to see the advantages of a much larger soybean industry and provided CDN $5,575 to finance the proposal. That meant it was time to get to work.

The timing was excellent because several research pathways were coming together. Dr. Harvey Voldeng, at the Ottawa Research Station of Agriculture Canada, released a new, short-season, high-yielding soybean variety called "Maple Arrow" in 1976. When Maple Arrow had been tested in public variety trials for 3 years, it was found to be 6 days earlier and 25% higher yielding than the closest variety in maturity (Ontario Oil and Protein Seed Crop Committee 1978). Seed of that variety was made available for the county demonstration trials. Maple Arrow also represented a quantum leap in early soybeans because it incorporated a trait for chilling tolerance (Hume and Jackson 1981); chilling tolerance refers to the ability to form pods and seeds in the presence of low (<10°C) night-time temperatures during flowering. This tolerance had previously been unavailable in North American varieties with good agronomic characteristics. Maple Arrow had ancestry back to the lowlands of western Hokkaido, where soybeans had been selected for millennia to tolerate a maritime climate with cool nights.

The variety had one major shortcoming; its pods shattered and spilled their seeds if conditions were warm and dry before the crop was harvested. Nevertheless, this variety was of major importance in the expansion of soybeans.

At that time, adapted soybeans in the new short-season areas were small in stature. In order to get respectable yields in research plots, it was necessary to plant them in rows no further apart than 18 cm. That led to the concept of planting soybeans with a grain drill rather than a corn planter and that approach was taken in the on-farm demonstration strips. Trials had already started on population densities, methods to achieve them with a grain drill and optimum dates of planting.

If soybeans were to be planted in narrow rows, then inter-row cultivation was not an option, so chemical weed control was also needed. Fortunately, at that time, trifluralin was available, which provided weed control of most, but not all, weed species.

None of the soils into which soybeans were being introduced contained any populations of *Bradyrhizobium japonicum*, the bacterium that, with soybean, fixes atmospheric N_2. In extensive testing, it had been shown that granular *B. japonicum* inoculants were more effective than those using powdered peat carriers (Muldoon et al. 1980). That led to trials with grain drills to optimise delivery of effective inoculation as well as trials to identify the best strains of *B. japonicum* and to get the inoculant companies to use those strains in their products. We also asked for and were generously provided with granular soybean inoculant for the project by the Nitragin Company, the major inoculant manufacturer in North America at the time.

The various components of a recipe for soybean production in short-season areas were coming together. These were written into a ten-page, detailed recipe (Hume 1977) and 1,500 copies were distributed. Much of that information was also used in a chapter about soybean production over a wider geographic area (Tanner and Hume 1978).

The concept of on-farm, field-scale, strip trial plantings of soybeans was publicised through the OSCIA branches and numerous meetings with farm groups during the winter and early spring. The response was overwhelming and 42 county locations were signed up for the spring of 1977. Seed and inoculant were supplied but the farmer co-operators were asked to finance the rest of the costs.

It was impossible for the researchers to be at each location at planting time, so most of the new growers had to work from a printed recipe. Fortunately, stands and growth were good and crops at most of the locations fared well. At that time, some harvest losses were unavoidable because flexible, floating cutterbars were not yet available. On the other hand, the fact that the co-operators' peers in the county were keen, interested observers probably helped keep harvest losses to a minimum.

Average yield for the on-farm sites was 2.4 t/ha, compared to 2.6 for the province as a whole, and, more importantly, the crop returned a profit. The area planted to soybeans in Ontario in 1977 was up 46% from the previous year. It is difficult to know how much effect the extension efforts had on this expansion but what it showed was that soybeans were a viable crop in Ontario.

29.2.2 Soybean Expansion

After the introduction of soybeans into lands east and north of the previous production area in Ontario, there was a sustained and rapid increase in area (Fig. 29.2). This was accompanied by a sustained, almost linear increase in provincial average yields (Fig. 29.3). The increased production of soybeans went to on-farm feeding of livestock and replacement of imported soybeans from the U.S.A.

Not only was there a rapid rise in the area planted to soybeans, beginning in the 1970s, but there was no evidence of a decline in grain yields during this expansion period. Rather, they tended to increase (Fig. 29.3), indicating that, on average, yields in the new areas were just as good as those in the older, more traditional areas. This directed attention to the adaptability of the cold-tolerant soybean cultivars which were selected for field trials in new areas of Ontario. Subsequent analysis (Pearson et al. 2008) suggests that the introduced soybeans had a far greater yield

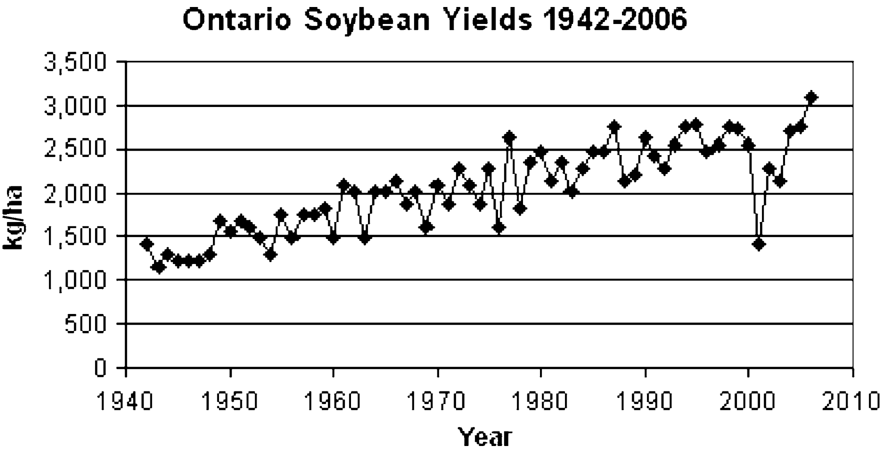

Fig. 29.3 Increases in Ontario average soybean yields from 1942 to 2006. (Sources: Ontario Soybean Growers 2004 and Cumming 2006)

tolerance to low temperatures (i.e. low heat units) than did corn, when grown commercially throughout the same region. This tolerance, and the yield record itself (Fig. 29.3), show that the soybean cultivars introduced were well adapted to the area. Further, the growing seasons in the period 1960–2005 showed a mild increase in heat units or seasonal integrated growth indices; MIGI values (Pearson et al. 2008). This increase may have assisted in avoiding crop failures due to exceptionally cool growing seasons. The one catastrophic year across the region occurred in 2001 (Fig. 29.3), which had an extremely dry growing season coupled with a serious, first-time infestation of soybean aphids (*Aphis glycines* Matsamura).

Keddie and Wandel (2001) identified three factors which resulted in the expansion of the soybean crop into new areas:

1. The development of improved cultivars and other technological innovations
2. The link with the earlier expansion of grain corn
3. The net returns for soybeans were better than those of other competing field crops; that is soybean grain prices were sufficiently higher than those of corn to create higher profits per hectare.

The net result, occurring in two waves (grain corn and then soybeans), was that Ontario changed from having an agriculture in 1950 with three major crops of hay, mixed grain (oats and barley) and wheat to a cropping system by 2000 that had major crops of hay, grain corn and soybeans (White et al. 2007). The increases in the areas devoted to corn and soybean production resulted in the decline in area of most cereal grains except wheat (Fig. 29.4). Since 1960, the total reduction in oat and mixed grain areas has amounted to about 1.25 million hectares, while there has been a slight increase in the area devoted to winter wheat. When grain corn was

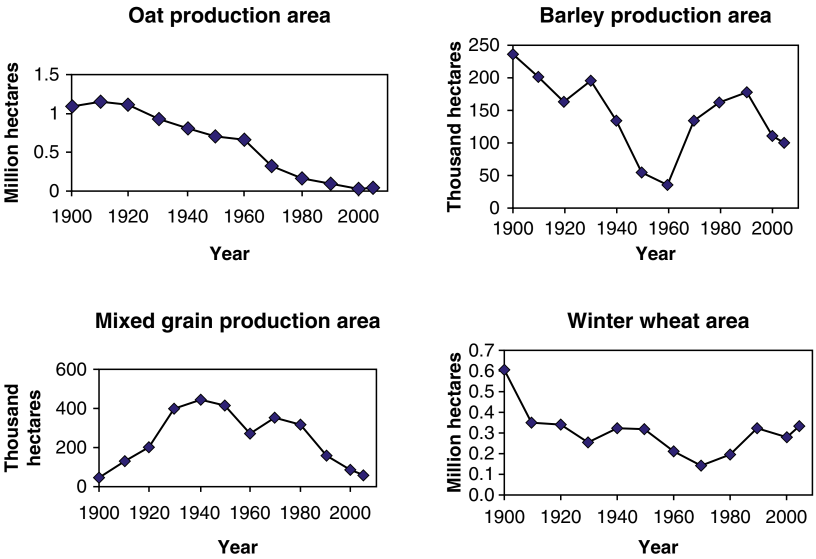

Fig. 29.4 Changes in the area devoted to oats, barley, mixed grain (mainly oats and barley grown together) and wheat in Ontario between 1900 and 2005

increasing in area between 1960 and 1980, the barley area also increased, even though the two crops were both used as feed grains. One of the reasons was a rapid expansion in hog production in Ontario during that period. Later, the barley area declined as both cattle and hog producers switched to rations that included more grain corn, and as corn yields continued to increase but barley yields did not. Soybean yields also showed a sustained increase until three poor years from 2001 to 2003 (Fig 29.3), largely a result of low rainfall.

A number of factors contributed to the adoption of the Midwest U.S. system of agriculture. The major contribution came from breeding for higher yields, earlier maturity and better resistance to pests and lodging (falling over) at maturity. The changeover spawned a whole new industry in plant breeding. Initially most of the corn inbreds and soybean varieties were developed at government-supported research institutions. As the crops developed, however, private industry took over the breeding.

Corn was introduced first and was successful largely because of its higher productivity compared to cereals, and also because of well-developed feeding programs using grain corn, which were readily available through U.S. research and extension. Then soybean area increased to the point where it became greater than that of corn. This was because of the ability of soybean to fix all of its own nitrogen, use residual fertility, and avoid drying costs, and therefore greatly reduce input costs. The introduction of soybeans decreased the use of fertilisers and pesticides. Before the widespread adoption of soybeans, grain corn was grown in a monoculture, with corn following corn in the rotation. Fertiliser use in Ontario peaked in 1985

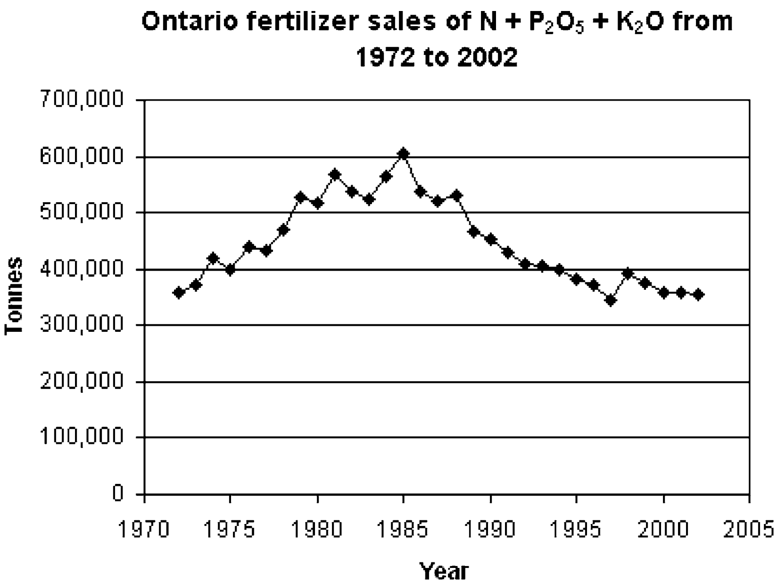

Fig. 29.5 Changes in fertiliser use in Ontario from 1972 to 2002 (Source: Korol 2002)

(The Fertiliser Institute of Ontario Foundation 2001), and has continued to decline since then (Fig. 29.5). The decline occurred because the dominant crop rotation became corn, followed by soybeans and then winter wheat. In this rotation, one third of the area (the soybeans) did not receive nitrogen fertiliser, resulting in a large drop in tonnage used. Soybeans also received relatively little P and K fertilisers because they were good 'second feeders', using these nutrients that the corn crop did not fully remove. The continuing decline in fertiliser use also reflects advances in breeding of corn for better N utilisation together with improved fertiliser technology, including side-banding of fertiliser blends, use of phosphorus to stimulate early growth, and a better understanding of how yields were limited by minor elements, such as zinc.

Corn after corn in a monoculture rapidly led to large populations of corn rootworm insects, and large amounts of insecticides were used to combat this pest. After soybeans were introduced, the problem essentially disappeared because the rootworms could not reproduce in soybean and wheat fields. Total tonnes of pesticides used on crops in Ontario decreased by 52% between 1983 and 2003 (McGee et al. 2004). Some of this reduction was attributable to the decline in rootworm insecticide use but another factor was a changeover in herbicide, insecticide and fungicide formulations per hectare from kilogram to gram quantities. The decline in use of the active ingredients in insecticides and fungicides is shown in Fig. 29.6.

The allocation of land resources by producers into grain corn and soybeans, rather than cereals other than wheat, occurred in waves. Each wave appeared to be motivated by better economic returns rather than by decreasing inputs. The first

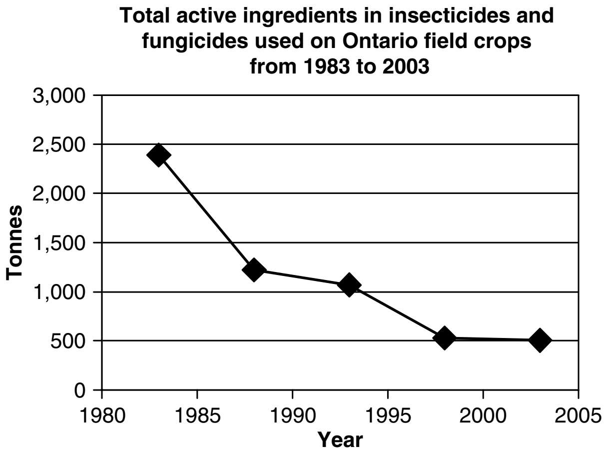

Fig. 29.6 Change in the use of insecticides and fungicides in Ontario from 1983 to 2003 (Source: McGee et al. 2004)

shift to grain corn involved widespread use of the persistent herbicide, atrazine, and a large increase in rootworm insecticides. The second shift to include soybeans, however, brought with it a more environmentally-friendly rotation with less fertiliser and insecticide use. Later, the adoption of no-till planting was relatively easy to do with soybeans and wheat, whereas corn yields were generally lower when no-till was adopted than with conventional tillage.

The changeover to include more grain corn and soybeans still continues in Ontario, with these crops continuing to be adopted in shorter growing-season areas. Recently, the pattern has begun to repeat itself on the Canadian prairies as corn and soybeans make cropping inroads into southern Manitoba.

29.3 Discussion

The shift to cropping systems which included soybeans occurred rapidly and achieved a number of outcomes, some intentional and some unforeseen.

With the benefit of hindsight, the speed of adoption of soybeans was related to several things: development of soybean cultivars adapted to these new areas, effective rhizobia and inoculants, a cropping system that utilised field machinery that farmers already owned, and readily-apparent economic benefits. Breeding of short-season soybeans for these cooler areas was initially conducted by publicly-supported breeding programs; after a market was established, private companies took over.

The ability of short-season, adapted soybeans to yield as well as their longer-season counterparts in southwestern Ontario was a pleasant surprise. Recently, Pearson et al. (2008) have shown that yields of soybeans, now grown widely in eastern Canada, are much less closely related to seasonal temperature (assessed by heat units- see Fig. 29.1, or median integrated growth index) than are yields of corn growing across the same regions. This temperature tolerance might account for the good yields, so important in the early years of introduction. Relatively high yields from the outset were also related to the use of elite rhizobia, imported from Brazil (Hume and Shelp 1990), and the absence of native *Bradyrhizobium japonicum*, so that the introduced elite strains were not out-competed by less efficient indigenous strains.

Early success also resulted from the pioneering work in soybean breeding at Agriculture and Agri-Food Canada in Ottawa (see Voldeng et al. 1997) and subsequent breeding at the University of Guelph, supported by the Ontario Ministry of Agriculture, Food & Rural Affairs. Early progress was also accelerated by a locally-committed, private soybean breeding company, which was a cooperative of growers, called First Line Seeds. It is interesting to speculate on whether adoption would have been as rapid, or indeed successful at all, had it depended only on cold-tolerant genotypes being developed by private companies based in warmer areas of larger, U.S. seed markets.

Given that soybeans have been shown to be well adapted to Ontario's long days and cool nights, and given the benefits from changing to a legume-based system capable of fixing all of its own N requirements, it is possible that soybean-based cropping systems might be adapted and economical in even cooler areas of Canada, such as the higher rainfall areas of the western prairie provinces.

The beneficial consequences of the expansion of soybeans include environmental benefits, increased efficiency of production and benefits to farm income. The environmental benefits have been discussed in the body of this chapter but, to sum up: (1) no-till planting was easier to embed within the system of soybeans/wheat than with corn or corn/wheat; (2) insecticide use was greatly diminished, in large part because it became unnecessary to apply insecticides for corn rootworm; and (3) soil nitrogen was easier to maintain, with lower fertiliser inputs, with a legume in the system.

The introduction of soybean-based systems improved the production efficiency, or yield per unit of inputs, for cropping in Ontario. The period of expansion of soybeans coincided with trends of declining farm numbers, increasing farm size and in income becoming more polarised between large and small producers. These trends were shared by Ontario with most, if not all, of the world's agricultural regions. By 2004, Ontario, like the rest of Canada, had more than half its farmers who were not financially viable and another 21% with gross annual revenue below $250,000, which is probably not sustainable in the long-term (Sparling 2006). The introduction of soybeans maintained income, or at least slowed the decline in farm income relative to what would have occurred with the older, cereal-based systems.

Yet while farm incomes declined and became more polarised throughout this period, regional incomes and regional social capital increased in most of Ontario, because the decline in numbers of farmers was more than offset by growth in jobs in a more educated, rural-based service sector (Bucknell and Pearson 2006). It remains to be seen whether soybeans, with their opportunity to contribute to the coming bio-based economy of plant-derived fuels, fibres, and nutraceuticals, will provide a base for new, more viable cropping systems for intermediate- and large-scale agriculture as well as for continued growth in rural-based manufacturing and services.

In conclusion, this chapter was an attempt to analyse the effects of a change in a cropping system (the introduction of soybeans) in Ontario. Some of the effects were foreseen, such as decreases in fertiliser use, but other effects, including declining pesticide use, early adoption of no-till and sustained increases in provincial soybean yields were totally unforeseen when soybeans were being introduced.

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Chapter 30
The Social Dimensions of Mixed Farming Systems

Decision Making, Drought and Implications for Extension

Nigel McGuckian and Lauren Rickards

Abstract Most mixed farms in Australia are family run, and so the goals of the family and of the farm are closely inter-related. This chapter describes and discusses social factors which influence decisions made on mixed farms with particular reference to the influence of drought. Decision making on mixed farms is an extremely complex process as many factors must be taken into account, some factors are difficult to quantify and uncertain variables such as climate and commodity prices are important. The factors influencing changes to the farming system and the influence of drought on changing the system are discussed. Some implications for research and extension are described. Two social research projects contribute to the chapter: the Grain and Graze Social Research project and the BCG—Critical Breaking Point research into effects of drought on farming families.

Keywords Mixed farms • Goals • Decision making • Social factors • Drought

30.1 Introduction

Most farming systems in Australia are run by farming families. These are often multi-generational, the farm having been held in the family for many years, often with a strong emotional tie to the land. The farming system adopted by a family is also often strongly linked to tradition and the preferences of the individuals involved. Farming systems have always been under pressure to adapt and improve in response to both external and internal change. In this process, it is vital to understand the social elements operating in the context of the whole system, especially when the farming system is under some sort of threat, such as drought. The majority of farming systems in Australia are mixed, especially rainfed, family owned ones, with livestock and cropping enterprises managed by the same family. These enterprises often use the same land in any one year and complement each other; for example, crop residues

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_30,

after harvest are often grazed. This mixed type of farming system has evolved not only because it is the basis of the early, self-sufficiency emphasis in Australian agriculture (see Davidson 1981), but also because most Australian soils are of 'mixed' quality and farmers have become skilled at using diversification to manage this and other risks. Some soils (and rainfall) are good enough for continuous cropping. However, if soils are not growing crops, they can be growing pastures for grazing animals. The proportions of the farm allocated to crops and livestock depend on factors such as soil types, enterprise profitability, farmer preference and climatic conditions (see also Chaps. 11 and 26). A mixed crop–livestock farmer may move in or out of these enterprises over time. In this chapter, a mixed farm is defined as one operating more than one enterprise, usually both crops and livestock. The recent drought in Australia and predictions of more frequent and intense droughts under climate change are making decisions on proportions of enterprises in the mix especially complex.

This chapter aims to provide an understanding of three main aspects of mixed farming:

1. the types of decisions faced by mixed farming families, particularly in the context of drought
2. some of the factors involved in modifying mixed farming systems
3. the consequences of these findings for agricultural extension.

This understanding is based on the authors' experience of working with farming families as management consultants over about 20 years, and with the results of social research conducted in two large projects, 'Grain and Graze[1]' and the Birchip Cropping Group's 'Critical Breaking Point?'.

'Grain and Graze' is a research, development and extension program working to improve the economic, environmental and social sustainability of mixed farms in southern Australia.[2] It is a 5-year project that started in 2003, and includes extensive research to improve understanding of the social dimensions of mixed farming systems—in particular, how farming families make decisions about their farms. As part of this research, in-depth interviews were conducted with about 100 mixed farming families and advisors.

All farmers interviewed were or had been running livestock and growing crops. The livestock enterprises included sheep for wool and meat, and/or cattle for breeding and fattening; crops included wheat, barley, oats, canola and grain legumes.

To explore how farm businesses make decisions, people were asked a range of questions such as:

- What are the strengths and weaknesses of your farming system?
- How and why has your system evolved to where it is now?

[1] Grain and Graze is run by Meat and Livestock Australia, Grain Research and Development Corporation, Australian Wool Innovation and Land and Water Australia. http://www.grainandgraze.com.au/

[2] The social research project of 'Grain and Graze' involved 1–1.5 h, in-person interviews with 80 farming families and 20 advisors based in 9 regions between February 2006 and February 2007. Interviewees were chosen using a combination of random sampling and snow-balling (Bryman 2004). Detailed notes of the interviews were analysed systematically and iteratively for their key themes.

- What has caused the changes in the system?
- What decisions have you made as you have changed your system?
- When deciding to change your land use/system, how do you work out if it would be more profitable?
- What approach do you take to looking after natural resources?
- Do you think mixed farming is more/less profitable than a single enterprise system and how do you know?
- How confident are you that it is more/less profitable?
- What tools did you use to work it out?
- In deciding for/against running a mixed farming business, describe what has influenced your decision (a range of prompts may be used, such as time, family, skills, money, workload, holidays)

The results of this research form the basis of 13 discussion papers, written to outline a range of social issues involved in managing mixed farming systems (McGuckian 2006). The results are also being used to inform extension activities throughout Australia.

'Critical Breaking Point?' (CBP) is a socially-oriented investigation into the effects of drought and other pressures on farming families in the Wimmera–Southern Mallee region of western Victoria (Birchip Cropping Group 2007). The award-winning Birchip Cropping Group, organized interviews with approximately 60 mainly mixed farming families about their experiences of drought. These were followed by 6-month follow-up interviews with a sub-set of 20 farming families, to be repeated in another 6 months. This will help in understanding how farming families' experiences, with the decisions they make, change over time.[3] As in 'Grain and

[3] In the 'Critical Breaking Point?' project, 60 farmers and their families were randomly selected from across the Wimmera Southern Mallee region. Interviewees were not screened to select only those 'badly affected' by the drought, but included those who felt they have been only negligibly affected. Each interview was semi-structured and lasted on average 2 h, with the shortest being approximately 1 h and the longest being over 4 h. Interviews were fully transcribed and, in conjunction with the handwritten interview notes, were analysed systematically by working through them and building a progressive code of key themes. These themes were then mapped in mind maps and tables, based on a grounded theory approach that prioritises data-driven and inductive conclusions (Alvesson and Skoldberg 2000; Glaser and Strauss 1967; Glaser 1993). In keeping with this methodology, themes were re-tested against transcripts in an iterative process until the key findings emerged.

A key to this research was using local interviewers. This not only helped to illicit more insightful information, but provided the interviewers with listening and research skills they can use elsewhere, including in further research in their community. Four suitable, local people were recruited for the task with the assistance of BCG. They signed a contract with BCG including a confidentiality clause and were remunerated for their work. Interviewers were trained intensively in qualitative research and interview technique, were accompanied on their first interviews, and were debriefed during and at the completion of the interview process.

The first phase of this research was conducted over a 2-week period in February 2007. A second phase of interviews was conducted, 6 months after the original interviews. This phase is based on a sub-sample of 20 families from the original 60, which is skewed towards younger and older farming families to follow up issues specific to them that were highlighted during the first phase.

Graze' 'Critical Breaking Point?' explores farming families' decisions and decision-making processes, with explicit interest in the role of 'external' pressures such as drought, cost of inputs and 'rural decline'. As with 'Grain and Graze', also, the results are being used to inform both extension activities, and government policy on rural needs.

The present chapter first discusses the multi-layered complexity of the decisions farming families make. It then examines the decisions that interviewees in the Grain and Graze research have been making about modifying their mixed farming systems. The Birchip Cropping Group's CBP research is discussed in terms of the impact of drought on farming families' decision making.

30.1.1 Types of Decisions

A discussion with a farmer about a farming system covers a vast range of topics. For example, Grain and Graze interviewees, stated that matters they have to consider in a calendar year include: lambing time; fertilisers for crops and pastures; calving time; reproductive management; crop choice; sowing method; leasing or owning a harvester; labour requirements; grazing crops; planting trees for erosion control; shelter for lambs; targeting lamb markets; animal health; climatic risk; cash flow; and capital purchases. All of these considerations are inter-related and interact continuously, as farmers react to changing circumstances. In doing so, they create other circumstances requiring response.

Our research highlights how farmers must consider 'family' elements, such as availability of family labour, family preferences and targets, services and opportunities available in the local area, off-farm income, large family expenses, if and when to have a holiday and farm succession. These family elements interconnect with those of the wider non-agricultural community. Overall, farm production decisions are encased in many layers of 'non-production' and even 'non-farm' concerns that farmers explicitly or implicitly take into account (Fig. 30.1).

The Cynefin Institute (Snowden 2003) usefully describes decision making as simple, complicated, complex or chaotic. A **simple decision** has one right answer. For example, choosing where to file a document in the office is a simple decision—if the office has an organised system. A **complicated decision** has a right answer but there are many factors involved and it is difficult to know the answer. For example, building a piece of machinery is complicated but, if it is done correctly, it will work. Choice of herbicides in a farm system is often complicated as it requires a depth of knowledge to make the recommendation, but often there is a right answer. Because these decisions are 'straight forward', decision making tools such as computer models can be used to work out the right answer. Such decisions can also be delegated to external experts such as consultants. In contrast, a **complex decision** involves many factors and has many 'right' answers. Some of these factors cannot be easily understood, measured or compared. Rational decision-making approaches such as cost-benefit analyses need to be complemented in these situations

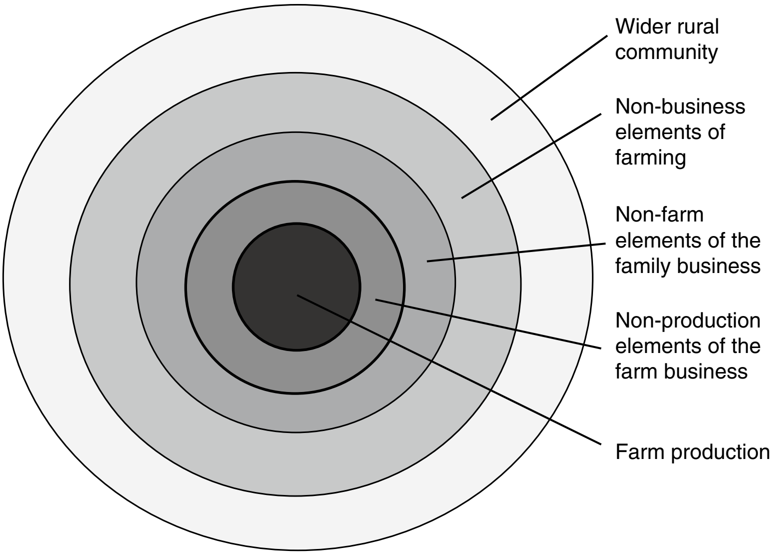

Fig. 30.1 The many layers of factors that farmers take into account in their decision making

with ‘non-rational’ tools such as ‘gut feel’ or intuition. Although parts of a complex decision can be delegated, ultimately it is up to the farm family or manager to make the decision.

In mixed farming systems, much decision making is complex. There are many considerations, which are constantly changing, many of the factors involved are unknown or difficult to quantify, or their relationship with other factors is poorly understood. For example, how heavily to graze a pasture on light soil can be a complex decision. The decision will depend on how much pasture is available for the sheep and what quality is required at a particular stage in pregnancy. It will also depend on how much damage grazing does to the soil (which differs between wet soil and dry), on the farmer’s attitude to soil management and to the environmental values of the property. Running more sheep may make the property more viable in the short term, yet affect the family’s ability to manage other enterprises or to go on holidays; and may lead to a workload that is too much for the family to handle. Questions about the sustainability and desirability of the situation and ultimately the question of whether the family can or should stay on the farm may then come into play. In this way, a myriad of interconnected factors and increasingly profound questions flow from a seemingly simple grazing management decision, thus illustrating the complexity of many seemingly simple decisions on a farm.

The relative complexity of mixed farm systems is increased if, as is common, they are family-operated. This is a consequence of there being multiple decision makers in often intricate relationships, and with a blurred professional-personal divide which stems inevitably from living in one’s work place.

The vital social dimensions and consequent complexity of decision making on farms are often not acknowledged by farmers, nor taken into account by extension workers and researchers. Yet, our surveys suggest that the fundamental reasons for the farming family choosing their occupation are social ones; These reasons include: flexibility of lifestyle; the opportunity to work alongside their children; an attachment to the land; or simply that they like doing it. These, of course, are similar to the 'social' reasons used by most of the human population to make choices in life such as preference, family or convenience. Many business people make choices based on social reasons. For example, a builder may choose to run his own business because 'he wants to work for himself'. Farmers are sometimes criticised by the claim—'farming is not conducted as a business'. In fact, farming is a serious and professional business where the business owners, like many others, are motivated strongly by social drivers.

30.2 Changing Mixed Farming Systems

The arrangement of sub-systems on a mixed farm is constantly changing and being redesigned by the farm manager. Social factors strongly influence this also. It is often the view that farmers will change their system when the financial incentive is sufficient and that they will respond to market signals. But a change in commodity price does not necessarily lead to increased production of that commodity; there are many other factors at work. Because mixed farming systems are complex, changing them is also complex, as the farmer has to 'rejuggle' many interacting components. Adopting a suggested new practice therefore is not simply about the merits of that practice; it is about how it would fit into the farmer's whole system.

There is a long history of investigating how to encourage farmers to adopt what are perceived to be desirable new practices and technologies. Motivated initially by a desire to increase farm production, and more recently by a desire to improve agriculture's environmental sustainability, much of the literature on the topic has focused on identifying 'barriers' to the adoption of these 'desirable' behaviours.[4] Work by Pannell et al. (2006) and others has identified key influences on whether a farmer is likely to adopt an innovation such as a new enterprise. These factors can be summarised as: landholder goals; landholder circumstances; landholder perception of the messenger; the transaction cost of change; and the practices already available to the landholder (Fig. 30.2).

All of these factors are taken into account when mixed farmers consider whether and how to change their system. If, for example, the *goal* of a mixed farmer is to

[4] It is important to realise that, as Vanclay (2004) argues, 'barriers to adoption' is an implicitly arrogant idea that denies the fact that from an individual's perspective, all of their decisions are made for legitimate reasons, even if those reasons are poorly understood by others.

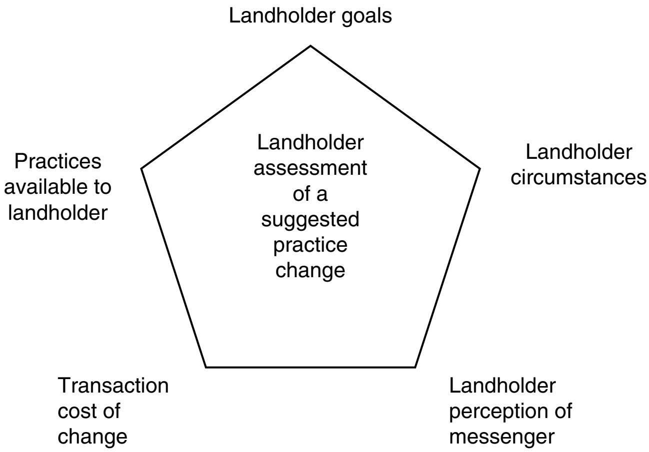

Fig. 30.2 An overview of five central factors landholders take into account when assessing any new practice or technology

maintain a well-balanced mixed system, the technical or financial merits of a change within a single enterprise may be tempered by the effects of that change on the overall balance of the system. The *circumstances* of mixed farmers are such that they have multiple enterprises to take into account and, as a result, they have many *practices already available for adoption*—both in theory and on the ground. A change in one enterprise may affect other enterprises, either directly or indirectly, such as through its effect on the farmer's time or resources. *Transaction costs* can therefore be significant. Finally, like all farmers, a mixed farmer's *perception of the 'messenger'* of a desired change (such as an extension officer or agribusiness representative) influences the farmer's level of interest in the proposed change. How trustworthy the messenger is perceived to be (which is often a factor of how long the farmer has worked with the person) is particularly important.

The Grain and Graze research attests to the centrality of the above five influences (Fig. 30.2) on farmers' willingness and ability to change. It also found that most farmers are uncertain about the best way to analyse information to make a decision about a potential change in land use. Many farmers use 'tools' to help them, but the variable way in which they use them points to the underlying complexity involved in their decisions. In determining their enterprise mix, for example, which is the area in which a large proportion of their on-farm changes are made, mixed farmers mentioned that gross margins, bench-marking, the accountant's figures, 'what the consultant says', and 'rules of thumb' are among the main things they consider.

Calculating gross margins has been one of the changes that some extension efforts have encouraged farmers to adopt in an effort to make them more 'rational' in their decision making. Some farmers indicated they are sceptical of the value of this tool. Others indicated that, even if they do not actually calculate their gross margins, they thought it would be a useful exercise or they used some approximation of it. When pressed in the interview to say exactly how they analysed information to make decisions, the typical responses included:

> Can't tell you exact figures but we know what is profitable.
> If we didn't have sheep over the last four years, we would have struggled—we do figures in our head, per hectare.
> We are confident it is the best land use. We need models to compare cattle options.
> We haven't seen anything to prove cropping is better. We are interested in the bottom line. It's what we want to do.
> We are often not comfortable about the numbers.
> Got to keep the balance—numbers don't matter so much.
> The last thing you do is the books.
> We are not confident—which makes me worried.
> Economics are important but we stopped chasing production and are trying to develop a long term ecological state.
> What we want to do influences how we do the figures.

This range of responses was consistent throughout most interviews. The attitudes in these quotes could be summarised as:

- The tools to make decisions are either not well understood or are not adequate to make complex mixed farming decisions.
- Because the decisions are complex and have many unknown variables and risks, a detailed assessment of the costs and returns is considered of little value.

Rather, as mentioned above, it is social factors that predominantly determine decisions about land use. The Grain and Graze research suggests that the overall mixed system designed by farmers is driven by four main factors:

- hassle reduction—the desire to keep a system simple and avoid complexity
- labour—the desire to use labour more efficiently and the ability to find it when required
- recreation—the desire to find time for recreation
- personal preference—the desire for a system that (predominantly) includes the enterprises a farmer enjoys.

We will now look at each of these in turn.

30.2.1 Hassle Reduction (Simplicity)

Like the general public, many farmers are looking for ways to make life simpler and easier. Simple farming systems are generally preferred because less can go wrong, they lower costs and they are easier to manage with less skilled labour. People will often avoid a new technology because it adds to the complexity of the system; this becomes more important as farms become larger and are run by a smaller labour force.

30.2.2 Labour

Many farmers are now designing their systems around the available labour force,—which increasingly is just the farm family. While farms commonly employed labour in the past, it is difficult to finding reliable labour with the required skills among declining rural populations. Further, the growing bureaucratic complexity of employing a worker (through requirements in tax, occupational health and safety, training and professional development) has meant that most farming families have opted, instead, to either work harder or reduce the workload on the farm. This decision then further reduces the employment available in the region and accelerates the process of rural depopulation.

Given the desire or goal of simplicity, much technology adoption is driven specifically by the desire to reduce the need for labour. For example, the adoption of laser grading of land for flood irrigation in Australia was encouraged by extension officers to reduce soil salinity. But its rapid and widespread adoption often occurred because it allowed a farmer to manage more irrigation water and therefore run a larger farm, without employing extra staff.

It should be noted that a few interviewees actually reported a preference for labour-intensive enterprises because it allowed them to keep on a full time employee. As one interviewee said: 'If we didn't have the sheep, we would have to let him go and then we wouldn't have someone to do all the jobs'.

30.2.3 Recreation

Associated with the workload or labour requirements of a farm is the degree of freedom the farm offers farming families to participate in other things, such as off-farm employment or recreation. The ability to have a family holiday emerged in the Grain and Graze research as a real concern for some families. A perceived limitation of mixed crop–livestock farming systems is that they require not only a higher workload, but also a more constant workload throughout the year. Keeping sheep on a mixed farm, for example, means stock need to be checked throughout summer, especially during drought conditions. This often means the family cannot leave the farm during the school holidays. Many families reported having great difficulty finding a time for their family to have a holiday. Such a lack of time off can increase the stress the family experiences, as discussed further below.

30.2.4 Personal Preference for an Enterprise

A preference for particular enterprises also strongly influences overall system design. Farmers interviewed often had a strong preference for or were against an enterprise because of factors involving labour, or for more intrinsic or personal reasons.

Two-thirds of farmers, for example, expressed a strong aversion to running sheep. While for some this is because of the level of work required—'Running sheep wouldn't allow us to have our holiday'—for others it was because of a lack of familiarity or confidence with sheep or a simple dislike of the animal. As one farmer stated simply: 'I hate the sheep'.

Others expressed a strong positive preference for working with sheep. As one interviewee explained, he found working the sheep the most enjoyable work on the farm because it meant he got to work with his sheep dogs. Others value sheep because of their role in the system, above and beyond their functional contribution. As one interviewee said: 'A farm without sheep is a dead farm. You've got to have some life out there'.

Positive preference was also expressed for other enterprises. Many farmers, especially younger ones, have a strong preference for growing crops because of their interest in agronomy, reduced tillage technology or machinery in general. Others are drawn to the visual satisfaction crops can provide. Looking out over a freshly sown field or tall green crop, farmers can see the 'fruits' of their hard work. The intrinsic motivation such an experience provides should not be underrated.

30.3 The Role of Drought

30.3.1 The Difficulty of Decision Making

The CBP research suggests that the current drought in Australia is increasing farmers' desire to improve their systems in order to reduce their vulnerability to drought effects. Drought adds a large degree of uncertainty and introduces an increasing number of issues for farming families to deal with. Problems in one area (e.g. mental health and family cohesion) flow through to other areas (e.g. ability to cope with work load and financial decisions), flowing back in positive feedback loops (Fig. 30.3). Farming families' physical, financial and social/personal reserves are

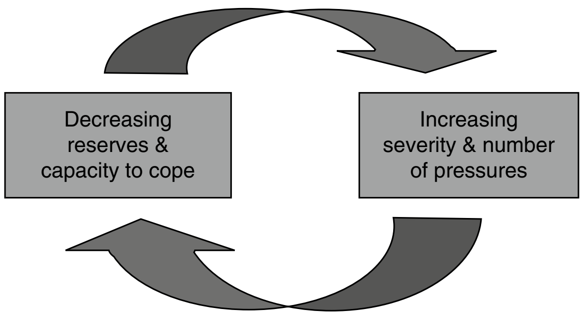

Fig. 30.3 An illustration of the positive feedback that drought sets in place between a family's reserves and capacity to cope, and the severity and number of pressures they face

intimately interlinked, and drought eats away at all of these. This means drought can dramatically increase the complexity of decisions facing farmers at a time when their desire to reduce hassle (stress) is maximal. The CBP research suggests that despite farming families' desire to improve their situation and reduce their vulnerability to drought effects, the complexity that drought introduces, combined with their reduced ability to cope with complexity while under stress, mean that drought also stalls their decision making. There are too many factors involved and too many are unknown. Thus, although farming families want to act to improve their circumstances, many feel unable to do so.

The CBP research suggests that farming families are asking more difficult and profound questions about their actions and their future than many have ever asked before. As they question their goals and try to understand their circumstances, the 'practices available' to them (Fig. 30.3) come into question. In particular, the question of 'whether to stay or go' is one that some are facing for the first time. Often this decision is constrained not only by a stalling on all decisions, but by a perceived lack of alternatives.

Those who are deciding to stay on the farm despite drought are asking serious questions about how to do so. General approaches to farming—philosophies of management and 'rules of the game'—are being reassessed. There seems to be a move to a more low-input approach, forced by economic necessity but sparking interest in its other benefits. For risk management reasons there is a move among some farmers to more 'mixed' systems as families seek to reduce their vulnerability to drought effects by spreading their efforts over more enterprise types. Thus, just as drought is seriously challenging rainfed agriculture, it is also perhaps increasing the popularity of mixed farming. Understanding such systems and how best to help those involved in them is therefore more important than ever.

30.3.2 Choosing an Appropriate Enterprise Mix

Choosing an appropriate enterprise mix is a key to coping with drought. As discussed above, what is 'appropriate' for any particular farming family depends on a range of factors, many of which are social as much as financial. For example, many in farming families are looking to devote more time to off-farm employment, either because of immediate financial necessity or a desire to diversify their income away from farm income.

Drought also accentuates farming families' need to get away from the farm, either for temporary recreation or a holiday. Yet, due to the work required on the farm or the cost of fuel and other costs of socialising or holidaying, many farming families feel financially unable to leave the farm. This can reduce their social and financial involvement in their local community, which is, in turn, also affected.

The desire to have time for something other than farming—work or rest—has implications for the kind of enterprises farmers choose to run. For this reason, and the desire to save on employee costs, the labour requirements of different enterprises are more pertinent than ever and are part of the mix as farmers try to weigh up the pros and cons of different enterprise types and combinations.

Drought accentuates the greater labour demanded by livestock by often requiring that water and feed are carted. The need for livestock feed illustrates how the links between crops and livestock can be accentuated during drought, as either grain or crops-cut-as-hay are used for feed. Other stresses of keeping livestock include animal welfare issues, which can engender an extra sense of responsibility to livestock, relative to crops—'like having 10,000 hungry children' as one farmer in the CBP research put it. Watching hungry animals become increasingly distressed during drought can take a serious toll on farmers, as can watching crops dying. One of the reasons why farmers and their families should have some recreation time during drought is to get away from such scenes, especially given that they live as well as work with them.

In contrast to the difficulties livestock create in a drought, they have two important benefits. One is a degree of financial security relative to crops. A mob or herd represents a source of equity that can be sold at a later date or used to start off a post-drought recovery. The work involved in looking after animals during drought can also be an advantage. While over-work can be an issue of concern, the need to look after livestock during drought does avoid the negative consequences of underwork that 'pure croppers' can experience during drought, when there are no crops to manage. Given that work plays an essential role in meeting our psychological as well as physiological needs—giving us a social role and social interaction—the loss of work can be a serious cause of stress. Thus the continuity of livestock during drought can be important in maintaining a sense of normality and purpose for farmers.

30.3.3 Decision-Making Assistance

Financial management and decision-making emerged in the CBP research as two areas farming families are focused on and would like to be helped in. While there is a desire for technical production assistance concerned with 'drought-proofing' farms, it is the higher level family, financial and business decisions that seem to be weighing on people's minds. Part of the reason for this is a felt lack of skill in this area. Many older farmers, for example, are less skilled in financial and business management than technical production because of the past emphasis in formal agricultural education and extension on science and production issues. The complexity of the financial environment has also increased rapidly over time. Profitability is now seen as more important than production *per se* and there is a desire to become more confident in making the business decisions needed to improve the profitability of the farm business—or family income—as an entirety. Training is therefore needed in this area.

In the shorter term, many farming families expressed their desire for assistance with the immediate decisions they are facing about their future. Such assistance needs to be offered with a deep understanding of the complex array of factors that farming families are likely to take into account. Given the impossibility of understanding all the intangible factors they will be considering, such assistance also needs to be offered with an appreciation that the ultimate decision rests with the individuals involved and, as Vanclay (2004) emphasises, even if the decision is nonsensical to an outsider, it needs to be respected.

More than by introducing completely new issues, the main way the drought is affecting families and communities is by exacerbating existing issues, making them more complex than ever. These existing issues include the decline of Australia's rural communities as people move away because it is no longer economically, socially or emotionally viable for them to remain. Other non-farming businesses and families in rural towns are being forced to ask profound questions about their future as the impact of a declining agricultural population flows through to the towns. This loss of non-farming community and services in turn flows back to the farming families that rely on them (WDA 2007). Farming families indicated in the research that what others in their region do, including those in the towns, is a major factor in their decisions about whether to stay or go, as the options for off-farm employment, education and social interaction for family members, among other things, are affected. Often it is difficult for them to put these factors into words, much less quantify them or weigh them up against the predicted financial viability of their business. Yet such factors are no less influential in determining the future direction a farming family will take.

30.4 Implications for Extension

This chapter highlights both the importance and limitations of extension. Extension is important because many farming families want and need assistance with the increasingly complex decisions they are facing. It is limited because outsiders can help their complex decision-making only so far.

There are three main ways in which advisors/extension officers can help farming families with their complex decision making:

1. providing information and advice about particular complicated 'bits' of the complex decisions
2. providing a listening ear or small group forum in which farming families can learn from each other and about themselves through 'telling their story' and talking through their decisions
3. providing strategies, tools and models to help farming families streamline or simplify their farming systems and decisions.

We will now look briefly at each of these in turn.

30.4.1 Providing Information and Advice

There are many types of information farming families need to accumulate to make informed decisions. Yet conditions are changing so rapidly for farming families that it is difficult for them to know the questions to ask, much less the answers to act on. There is also an increasing amount of information available. Sorting through this ‘information glut’ to find the most credible and pertinent pieces of information is one of the most important services extension officers can provide. The Grain and Graze and Birchip Cropping Group social research suggests that the following issues are currently areas of particular interest for many farming families.

30.4.1.1 Financial and Business Management

Traditionally, financial and business management skills have been neglected in agricultural extension and formal education relative to science-based technical skills. But, with the financial and business environment in which farm enterprises are operating becoming more complex and arguably more difficult, this is a key area for skill development for many farmers. The CBP research in particular highlights that, with the current drought reducing the amount of time many farming families are currently spending on production decisions (due to crop failure or selling of livestock, for example), and with it also creating painful financial and business problems, many families have turned their focus towards financial and business management.

30.4.1.2 Best Management Practices in the Field and Beyond

One of the consequences of the extended drought is that the practical ‘rules of thumb’ farmers have used are now in question. There is therefore a strong need to advise farmers on how best to operate in the current changed conditions. Farmers are told to work on ‘drought-proofing’ their farms yet there is little up-to-date information on how to go about this. What enterprise mix is best in their area during a drought, or in anticipation of longer term climate change? Much research is needed into technical production issues such as crop choice in the context of drought and climate change. Locally-specific climate projections are also needed to help farmers plan for the future.

‘Best management practice’ is also needed, including calls for managing risk through diversified investments. The drought has highlighted that assistance with managing superannuation and succession issues would be helpful for many.

30.4.1.3 Sector and Regional Information

Climate projections are one sort of information that helps farming families understand the context in which they are living and working. The CBP research found that many farming families are hungry for information about the changes going on around them in both the agricultural sector and more broadly. How is their region or local community changing? What are the trends? What is the likelihood of key services remaining local? What is happening to agribusiness, employment opportunities and schools in the area? This kind of information will help them understand the environment in which they are living and working and so to plan for the future.

Helping farming families with particular 'bits' of information for making their complex decisions is far more effective when it is done with a sharp awareness of the larger picture that the 'bits' fit into. This does not mean that advisors need to understand all aspects of farming families' work and life situations, but it does mean that they need to understand that these aspects exist and that the information and advice they provide will be integrated with factors that the advisor is not privy too. Advisors should not be prescriptive or patronising in offering their information or advice.

30.4.2 Providing a Forum for Story Telling

While providing information and advice is useful, putting it all together and deciding how to act on it that is hardest. An advisor can assist farming families in this process by encouraging them to work out what is important and best for them through telling their 'story', to themselves and/or to others. Telling one's story involves reflecting on and implicitly communicating where you have come from, the choices you have made, why you made those choices and what the implications have been. It involves bringing together such aspects of life as your patterns, assumptions, limitations, motivations, goals and the personal preferences discussed above. This process can be enormously helpful in establishing the 'boundaries' in which one can reasonably make future decisions. By setting the bounds on one's decision making in this way, the process is significantly simplified and the appropriate options can become clearer.

Often it is easier to see the above aspects of story telling when one is listening to others tell their stories. Creating a safe, confidential environment in which people can listen to and help each other reflect can be an enormously valuable role that an extension officer can fulfil. Small discussion groups can also share financial and other data to help clarify the circumstances each person is in. This 'benchmarking' also helps to satisfy people's hunger for information about what is going on around them and how they are progressing relative to others; such information can quickly shine a light on people's relative strengths and weaknesses.

Communicating in this open way can be a serious challenge for many people. Skills training and role modelling of the kind of honesty and empathy that is needed is another area for extension to provide, both for many extension officers as well as for farming families.

30.4.3 Providing Strategies and Tools for Streamlining Complex Systems

As suggested in the discussion above about reducing hassle (Sect. 30.2.1), another way to help set 'bounds' on complex decisions is to help streamline complex farming or business systems. There is a range of financial and production tools that can help to highlight the pertinent information about a business. This allows farming families to better understand their current situation and options for the future. For example, at RMCG (RM Consulting Group), we have designed a simple spreadsheet which helps farmers to see on one page what their figures suggest about three central questions:

- Am I profitable enough?
- Can we afford to expand/contract?
- Can we afford to retire?

The Grain and Graze research confirms what years of consulting experience have found, that these three questions encapsulate much of the complex decision-making that many farming families face. By even posing these three questions, advisors can assist farming families to focus in on what they need to decide.

Specific ways in which farming families can work to streamline their farming systems include reducing their requirement for labour, including their own labour, and reducing enterprises that they dislike.

Overall, extension has a critical role in helping farming families make decisions, particularly the complex decisions that many are facing about their future plans in a changing environment. Yet, it is also vital to understand and respect the limitations of any advisory role with farming families. In the end, the farming family must decide for themselves what they want to do even though this decision may not be readily understandable from an outside perspective. Hopefully, the support and assistance that has been provided to them along the way means that the decisions they make are not just complex, but confident and constructive.

30.5 Conclusions

To improve the social, environmental and financial sustainability of rainfed farming systems, we need to understand better the decisions that farming families are making about them. This chapter has presented some concepts and empirical data drawn from extensive social research into the decision making of mixed farming families in southern Australia. It highlights the importance of understanding the social character of, and social influences on, decision-making. These may be in terms of the multiple influences involved in a farmer's decision to adopt an innovation, or in terms of large questions many are asking about their future role in the agricultural sector and the rural communities they live in. In particular, this research highlights the importance of understanding the inherent complexity of many decisions in the farming environment.

Mixed farming is an important component system of Australian agriculture that is being both encouraged and tested by the severe drought conditions many areas of the country are experiencing. On the one hand, the risk management approach that multiple enterprises inherently involve is proving even more necessary than ever.

On the other hand, the complexity and challenges of mixed farming are also being heightened by drought. Many farming families are seriously asking whether it is desirable or even possible to stay in their business. It is important to assist them with this decision to stay or to go. If assistance such as training in decision-making skills or advice about specific issues is offered with a sophisticated and empathetic understanding of the types of factors and decisions farming families make, it promises to help provide mixed farming with a more sustainable basis.

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Chapter 31
A Study in the Development of a Farm System on the Canadian Prairies

Scott Day

Abstract The Day farm on the Eastern Canadian Prairies is an example of development of a system able to cope with extremes of climate and particular soils yet sustainable and profitable. The Days have embraced technology such as no-till and genetically modified crops to maintain their system. Other strategies include having a range of crops, maximizing resources such as soil moisture and minimizing inputs where possible.

Keywords Canadian Prairies • No-till • Crop diversity • Rotations • System improvement • Genetically modified crops

31.1 Introduction

The Day family farm is located on the Eastern Prairies in the very centre of North America. The family operation, known as Treelane Farms Ltd., is near Deloraine, Manitoba, Canada, some 70 km east of the Saskatchewan border and 40 km north of the North Dakota border—just north of the 49th parallel. Other members of the immediate family farm close by; thus farming is a family affair, with decisions and motivation always taken in consideration of the benefits to all generations (Fig. 31.1).

Most of this region was opened up to farming in the late 1880s, and the Day family has been farming there for over 100 years. Epic droughts in 1936, 1961 and 1989 coincided with the times when three generations of the Day family started their farming careers. This has left them cautious, giving them great respect for conservation and climate risk. It quickly became apparent that the protection of their soil resource was paramount and that this would come with improved soil water conservation and yield potential.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_31,

Fig. 31.1 Day family

This chapter presents an overview of the multi-generational farm, its resources, its challenges and its management to survive and prosper in this harsh location.

31.2 Climatic and Weather Factors

Local precipitation in the form of rain, sleet and snow averages about 475 mm of water equivalent a year, but there is rarely an average year. Rainstorms can drop 100 mm in an hour, or 3 months can go by without any precipitation. The ground is completely frozen for at least 5 months of the year, and snow is stored to be released, hopefully in April, just prior to sowing. Thus good yields can be produced even if only 150 mm of well-timed rain falls during the growing period. Management aims to store as much as possible of that winter moisture (usually one third of the total annual precipitation) until it is needed in the spring. Whereas, previously, tillage left a smooth surface that allowed the snow to blow away into the ditches and trees, no-till farming now enables as much snow as possible to be caught in the standing stubble (see Fig. 31.2). This standing stubble that is maintained through no-till also reduces evaporation from the soil surface because of the insulating protection from the straw residue.

Weather is the universal topic of farmer conversation anywhere in the world; the Days experience extremes of weather because of their location in the centre of a

Fig. 31.2 Scott Day standing in his wheat stubble full of snow

continental mass. Within a 6-month period, Scott has seen −50°C and +43°C on the same thermometer at the farm. There can be snow or frost in every month except July. Average maximum temperatures are: January (winter) −11°C, April (spring) 10°C, July (summer) 26°C, and October (autumn) 12°C, but all four seasons can occur in the same week. Planting may occur during spring snow fall (Fig. 31.4).

The last spring frost is usually in the middle of May and the first fall frost is often in the middle of September, giving about 115 frost-free days for the growing period. However, the long day-length during summer means that total radiation, and hence plant growth rate, is high.

Although a long cold winter kills many crop pests, a thick layer of snow can provide good insulation and allow many fragile plants and pests to survive. Thousands of tiny volunteer canola and wheat plants along with several weeds can still be alive when the snow starts to melt in the spring.

31.3 Landscape and Soils

In general, rainfall in the Canadian Prairies decreases towards the west—from Manitoba to the Rockies in Alberta—and increases from the US border to the parkland regions in the north. There are five soil zones, named in accordance with the base colour of the soil—the higher the precipitation, the higher the organic matter and the darker the soil (see Chap. 19 on Canadian Farming Systems). Glacial activity as recent as 10,000 years ago has left small depressions, called potholes, which dot the farm (Fig. 31.3). These create significant obstacles for farming with large

Fig. 31.3 Day family farm during a wet spring—notice the 'potholes'

Fig. 31.4 Day sowing unit in late spring snow storm

modern equipment but, as they can hold water year round, they attract all kinds of wildlife, especially waterfowl. On any given day, all manner of wildlife can be seen on or near the farm; these include moose, elk, deer, wolves, coyotes, badger, fox, bald eagles, hawks, owls, prairie chicken, as well as hundreds of song and shore birds, and thousands of geese and ducks during their seasonal migration.

Modern farming methods do not seem to be having a significant detrimental effect on most wildlife (Fig. 31.5), but farmers have to be aware of this delicate balance and maintain suitable habitats wherever possible. Bird watching is a growing industry in the area.

Fig. 31.5 Rare ground nesting owls in wheat stubble on the Day farm

Despite hunting being an important activity and industry in the region, more wildlife can be seen every year—to the extent that they can become a nuisance. If harvest is delayed, migrating waterfowl will feed on considerable areas of maturing crop, while deer, elk and moose can eat large amounts of livestock feed and black bears will eat oats. These and other large predators are also a danger to livestock and household pets.

Rocks and boulders are another legacy from the glaciers. Although most of the big boulders have been removed in the 100 years of farming, a few more emerge every year with the freeze-thaw action in the soil each winter. This annual freeze-thaw action does, however, reduce compaction problems in the soil.

The Day farm is in the Black soil zone in south-west Manitoba. The black layer of clay loam top soil is only about 10 cm thick, overlying heavier clay that becomes lighter in colour with depth. The young, glacially derived soils have few nutrient deficiencies. Soil tests to a depth of half a metre show moderate requirements of nitrogen (N) and phosphorus (P) are needed for optimal crop production. Sulphur (S) rarely shows as deficient in soil tests but the Days apply 10–15 kg/ha of S as ammonium sulphate when planting canola. Sulphur levels can be extremely variable across the landscape, and the small amount applied with canola will often help to maximise yields.

The calcareous soils provide plants with adequate levels of calcium and magnesium and maintain soil pH levels at 7.5–8.0. Soil organic matter levels are around 3.5–4%, which is only about half of the organic matter levels when the soil was first cultivated more than 100 years ago.

The first farmers were able to take advantage of the high level of natural fertility in the original grass prairie. As that fertility began to decline, the summer-fallow system became popular in the late 1920s and early 1930s. In this system, the field was left ‘fallow’ for 1 year between 1 or 2 years of cropping to accumulate mineralised nitrogen and moisture for the following crop. During the fallow year, the field would be regularly tilled to control weeds; this exposed the soil to the elements, causing a faster release of nutrients from the organic matter but also creating a high erosion risk. Summer-fallow was popular until the 1970s, when commercial fertiliser became more effective for providing mineral nitrogen and herbicides more effective for controlling weeds.

31.4 Early Development and Changes to Farm System, Enterprises and Management

Over 45 years ago, Scott’s grandfather and father made a concerted effort to do whatever they could to protect their thin layer of topsoil. They stopped using summer-fallow and began using the latest herbicides and fertilisers to reduce the need for tillage. They exchanged the mouldboard plow for a shank cultivator, and started to seed with a disker-seeder that could handle higher levels of crop residue.

In the 1960s, their farm was a typical size of ‘one section’ (1 $mile^2$) which is 260 ha (640 acres). The senior Days had a small herd of cattle and some hogs (pigs), and grew barley, wheat, flax and oats,[1] with some land for livestock feed and pasture. Scott’s father then decided that the farm was best suited to being a hog operation. Thus grain production was used primarily for adding value as a livestock feed and with surplus as a cash crop. Profits from grain were low, while hog production was more profitable and provided year-round cash flow. For 35 years, they ran a 50-sow farrow-to-finish operation processing their own feed on the farm; later they fattened hogs with weanlings bought from another farm. Since Scott’s return to the farm, their focus has gradually shifted back towards the grain production side of farming to the point that, between rented and owned land, they now farm 1000 ha. In late 2007, they sold off all their hogs because market prices had dropped significantly and costs of inputs such as feed had skyrocketed. Also Scott’s father wanted to retire from the daily responsibility of livestock. Hog production had meant a lot of extra work for the family but it provided a stable cash flow to a small family farm that would not have survived on grain alone. The manure from the hogs also helped replace much of the nutrients and organic matter lost through previous generations of tillage, particularly on the hills, where erosion was worst.

[1] See Glossary for botanical names.

31.5 Drivers of Change in Recent Years

31.5.1 On the Home Farm

The reliability of the hog operation also allowed the family to take some risks with reduced tillage for grain production even when, at the beginning, the economics were not favourable. As the small size of the farm made it necessary to limit expenditure on new machinery, the opportunity to hire no-till sowing equipment from the local Conservation District to test for the most suitable system was greatly appreciated. The Days wanted to produce a crop by utilising all available moisture as efficiently as possible, to improve the soil and to eliminate erosion. No-till was the best way to accomplish these goals. It took about 4 years from their first trial to the complete adoption of no-till, and they learned much over this period of adjustment. They say that if they had switched all at once, they would probably have become discouraged from continuing.

A major concern with reducing tillage was that it could result in many more weeds, in particular quackgrass (*Agropyron repens*). When tillage was reduced in the early 1990s, more and more of this perennial, rhizomatous weed appeared all over the farm, and it was thought that quackgrass would grow out of control with complete no-till. However, a farmer who was a director of Manitoba–North Dakota No-till Farmers' Association claimed that reducing, rather than eliminating tillage would result in the retention of the problems associated with soil disturbance, while not providing all the benefits of no-till. Such benefits include not transporting the quackgrass rhizomes or incorporating weed seeds into the soil. This was the opposite of what had been expected but it turned out to be true. As the Days moved to full no-till, quackgrass seemed to disappear, and today it is no longer a problem on the farm.

The Days have found that the benefits of no-till are:

1. Soil erosion is reduced to almost nil. The sky no longer turns dark with blowing soil.
2. More snow is trapped and evaporation losses are reduced with no-till.
3. The soil also develops greater internal permeability by not being cultivated. Even with a deluge of rain, the water will soak into the soil.
4. No-till provides greater efficiencies of machine and fuel use.
5. Equipment costs are reduced by not needing cultivators, disks or plows. A no-till field provides a firm and moist seedbed and a good start for the crop.
6. No-till practice helps reduce certain weeds and can have a negative effect on other pests.
7. Many of the *good* soil organisms such as earthworms thrive in no-till environments.
8. No-till fields provide better habitats for ground-nesting birds and other wildlife.

The Days consider the drawbacks of no-till to include:

1. Greater soil water retention under no-till can increase salinity problems in very wet years and in heavy soils. Salinity can be reduced with no-till in most situations but, where salt occurs at depth, a soil profile full of water may cause salt

to rise to the surface. The added moisture associated with no-till can also lead to greater soil water levels that may rise above the soil in low lying areas of the field, once again taking salts to the surface. Inclusion of high water-use crops and forages in the rotation is one method of managing excess water in areas of high salinity risk.
2. In no-till, the entire crop residue is retained on the surface where it can host diseases and other pests for a longer time than with tillage.
3. This thick residue layer can also impede seed drill operation and keep soil temperatures low, but appropriate rotations and equipment can address these concerns. A diversity of crops that produce different levels of residue allows an earlier start for sowing and more optimum soil temperatures. For example, crops can be seeded earliest into the stubble of lower residue crops such as peas and sunflowers, followed by sowing into heavier wheat stubble later in the spring when the soil is warmer and usually drier.

Overall the benefits of no-till far outweigh the limitations and that is why the Days are now joined by at least 90% of the farmers in their area in no-till farming.

The need to make best use of available moisture, control pests and diseases, manage risk and spread sowing and harvest workload has led to a diversity of crops and rotations. Such diversity also plays a major role in the management of weeds, allowing flexibility in herbicide choice to minimise herbicide resistance in weeds. The Days probably grow a wider range of crops than is usual for a farm of their size but they feel that it will pay off in future years with reduced inputs (fertilisers and herbicides) and a more sustainable system. It can also ensure cash flow when traditional crops are still awaiting sale. However, alternative crops may bring greater risk and extra work, and they do not always pay off. In the 10 years leading up to 2007, the following crops have been grown: lentils (*Lens culinaris*), navy beans (*Phaseolus vulgaris*), pinto beans (*P. vulgaris*), confectionary sunflowers (*Helianthus annuus*), yellow peas (*Lathyrus aphaca*), marrowfat peas (*Pisum sativum*), durum wheat (*Triticum durum*), winter wheat, spring wheat, prairie spring wheat (*Triticum aestivum)*, feed and malt barley *(Hordeum vulgare*), rapeseed (*Brassica napus*) and all types of canola (*Brassica* spp.).

After university and when Scott returned from working on farms in Ireland and Australia, he purchased the 'half section' or 130 ha (320 acres) directly north of their farmyard. At the same time, he was also offered the job as a local extension agronomist (Ag Rep) for Manitoba Agriculture, and has remained an extension specialist ever since. These positions and activities complement each other; he learns a great deal from the farmers he works with and can identify with them by often experiencing the same problems. The dual role is only possible through the support of his family.

31.5.2 Drivers of Change in Newly Acquired Land

The new land that Scott purchased in 1989 had always been farmed organically—probably one of the few pieces of commercial grain land in western Canada that had always been farmed in this way. The previous farmer had been one of the pioneers of 'organic farming' in modern times, and had never used commercial fertilisers or pesticides. He used legumes such as clover along with fish parts and other natural products whenever possible to try to replenish nutrients. He used tillage and summer-fallow to control weeds, but he did this as sparingly as possible.

Thus, this land was in poor condition compared to the Day's home farm across the fence. The soil organic matter levels were only two-thirds of that of the home farm, and weeds were rampant. The soil phosphorus level was only 1 kg/ha available P—the lowest level the soil testing laboratory had ever observed.

This land was a good test case for the long-term effects of organic grain farming in the region. After more than 20 years of careful stewardship by the Days, this 'organic' land is still not up to the standard of the adjacent home farm. It still has a lower level of soil organic matter and lower productivity, and it still has troublesome weeds. This illustrates the tremendous effort required to restore the health and productivity of land after many years of nutrient removal, fallowing, intensive tillage and poor weed control.

31.6 The Pathways Chosen to Improve the System and Achieve the Family's Goals of Profitability and Sustainability

The pathway chosen in recent years to achieve the family's goals include a no-till system, continuous cropping with a diverse rotation and an optimal use of precipitation and inputs.

Over the years, the Day's farm machinery has changed from the plow to a shank cultivator and from a disker seeder to a lower disturbance double disk drill. Summer-fallow was discontinued in favour of continuous cropping. In 1993, they purchased a second-hand 5000 Flexi-Coil air drill, planting at 16 cm spacing. All of the nitrogen was applied in a separate pass as anhydrous ammonia through a heavy-duty cultivator, retro-fitted with narrow carbide-tipped knife openers. This basic type of system quickly became one of the most popular sowing systems on the Canadian Prairies at that time. The ammonia would usually be applied in the early spring, immediately before sowing, with the remaining nutrients going down the seed tube. Most farmers are now sowing with one pass, all the nutrients being applied at the same time as sowing, including anhydrous ammonia as the main N source.

In 2001, the Days made the switch to a true one-pass, no-till sowing system using a *SeedHawk* with 23 cm row spacing fitted with an ammonia tank and auto-rate applicator mounted on the drill (see Fig. 31.6). This drill places the seed in one furrow with a very narrow knife opener, on a shelf usually about 1.5 cm into the ground, while a second narrow knife opener places fertiliser 4 cm to the side of the seed row and 4 cm deep into the ground. This unit allows sowing and fertilising the entire 650 ha of crop in only 100 h with a 170 kW (225 hp) tractor, and greatly

Fig. 31.6 The Day's sowing canola into wheat stubble with their SeedHawk toolbar and Morris air tank

reduces fuel use compared to the old tillage practices. It is hard to imagine a more efficient sowing system at this time.

Controlling weeds by low soil disturbance has merit but, in practice, is insufficient; variation of crops and management must also be applied to the farm system. Some weeds, such as quackgrass, have become less of a problem in a low disturbance system but new weeds are becoming dominant. The biggest problem seems to be weeds with tiny seeds—including dandelion (*Taraxacum officinale*), Canada thistle (*Cirsium arvense*), kochia (*Kochia scoparia*), and foxtail barley (*Hordeum jubatum*). Some of these weeds were a problem under tillage, and they are still a problem with no-till. Herbicides have been of great value, especially combined with crop diversification, but the development of herbicide resistance in some weeds has shown that the effectiveness of any herbicide to control particular weeds is never permanent.

The first weed in the world found to be tolerant of treflan (trifluralin), green foxtail (*Setaria viridis*), was identified in 1987 on a neighbour's farm, and this was a result of using treflan to control weeds in most crops in the rotation for many years. Twenty years later, the green foxtail in that field was still totally resistant to the treflan-based herbicides.

The Days had already made the move to reducing tillage at that time, using newer herbicides that did not need to be incorporated into the soil. On the few times that treflan has been used on their farm, it has still given good weed control.

More recently, one of the most important tools for achieving effective no-till on the Day farm has been GM[2] canola. Scott worked with this technology as a research

[2] Genetically modified.

assistant in 1987, and adopted the technology on their farm as soon as it was available in the mid-1990s. GM canola has been a central feature of the Days' farm system management, as it has with most cropping farms in Western Canada.

31.7 Putting It All Together – Managing the Whole

31.7.1 The Timing of Farm Operations

On the Canadian Prairies, farmers have a very short period of time in which to maximise their crop potential. Most of the crop must be planted within the first week of May; even waiting until the second week in May can result in a small reduction in yield. Sowing as late as June can cause a substantial loss of yield, although most crops can still be insured if they are seeded before the middle of June. Later-seeded crops have less yield potential because they are more susceptible to the heat and drought that often occur in the latter part of summer. Later sowing also increases exposure to many pests that often build up in number as the summer progresses. As a result, once sowing starts it is important to try to seed 10% of the cropping area each day, no matter what the size of the farm. With the usual weather delays at sowing (see Fig. 31.4), completion of spring sowing in 2 weeks is about as good as can be expected.

Harvest time is equally busy, although the urgency is less than in spring. Most of the Day's crops will mature in 90–100 days; at these high latitudes long periods of sunlight during summer enhance the growing season. Harvest capacity with the type of machinery used by the Days should be at least 5% of crop area per day—with 7.5% preferable. Larger farms are able to stretch their harvest capacity over a greater area by growing crops that have different harvest periods, for example winter wheat and peas at the start of harvest time and sunflowers at the end. The long distance to major export market terminals means that most Prairie farms must be able to store all their production on the farm, and this is why there are so many grain bins on Prairie farms. Storage capacity must also be considered when estimating overall harvest capacity and efficiency; handling, drying and storage capacity must be large enough to match the rates of harvesting (Fig. 31.7) without delays.

This very tight timeline means there is little room for error or delay when it comes to sowing. If sowing is too deep, or poor-quality seed is used or anything jeopardizes emergence, replanting will usually result in a reduced yield potential. The soil can be quite cold in spring and thus the hoe opener has remained popular even with low-disturbance sowing systems. Waiting until the soil gets to the perfect temperature might make sowing too late, whereas the sowing hoe or tine exposes a narrow ribbon of black soil that warms up a few degrees higher than covered ground—thus increasing emergence and plant growth rate. Disc drills were also tried in the 1990s but they have not always been consistent in sowing effectively in the wide range of conditions found in Manitoba.

Fig. 31.7 The Days harvesting canola with snow in the forecast

31.7.2 Using Herbicide-Tolerant Canola

The Days use herbicide-tolerant canola as a significant management tool that increases both the effectiveness of herbicides and the capacity to avoid herbicide resistance in weeds. They have used three separate systems of herbicide plus tolerant crop, and have determined how each can serve their purposes for weed management. The Day's have found that the excellent weed control with GM canola makes the elimination of tillage in their production system much easier and more efficient.

They started growing herbicide-tolerant canola with the Clearfield–Group 2[3] resistant system (mutagenic system) in the mid 1990s, then moved to the genetically modified (transgenic) Roundup Ready (RR) system and on to the Liberty Link (LL) system (also a transgenic system) when superior yielding LL hybrid canolas were developed.

Clearfield canola was developed through mutagenics and is resistant to many 'imi' herbicides that are also referred to as group '2' or group 'B' herbicides. This group of herbicides is often persistent in the soil which can help control weeds such as bedstraw/cleavers (*Galium aparine*) that can germinate all year. As a result, this system has merit where these types of weeds are a concern. However, these group '2's do not kill all weeds, and the Clearfield system can be less effective at weed control than the Liberty or Roundup Ready systems.

More recently, the Group 2 herbicides, known as the 'IMIs' (imidazolinone), have developed resistance issues. To maintain as much variability in their system as

[3] Herbicides may be grouped according to 'site of action' (common in North America and numbered) or 'mode of action' (common in Australia using letters). See Glossary for more information.

possible, the Days would like to use other 'imi' herbicides only on crops such as wheat and peas, so Clearfield Canolas are no longer considered by them. The unique mode of action of Liberty and the unique use of glyphosate 'in crop' provide more diversity to their system than the 'Clearfield' system. Growing Clearfield wheat on the same farm as Clearfield canola needs care; volunteer Clearfield wheat plants growing in Clearfield canola would require additional herbicides, and vice versa. However, Clearfield is the least expensive system to use, and can still be the best choice in certain situations.

Triazine (Atrazine)-tolerant (TT) canolas were developed in Canada but became obsolete when the GM canolas were introduced in the mid 1990s. The TT canolas always had a yield penalty compared to the other types of canola and many farmers did not want to use atrazine on their farms; TT canolas have not been grown or available for over a decade in Canada.

The Prairie farmer's adoption of GM technology has been one of the fastest ever acceptances of any new farming technology; the two transgenic GM systems of Roundup-resistant and Liberty-resistant canolas now account for over 92% of the canola area in western Canada. RR canola's resistance to glyphosate means that applying glyphosate amounts several times greater than recommended will do little harm to the plants. Most farms in western Canada already use a considerable amount of glyphosate as it is the key to environmentally friendly, no-till farming systems. The Days have found that the opportunity to use glyphosate on a growing crop adds versatility to its use. They consider that they are not necessarily using more glyphosate because they are now growing RR canola; rather that they are applying it at a different time in the growing season. This variation in timing could delay resistance to glyphosate in others weeds. The 'in crop' RR system encourages crop competition to play a role in weed control, in contrast to the use of glyphosate at pre-sowing or post-harvest. The Days realise that having another type of RR crop, such as RR soybean, on one farm would force farmers to develop specific strategies to control volunteer plants. After 12 years of RR Canola use in Western Canada, no weed has yet been identified as resistant to glyphosate.

The Liberty Link package with canola adds further flexibility to the farm system in that the mode of action in Liberty-resistant canola is different from that of any other farm herbicide, and faster acting. Liberty Link canola varieties now cover almost the same area as the RR system across Western Canada, and LL varieties account for 60% of all canola sown in Manitoba. The Days have stayed with hybrid Liberty Link canola varieties because their yield potential was superior to other canolas and the disease package was usually good as well. They also like using Liberty's completely unique mode of action to add greater variability into their cropping and weed control program (Fig. 31.8).

Today, all systems offer hybrids and there is little yield difference between the three systems. The Days would return to Roundup Ready canola if particular weed problems suggested the need for glyphosate. Glyphosate, compared to Liberty, is more effective during adverse conditions and will provide a more complete kill of certain weeds—especially perennial weeds. Under these conditions, the Days would consider RR canola again. GM canola is a 'clean up' crop on the Days farm.

Fig. 31.8 Liberty Link canola emerging through barley stubble on the Day Farm

By killing all weeds in canola, they can reduce herbicide use in the subsequent crops. Without having to wait for the exact conditions needed by the old conventional canola herbicides, GM canola can be sown earlier to achieve the optimal sowing period.

31.7.3 Management Goals

The Days consider that if they had tried to continue to farm with the conventional tillage of the 1970s, they would no longer be farming. Back then, two cultivations and a harrowing following harvest were common, plus two more cultivations in spring and then another harrowing before the field was seeded—usually with a double disk drill. Farmers at that time were often judged by how well they ‘tilled’ the land. Although a good crop was often established, any surface moisture usually evaporated by the time the crop was sown, and the soil was left prone to erosion over much of the year. At today’s fuel prices, those extra four or five workings across a field would cost an extra $100–125/ha, or $80,000 on 647 ha (1,600 acres) of crop land. The cost of extra glyphosate and other products needed for no-till is less than a quarter of this, while no-till also conserves soil structure, organic matter and moisture.

The Days strive to make at least $325/ha above variable costs each year—a goal they do not always achieve. However, it is an important goal to keep ahead of depreciation, land costs, and other fixed costs as well as providing a living for the families. If they had remained a straight wheat and barley farm, with the occasional flax crop, this goal would rarely have been attainable. Now with dry beans, canola, winter wheat and a whole range of other crops in addition to wheat and barley, all grown with no tillage, achieving this goal is possible.

Despite a recent upswing in crop prices, the Days are still cautious as there has also been a rapid rise in input costs; therefore debt on a small farm must always be kept low. The hogs earlier, and the off-farm income now, have enabled the Days to do this, providing the freedom to make optimal management and marketing decisions and to ensure that they are working to provide for the family and not to repay debt. Minimising and carefully controlling debt is important, particularly on a smaller farm, by managing costs while maintaining (or improving) production or finding other sources of income.

31.8 Current Situation and Looking to the Future

In any farming system, it is vital to keep up with new information, technologies and methods. One regular source of innovation is the release of new crop cultivars better suited to the area. The Days' aim is to keep the farming system as dynamic as possible, and open to better cultivars, while using proven ones only while they are shown to be beneficial.

Other crops that can be popular in the district include flax and oats but these have not been used in their rotation recently. Hemp is starting to be grown with good success and may be a crop considered in the future. Once a workable, dynamic rotation is achieved, making significant changes each year because of potential market opportunities rarely pays in the long term.

In the last few years, the Days have settled on a few key crops to provide sufficient diversity without losing management focus. They grow winter wheat; a good crop for reducing inputs and adding diversity to the cropping system. However, it does not always survive −45°C winters, is susceptible to disease, and it can be difficult sowing winter wheat and harvesting the other crops at the same time. Its values in the rotation include the different sowing and harvest dates, greater water use efficiency (higher yield potential) and strong competitiveness with weeds.

The crop that makes the Day farm unique in their region is Pinto bean (Dry Bean). It is a warmer-season broadleaf legume, which is rare in their crop rotations. Contrary to traditional practice, the Days seed direct into wheat stubble, and then swath the beans before harvest. The following crop of wheat on bean stubble is always one of their best. Pinto beans need heat and rain at the right time and harvest is slow and difficult; however, they can be profitable and they fit into the Days' system of no-till, lower inputs, and high diversity.

The Days also grow many types of wheat, 2- and 6-row types of barley, while one quarter to one third of all their land each year is under GM canola. Although peas were replaced by Pinto beans when the pea price fell, they might consider growing them again. In addition to fixing their own nitrogen, peas are a good rotation crop because they add variability to operation timing, weed control and disease control. Steadily rising costs of fertiliser nitrogen make legumes more attractive. Flax could also be considered in the short term. Crop selection depends on forecasts of markets and weather conditions.

Treelane Farms Ltd. is still a small family farm with many goals to consider but it also has a strong business focus; it is now a corporation. The business structure is important for income management, tax management and succession planning, but it also helps maintain a more business-like approach. Management tools such as business plans, projections, marketing strategies, purchases and inventory all become more focused under a corporation.

31.9 Conclusions

All of the changes to the Day farm came with a great deal of discussion and some trepidation, but the goals remained the same. While flexible with their farm plans, the Days have a core goal of growing each crop without tillage. This protection of the soil resource is paramount, and with that comes better water conservation and yield potential. Thankfully, profitability is now best with no-till—but even if that was not the case they indicate that they would probably still be using this system. If it is claimed that a crop can only be grown with tillage, the Days will search for a way not to do so, as with Pinto beans, or they simply will not grow it.

Another goal is to keep their system sustainable, using maximum diversity with different crops, different varieties, different pesticides and different markets. Livestock were once part of the farm diversity, as is currently off-farm employment by family members. As the Days are focused on maximising input utilisation efficiency, they apply fertiliser precisely and only where and when it is needed, and their machinery is matched to the capabilities needed on the Prairies.

Profitability is their most important current goal—although often the most elusive—but a strong, diverse system that has elements working positively together will be profitable. Minimising costs while maintaining production is the most important balancing act in making a farm profitable, but with no-till, the latest affordable technology, and a wide diversity of complimentary crops, this balancing act is easier to perform. Profitability also requires finding ways to add value to production, and this can also be an elusive quest. Livestock were one way to do this, local processing and consumption has been another. The Days will continue to search for ways to add value to their production in the future.

In summary, the Days feel the key to successful ‘Rainfed Farming’ in their part of the world is a no-till sowing program with a diverse cropping system and a judicious use of inputs. This can involve many different factors such as the use of GM canola, maximising resources such as soil moisture and minimising inputs where possible. Maintaining this system means their farm will continue to evolve and explore new opportunities, but the main focus of maintaining the soil resource for current and future generations will always prevail.

Chapter 32
Improving Traditional Crop-Pasture Farming Systems with Lucerne South East Australia

Kieran Ransom and Lindsay Trapnell

Abstract This chapter is based a study of 13 farmers in south east Australia who have improved their farming system by introducing lucerne pastures while conducting intensive, and often no-till, cropping. Growing lucerne did not reduce cropping intensity, and there was no consistent effect on crop profitability. Replacing annual pastures with perennial lucerne improved overall profitability on all the farms. This was associated with large increases in stocking rate and a greater emphasis on prime meat production rather than on store stock or wool production. The claimed advantages of lucerne were: (i) providing a profitable pasture phase; (ii) spreading risk with income from two major enterprises (grain and livestock); (iii) using summer rainfall; (iv) reducing the rates of nitrogen fertiliser applied to following crops and (v) improved weed control in the lucerne phase carrying over into the crop phase. The key challenge to growing lucerne in rotation with grain crops is whether overall returns from this combination can match those from continuous cropping rotations, particularly given the greatly improved continuous cropping technology and equipment now available.

Keywords Lucerne • Crops • Profitability • Farming system • Livestock • Sheep

32.1 Introduction

In south-east Australia, mixed farming systems of crops and livestock are constantly evolving to meet new challenges and maintain economic viability. The systems are complex and variable in structure. For example, the percentage of a

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_32,

farm under crop varies between 30% and 90% (see also Chap. 26); some farms crop only cereals because of their ease of growing and reliability; other farms have substantial areas of oilseeds, usually canola, and grain legumes including peas, faba beans and lupins.[1] Sheep are the main livestock, with some cattle. On some farms, sheep are a key enterprise contributing to farm profit whereas, on others, they have a minor role of grazing stubble and helping control weeds.

This chapter is based on a study of 13 farms in south-east Australia where the farmers have successfully managed livestock and lucerne pastures in rotation with intensive and often no-till cropping (Ransom et al. 2006). Lucerne is used in rotation with cropping because of its ability to deplete deep subsoil moisture and thus reduce groundwater recharge. However, the adoption of perennial species such as lucerne is often limited by the perception that they are neither practical nor profitable.

32.1.1 Why Make the Change?

The case study farmers effectively replaced their annual legume-based (*Trifolium* and *Medicago* spp.) pastures with lucerne as part of broader changes in their farms management. They had been growing lucerne for an average of 15 years (10–40 years). Key advantages of lucerne were seen as: (i) providing a profitable pasture phase; (ii) spreading risk with income from two major enterprises (grain and livestock); (iii) using summer rainfall; (iv) reducing the rates of nitrogen fertiliser applied to crops; (v) improving weed control in the lucerne phase carrying over into the crop phase; (vi) providing a means to intensify production to offset the declining terms of trade; and (vii) providing an alternative system on soils unsuitable for continuous cropping. None of the farmers mentioned prevention of salinity as a key reason for introducing lucerne. This is in contrast to Western Australia, where farmers' main reason for growing lucerne is to reduce dryland salinity (Wilkinson 2007, personal communication).

Less tangible benefits of lucerne included reduced workloads, reduced stress, and the 'oasis factor'—that feeling of security and comfort that comes from looking over islands of green in a wide brown land in the depths of summer.

Changing to lucerne, however, has not been without its challenges. The farmers had to combat poor establishment rates, decreased yields of crops after lucerne in dry years, wind erosion in pure stands, poor utilisation of the excess spring feed, sink holes in fields, and 'red gut' (an acute haemorrhagic enteritis) in sheep.

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[1] See Glossary for botanical names.

32.2 Farm Background

The 13 farmers operate mixed-enterprise rainfed farms that range in size from 440 to 3,000 ha and are located across the northern Victorian cropping zone, from the Mallee area in the north-west, through the North Central district, to the North East (Fig. 32.1 and Table 32.1).

These family farms operate across a wide range of climatic and geographic environments, with average annual rainfalls varying from 300 mm in the northwest to 580 mm in the northeast, with corresponding growing season rainfalls (April to October) of 200–380 mm. About 34% of the annual rain falls in the warmer months from November to March. This is insufficient to grow annual summer crops, but is useful for lucerne growth. Soils range from sand hills in the Mallee, to friable red loams in the intermediate rainfall zones, to heavier clay-loams prone to water-logging. Some of these latter soils consist of only a few centimetres of topsoil overlying rocky sediments.

32.3 Fitting Lucerne into the Rotation

32.3.1 The Place of Lucerne in the Rotation

For 10 of the 13 farmers, lucerne will continue to be an important part of their rotations because of the complementary benefits of cropping and lucerne. The three farmers with reservations about the future of lucerne on their farms were more

Fig. 32.1 Location of the study area

Table 32.1 The location and key features of the farms

Farm	Average rainfall (mm)	Average GS rain[a] (mm)	Farm size (ha)	% Farm in lucerne	Soil description
Bridgewater	434	294	660	39	Red loams over clays with some volcanic soils on predominantly gently undulating country.
Charlton	377	259	1,100	21	Predominantly red loams over clays with smaller areas of heavy grey clays.
Corowa	523	343	780	38	Predominantly red loams over clays with some heavy clays and low sandy rises.
Dookie	554	375	670	19	Red volcanic soils on hilltops to clay loams and sandy loams on the flat.
Maryborough	493	351	440	20	Well-drained alluvial flats, with some heavy grey clays
Nyah West	324	212	1,700	8	Sand on dunes to sandy loams, on flats.
Rainbow	366	245	1,350	22	Mostly undulating sandy loams with some grey clays and red loams over clays.
Rutherglen	583	383	1,800	15	Well-drained clay loams on the flats, with stony clay loams on sedimentary hills.
Serpentine	430	286	1,000	40	Predominantly red loams over clays, with smaller areas of heavy grey clays.
Tungamah	515	342	1,900	11	Clay loams on undulating country, with gravelly hilltops and heavy cracking clays on the flats.
Underbool	300	200	2,995	27	Predominantly sandy loam and limestone, with about 20% sand hills.
Wedderburn	475	330	800	50	Clay loam topsoil overlying clay to fractured rock subsoils, with flat to undulating topography.
Wood Wood	324	212	1,600	20	Red and white sands on dunes to sandy loams on flats.

[a]GSRain – growing season rainfall (April to October)

focused on cropping than on livestock; they also had concerns about unreliable lucerne establishment although they indicated that, if they could reliably establish lucerne, it could continue as a short phase in their rotations.

32.3.2 *Effect of Lucerne on Cropping Intensity*

Growing lucerne did not mean less cropping. When the ‘crop–annual pasture’ and ‘crop–lucerne’ rotations on each farm were compared, the average cropping intensity

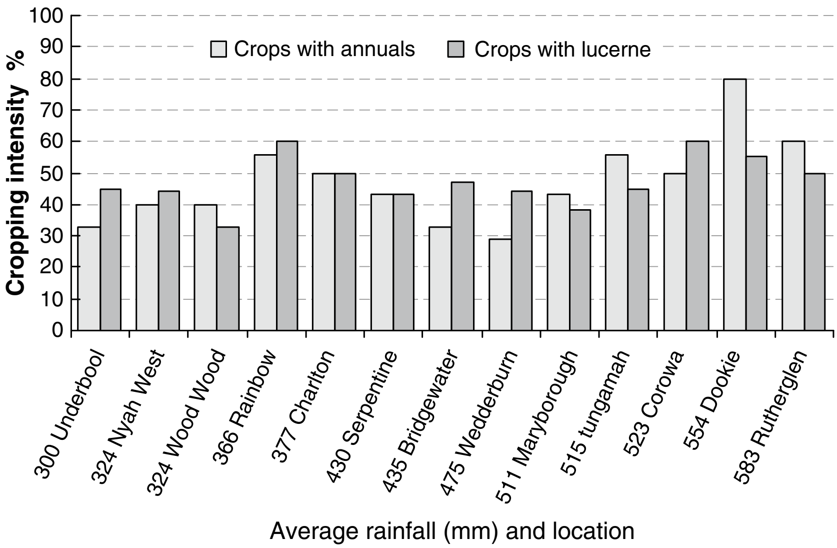

Fig. 32.2 The cropping intensity of 'crops after annual pastures' and 'crops after lucerne pasture' rotations on each farm

was 47% for both. However, each farmer had a different strategy: six had increased their cropping intensity, two had not changed and five had decreased it (Fig. 32.2).

The inclusion of lucerne often resulted in longer pasture phases, sometimes up to 5 years longer, but this did not necessarily mean reduced crop intensities, as the cropping phases also tended to be longer. For example, before lucerne, the rotation on the Bridgewater farm was typically 1 year of wheat followed by 2 years of annual pasture—33% cropping intensity; with lucerne, the pasture phase became 8 years long, and was followed by 7 years of crop—a 47% cropping intensity. Several farmers expressed a preference for short, 2-year phases of lucerne, but found it impractical because of unreliable establishment.

32.3.3 Crop Yields and Grain Protein Content After Lucerne

The farmers listed many advantages of lucerne for subsequent crops; these include: (i) improved soil nitrogen level, (ii) a slower release of nitrogen from the decaying lucerne roots, (iii) higher grain protein content, (iv) increased grain yield, (v) reduced winter waterlogging and (vi) easier grass and broadleaf weed control.

The main drawback was decreased grain yields of the first crop after lucerne on some farms and in some seasons. Grain yields of the first crop after lucerne could be up to 20% lower than those after annual pasture phases, and lower yields could carry over into the second crop. Several farmers indicated these yield reductions could be due to the recent run of dry seasons, and expected crop yields would be minimally affected in normal years, or even increased in wetter years because of less winter waterlogging. Most farmers were confident that lucerne had boosted the nitrogen levels of their soils, but could not be certain given the variability of fields and seasons. For example, one farmer reported consistently higher grain protein levels, but considered that the full nitrogen benefits do not fully accrue until the second crop. Other farmers thought that the nitrogen benefits of lucerne lasted longer than those from annual legumes.

32.3.4 Subsoil Moisture with Lucerne

Lucerne can use up to 150 mm more water from the top 180 cm of soil than annual pastures (Ridley et al. 2001). Dry subsoils after lucerne have reduced the incidence and severity of winter waterlogging on those farms with heavier soils. This has enabled lucerne to survive on what would previously have been waterlogged soils. While drier subsoils are a benefit to crops in wetter areas and wetter years, they have resulted in reduced grain yields in most drier areas because less subsoil water is available for the following crop, and there is a slower breakdown and release of nitrogen from lucerne residues. One farmer on heavy cracking soils attributed grain yield reductions following lucerne in the last few dry years to less carryover of soil moisture for the following crop, but remarked that drier subsoils might be a bonus in very wet years. Farmers on lighter or sandy soils have noticed yield reductions of 10–25% below expectations in their first crops after lucerne.

32.3.5 Higher-Value Crops

On some acidic soils prone to water-logging, lime applied prior to lucerne, and subsoil drying by lucerne, have enabled some farmers to grow higher-value crops with better gross margins, for example, more wheat and less triticale. On a red loamy soil, higher soil nitrogen following lucerne allowed more wheat to be grown in place of field peas, which had low and variable yields.

32.3.6 Better Weed Control Carries over into Crops

Farmers on sandy soils found a lucerne phase provided more options for weed control. For example, the control of wild radish (*Raphanus raphanistrum*) in the pasture phase was cheaper and more efficient; less herbicide was needed because the increased stocking rates resulted in preferential grazing of wild radish. One farmer estimated that his pasture chemical costs were reduced to one eighth of those incurred on annual pastures because of the more even grazing of weeds, such as brome grass, by cattle at higher stocking rates. All Mallee farmers reported better control of summer weeds, such as skeleton weed (*Chondrilla juncea*), caltrop (*Tribulus terrestris*), heliotrope (*Heliotropium europaeum*) and wild melons (C*itrullus lanatus*), in grazed lucerne pastures. Further, cutting the lucerne for hay reduced seed set of many weed species.

32.3.7 Intercropping

Intercropping of lucerne is a common practice on a number of farms in north central Victoria. The Wedderburn farmer on clay loams regularly direct sows barley and wheat crops into his second-year lucerne stands using knife points to minimise disturbance of lucerne plants. The lucerne can be established under a lupin crop; then intercropping with a cereal takes place in the second year to take advantage of the grass-free break created in the first year. Early-maturing grain crops such as barley are planted late to maximise late autumn grazing of the lucerne and are harvested first to reduce the risk of contaminating the grain with lucerne seed pods (Fig. 32.3).

Thus intercropping is a way of smoothing the transition between the pasture and crop phases, and obtaining a better return from second-year lucerne. This flexible, sustainable system maximises the use of rainfall and is responsive to changing prices for lambs and grain. The Maryborough farmer on well-drained alluvial flats sometimes direct sows oats into a mature lucerne stand to increase winter pasture production; this crop may then be cut for hay. Intercropping has disadvantages; for example, harvested grain may become contaminated with green lucerne seed pods, incurring the extra cost and inconvenience of having it cleaned.

32.3.8 Utilising Summer Rainfall

Many farmers mentioned how the rainfall from summer storms was profitably used by lucerne. For example, the Charlton farmer said that the lost opportunity presented

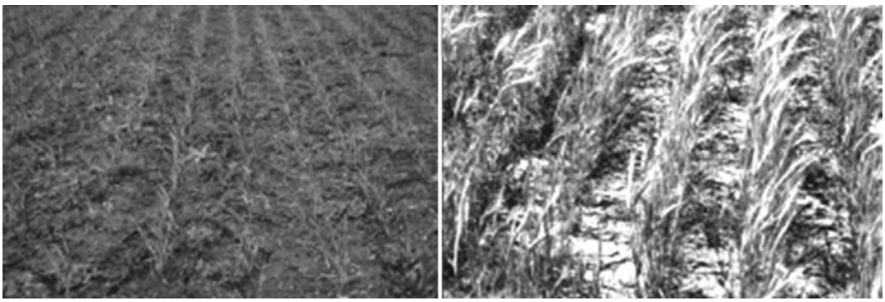

Fig. 32.3 Intercropping: The photo on the *left* shows drill rows of wheat in second year lucerne, while the photo on the *right* shows a barley intercrop prior to harvest in the 2002 drought

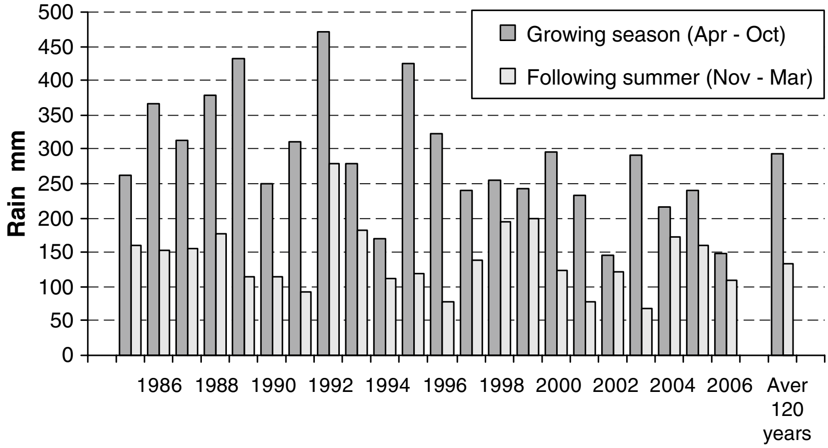

Fig. 32.4 The growing season (April to October) and following summer (November to March) rainfall totals at Charlton for the last 22 years

by summer rainfall (Fig. 32.4), plus problems of controlling summer weeds such as heliotrope, was what prompted him to try lucerne. He commented: "*I looked at the summer rainfall over the last 20 years and found that it was about a third of the annual rainfall. I wanted something that would grow in summer and utilise the available water. I now regard summer rainfall as a resource rather than a hindrance.*"

The Rainbow farmer recalls buying store lambs for finishing after summer storms in the 2002 drought. "*Lucerne has proved to be the drought-proof component of the farm. In the 2002–03 drought, the lucerne fields had the only grazing available. Most district farmers sold out their sheep or reduced their numbers. For example, rain in February 2003 enabled 800 lambs to be finished on lucerne while the rest of the district was in drought.*"

The Serpentine farmers reflected on managing the 2002–03 drought (Fig. 32.5): "*Through the drought, I was rapt in the way the place looked, compared to the '82 drought. Everywhere you went on the place we had green fields coming on. And that's what it does; you drive down the road, you've got a green field one side and the one next door is blowing; surely you've got to feel much better about your own place, and we had people comment about how it was.*"

32.3.9 Personal Impacts on Life and Work

Lucerne increased the personal satisfaction of some farmers. Many mentioned how much confidence it gave them to face the fluctuating prices and seasons, and it provided visual relief in summer.

Fig. 32.5 A paddock on the Serpentine farm in March 2003. There was still adequate pasture trash on the soil surface to minimise erosion, even after the drought year of 2002

There were both positive and negative comments about the impact of lucerne on workloads. The Charlton farmer was focused on making sheep work easier. Lucerne, coupled with a conservative stocking rate, meant less supplementary feeding and a simple management system of selling prime lambs before summer. Others recognised that more sheep meant more work. The Rainbow farmer summed it up: "*The green view of lucerne fields in summer and autumn gives a good feeling. However, there is more work as I am running more sheep. The more stock you run, the more you have to look after them. Instead of one day's shearing, it is now three days. Small things like that.*"

The aim of the Wedderburn farmer was to boost sheep profitability. While extra sheep meant extra work, he has planned his work program so that the main jobs on the farm are spread across the year, with a break after harvest. "*With regards to labour, the main jobs do not greatly interfere with each other. You need to be able do both parts of farming—cropping and sheep.*"

A more intensive cropping program with more years of crop in the rotation, and the trend toward farm specialisation, has made the Corowa farmer re-assess the role of sheep. He considers a farm needs a minimum flock size to make a sheep enterprise worthwhile because issues such as the maintenance of sheds, yards and equipment and getting shearers become more onerous with small flocks. For these reasons, he is considering abandoning sheep altogether. The Underbool farmer prefers cattle to sheep partly because of the lower labour requirement. Cattle are easier to manage, do not suffer from grass seeds or fly strike, and do not require shearing or crutching. He runs a base herd that requires little supplementary feeding, with extra cattle purchased or agisted in times of feed surpluses.

32.4 Establishing and Managing Lucerne

32.4.1 Establishing Lucerne

The two key issues for lucerne establishment are the chances of success and the costs. Sowing techniques used have included: (i) autumn sowing, usually under a cereal cover crop, but also under grain legumes; (ii) spring sowing, usually sown alone; and (iii) summer sowing immediately after heavy storms.

Establishment is likely to be more successful in late winter or early spring because air and soil temperatures are increasing and seedlings grow faster than those sown in late autumn. Slow-growing, autumn-sown lucerne seedlings are less likely to survive wet soils, insects and weed competition through winter; however, they can be more cost effective. Autumn establishment can be low-cost as the cover crop provides a good gross margin in the establishment year. The differences in cost between under-sowing in autumn and sowing alone in spring, where lime has been applied and no forage crops are sown, can be up to several hundred dollars per hectare.

The success of sowing lucerne in autumn with a cereal crop was mixed, but was consistently good on two farms when sown under lupins. Spring sowing was normally very successful in the higher rainfall areas.

32.4.2 Managing Lucerne

There was no consistent management approach. Recent research has focused on the effects of nitrogen and soil water on the following crops but the farmers also raised practical management issues with lucerne. These included: whether to grow pure lucerne or lucerne–annual pasture mix; the length of the lucerne phase; grazing practices; optimal densities of lucerne plants; lucerne removal techniques; and appropriate types and rates of chemicals, fertilisers and lime.

32.4.2.1 Pure Lucerne or Lucerne–Annual Pasture Mix?

There was no consistent approach to this question. The annual cool season grasses and legumes establishing in lucerne stands were actively encouraged on one farm (by managing pasture species composition and controlling weeds), allowing them to re-establish by default on others, or controlling them with selective herbicides, or by hay cutting on yet other farms. The decision about what role annual species should play in lucerne stands depends on many other management issues and preferences. These include: (1) the annuals out-competing the lucerne in some environments; (2) the need for winter feed from cool season annuals; (3) the risk of summer wind erosion; (4) pure legumes fixing more nitrogen than mixtures;

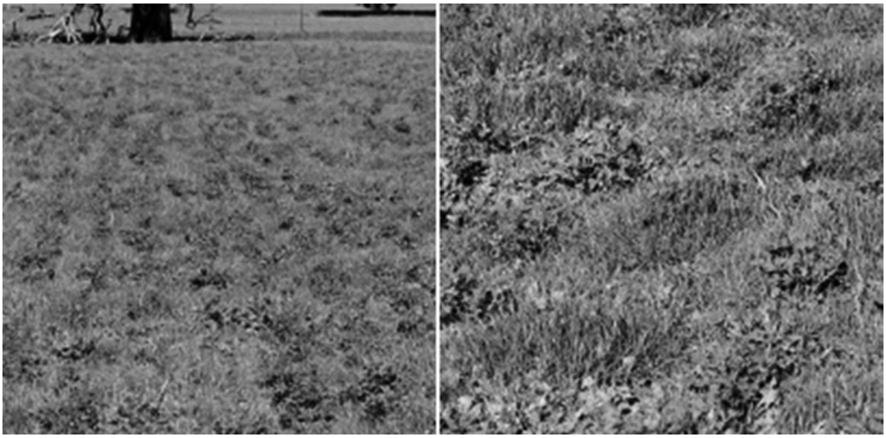

Fig. 32.6 Mixed pasture of lucerne, sub-clover and ryegrass on the Wedderburn farm. The photo on the *left* shows one such pasture in winter 2005, with a close-up of the same pasture on the *right*

(5) making good-quality lucerne hay; and (6) the risk of animal health problems developing on pure legumes. These issues are covered in detail elsewhere (Ransom et al. 2006) (Fig. 32.6).

32.4.2.2 Length of the Lucerne Phase

The word ‘Flexible’ best describes the farmers’ approach to the question of the most appropriate length of the lucerne phase. On most farms, it was 3–5 years, although on one farm the lucerne phase had lasted for up to 8 years.

32.4.2.3 Lucerne Chemical, Fertiliser and Lime Inputs

Once the lucerne had been established, inputs such as fertilisers and pasture-cleaning herbicides varied from none through to increased rates of both for high-quality hay production on the Maryborough farm (Fig. 32.7). Some farmers applied few or negligible maintenance inputs to their lucerne stands, primarily because they saw lucerne as only one component of a mixed pasture that included grasses and broadleaf weeds. On the Charlton farm, no inputs were applied over the 3–5 year lucerne phases while, on other farms, herbicides were applied only in the last 1–2 years to remove grasses and weeds in preparation for cropping. One farmer estimated that his lucerne pastures required only about one eighth the amounts of herbicide that his medic pastures required to keep them in a suitable condition for cropping.

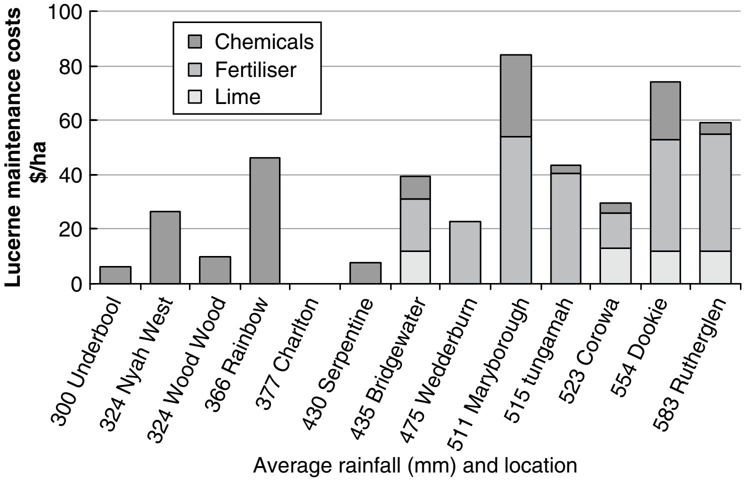

Fig. 32.7 Lucerne pasture maintenance costs ($/ha) for the 13 farms. Costs included: (1) chemicals, (2) fertilisers and (3) lime (cost annualised over 10 years)

32.5 Lucerne and Livestock

32.5.1 Attitudes to Livestock

There were markedly different approaches and attitudes to the livestock enterprises. Some saw livestock as a key profit driver that also minimised risk, while others viewed livestock as an aid to the cropping program through improved weed control and better stubble management. Nevertheless, even those farmers who had reservations about the role of sheep reported a range of benefits from the lucerne, including higher stocking rates, reduced supplementary feeding, easier stock management and better weed control.

32.5.2 Stocking Rate

Across all farms, lucerne increased both the numbers of stock carried and the amounts of hay and/or silage conserved. Figure 32.8 shows farmers' estimates of the increases in stocking rates (DSE[2]/ha) following the change from annual to lucerne-based pastures.

[2] Dry Shep Equivalent – see Glossary for explanation.

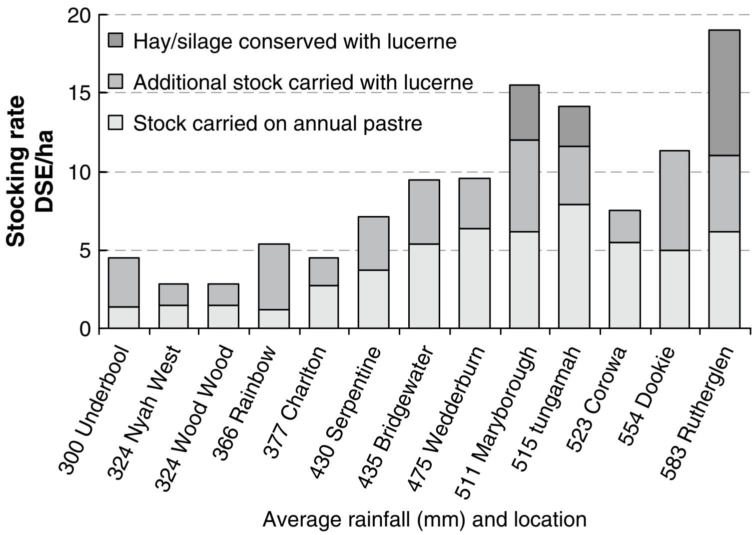

Fig. 32.8 Farmers' estimates of the increases in stocking rates (DSE/ha) following the change from annual to lucerne-based pastures

Where hay and/or silage were regularly cut, the DSE of the conserved fodder was calculated and included. For example, the stocking rate on the Rutherglen farm increased from 6.1 DSE/ha on annual pastures to 11 DSE/ha on lucerne; in addition, lucerne hay cut was equivalent to a further 8 DSE/ha. The average increase in effective stocking rate was 113%. Some farmers, especially those who regarded sheep as a tool to facilitate cropping, stocked conservatively because they felt that this minimised the financial impacts of poor seasons and associated risks, such as soil erosion in summer.

32.6 Lifting Profitability with Lucerne

32.6.1 Whole-Farm Profitability

Benefit cost analyses indicated that lucerne increased the profitability of all 13 case-study farms. The increase in the net present value of the 'before lucerne' and 'after-lucerne' rotations averaged 35% (9–63%). The key feature in increased profitability was the development of highly-profitable livestock enterprises on lucerne pastures, with less pronounced benefits to the profitability of the following crop phases. Three farmers said they would not be farming today if it were not for lucerne.

32.6.1.1 Spreading Income Risk

Several farmers indicated that crop incomes could be highly variable because of variable seasons, droughts, water-logging, flooding, frosts, pre-harvest rain damage and variable grain prices. These feelings were best summed up by the Wedderburn farmer: "*By spreading your income streams around, you do eliminate some risks. We now have three main enterprises—grain, meat and wool. You are not relying completely on cropping. The returns from lambs and wool help to stabilise income.*"

32.6.2 Cropping Profitability

32.6.2.1 Crop Responses

Growing lucerne did not mean a reduction in cropping; the average percentage of the farm cropped before and after lucerne was unchanged. There was no consistent effect of lucerne on crop gross margins (Fig. 32.9). Some farmers increased their crop gross margins, others showed little change, while yet others showed a decrease. The key features of the profitable cropping phases included good crop selection (easier after lucerne on some farms due to improved nitrogen fertility), the correction of soil acidity problems and the reduced chance of water-logging due to wet subsoils.

The benefits of improved wheat protein levels and reduced rates of nitrogen fertiliser helped offset the slightly lower yields in the first one or two crops after lucerne, although one farmer reported yield increases after lucerne due to improved soil fertility and less waterlogging.

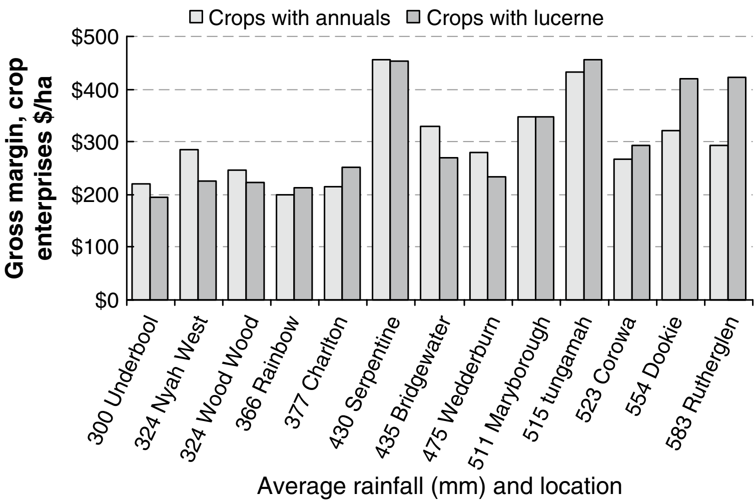

Fig. 32.9 The gross margins of the crop enterprises grown in rotation with 'annual' and 'lucerne' pastures on each farm (2000–2007 prices)

32.6.2.2 Crop Selection and Intensity

Wheat and barley had consistently higher gross margins than other crops such as lupins, triticale and sometimes canola. Thus, growing more wheat and barley crops in place of less-profitable crops such as peas, oats and triticale, increased the average gross margin of the cropping phase.

At Bridgewater, wheat was the only crop grown in the rotation with annual pastures, whereas crops with lower gross margins (canola and lupins) were grown in the lucerne rotation. This change reduced the average crop gross margin from $329 to $269/ha (Fig. 32.9), even though the cropping intensity had increased from 33% (one crop, 2 years annual pasture) to 47% with lucerne (8 years lucerne, followed by seven crops). This reduction was more than compensated by the increased livestock income.

32.6.3 Sheep and Cattle Profitability

The change to lucerne pastures boosted the gross margins of the animal enterprises on all farms (Fig. 32.10). This was attributed to increased stocking rates and the production of higher-value produce, such as prime lambs instead of medium wool or store lambs. The need for supplementary feeding was reduced and stock were healthier and more productive. Some farms had the bonus of lucerne hay for sale.

Sources of higher profitably included: (1) buying and finishing store lambs, for example on lucerne regrowth after summer storms; (2) boosting the profitability of

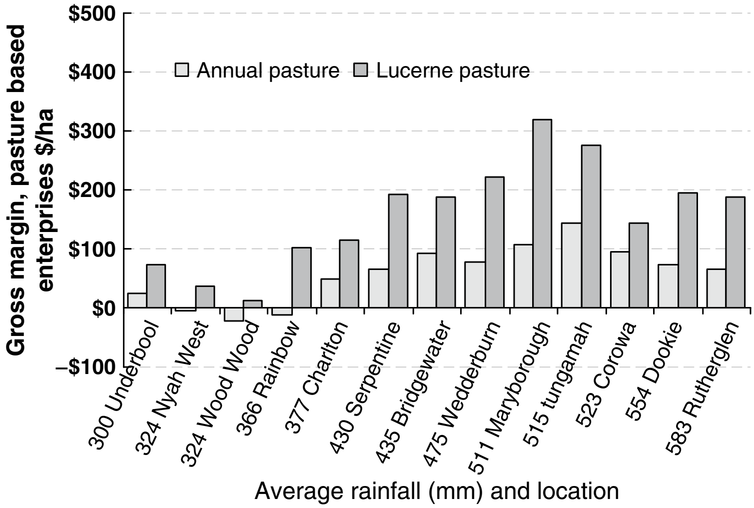

Fig. 32.10 The gross margins of pasture-based enterprises, (livestock, hay and silage). Enterprises based on 'annual' and 'lucerne' pastures on each farm (2000–2007 prices)

first-cross ewe production, for example, by selling lambs as prime in January and February rather than selling wethers as stores when the pastures dried off in late spring, and by selling the ewe portion as heavy-weight crossbred ewe lambs at 8 months of age; (3) selling Merino wethers as prime lambs (finished on dual-purpose cereals and grain in winter).

32.7 Challenges

The farmers identified a number of challenges associated with the introduction of lucerne. Three farmers thought that lucerne–crop rotations were likely to be less profitable than continuous cropping on good soils because of the relatively lower gross margins of livestock enterprises. Also many farmers prefer working with crops and machinery rather than with livestock.

32.7.1 The Challenge from Intensive Cropping

The key challenge to growing lucerne in rotation with grain crops is whether overall returns can match those from continuous cropping rotations, particularly given the greatly improved continuous cropping technology and equipment now available. Three of the farmers are currently intensifying their cropping programs at the expense of lucerne although all have left open the option of returning to lucerne should circumstances change. New information about managing crop diseases, crop sequences and soil fertility under continuous cropping conditions, as well as better stubble-handling machinery, contribute to make continuous cropping more attractive.

32.7.2 Wind Erosion in Summer

Wind erosion from pure lucerne stands which have bare soil between lucerne plants in summer is a concern for many farmers. Several farmers prefer mixed lucerne–grass pastures as the dead grass trash helps protect the soil (Fig. 32.11).

32.7.3 Managing Establishment Failure

Farmers who have not sown lucerne before are often deterred by the risk of establishment failure. However, the farmers in this study have developed a range of solutions so are not deterred by one or two failures.

Fig. 32.11 Potential risks of soil erosion in lucerne stands in summer and autumn, with bare spaces between lucerne plants and increased soil disturbance from running sheep

32.7.4 The Cost of Spring Establishment

Across the 13 farms, the gross margins in the lucerne establishment year ranged from $362/ha on the Serpentine farm to a negative gross margin of $80/ha on the Rutherglen farm. The former was due to good returns from the barley cover crop, while the costs of applying lime and having no cover crop impacted severely on the establishment costs on the Rutherglen farm. There is clearly a challenge to reduce establishment costs in some environments.

32.7.5 Lucerne Removal

A lack of information and local experience about successfully removing lucerne in preparation for cropping was frequently raised at grower meetings. Many farmers wanted to retain the summer grazing potential of their lucerne and so questions tended to centre on how to successfully remove lucerne plants in the autumn. This, however, was not an issue for the farmers who had, over time and through trial and error, developed effective strategies for removing lucerne in both spring and autumn.

32.7.6 Sink Holes

Sink holes 15–200 cm in diameter and up to 60 cm deep have been reported in 4–6 year old lucerne stands, especially in fields with swelling–shrinking subsoil clays.

Fig. 32.12 Sinkhole

These sinkholes can create major safety and damage problems for vehicles and machinery, particularly when cutting for hay. They could be a public liability risk when spotlight shooters enter fields at night without permission (Fig. 32.12).

32.7.7 Impacts of High Legume Diets on Animal Health

Deaths from 'red gut' in sheep and bloat in cattle were occasional problems for some farmers, especially in the early years of lucerne.

32.8 Conclusion

Farming systems are constantly evolving. There are many complex relationships operating between crops, pastures, soils, rainfall, seasonal climate variability, markets for grains, meat and wool as well as farmers personal aspirations. Innovative farmers are constantly sourcing new knowledge to improve their farming systems. Management factors are constantly under review; these currently include the length of the lucerne phases, the sequences of grain crops, crop management, the removal of lucerne, and livestock operations. An overhaul of sheep farming systems, which has included stocking rate, improved nutrition with lucerne, genetics, fine merino wool and prime lamb, has enabled some farms to increase their gross margins three fold.

Our economic analyses indicated that lucerne increased the profitability of all 13 case study farms. The key feature was the development of highly profitable livestock enterprises on lucerne pastures, with less pronounced benefits to the profitability of the following crop phases. Ten of the farmers will continue to grow lucerne in rotation with crops, whereas three see new intensive cropping techniques to be more profitable than lucerne phase farming systems.

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Chapter 33
Use of Conservation Agriculture to Improve Farming Systems in Developing Countries

Ken Sayre and Bram Govaerts

Abstract Farmers in both developed and developing countries are confronting new challenges related to the globalised economy, accelerating production costs and now climate change. Conventional farming practices that involve tillage for land preparation and weed control, removal or burning of crop residues and monocropping are associated with soil erosion and degradation of the soil health needed for efficient water productivity and sustainable crop production. Over the past 30 years, a new approach to farm management to address these issues includes reduced tillage, retention of crop residues and the use of more diversified crop rotations. This is now referred to as Conservation Agriculture. The results of research to compare the productivity and profitability of Conservation Agriculture (CA) with that of conventional farming are outlined in this chapter. Since achieving the benefits of CA requires major changes in attitude from conventional production, the successful extension and farmer adoption of CA requires farmer participation in the development and adaptation of CA technologies.

Keywords Conservation agriculture • Sustainable crop production • Zero till • Crop residue retention • Crop rotation

33.1 Introduction

Farmers throughout the world are beset by new challenges related to globalisation. These include the effects of climate change on their future productivity and shrinking budgets for agricultural research and extension. However serious these factors may be, we must always keep in mind that "*Man, despite his artistic pretensions, his sophistication, and his many accomplishments, owes his existence to a 15 cm layer of topsoil and the fact that it rains*" (Anon). This statement illustrates the importance of all farmers employing crop management systems which generate cost-effective

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_33,

crop production and make efficient use of scarce and increasingly erratic water supplies, while sustaining the soil resource base.

New crop production systems must also be compatible with crop diversification strategies that evolve to meet new markets. All this must be accomplished within a scenario of decreasing areas of land available for food production because of urban expansion and because of increasing use of land for other cropping purposes, including biofuel production. This further emphasises the need for sustainable and efficient use of soil and water resources.

Most farmers in developing countries have traditionally believed that:

- tillage is necessary for proper crop establishment
- crop residues can be continuously and completely removed for other purposes (livestock fodder) or burnt to facilitate tillage or enhance field sanitation
- Mono-cropping (usually driven by economics) is feasible over the long term.

Where traditional tillage and residue removal practices have been used over centuries, soil has been lost through erosion and the soil resource has been degraded physically, chemically and biologically. As a result, neither improved varieties of crops nor other inputs are able to deliver their potential contribution.

There are also increasing concerns about the contribution of agriculture to global greenhouse gas (GHG) emissions and climate change. Extensive tillage for land preparation or mechanical weed control can lead to the breakdown of soil organic matter with the associated release of CO_2 (Reicosky 2001); further CO_2 is released from burning fossil fuels for the associated tractor power. When these tillage operations are combined with burning of crop residues, the combined contribution to GHG from conventional farming practices is large. In addition, the continuing inefficient use of nitrogen fertilisers can increase production costs, contribute NO and NO_2 to GHGs, or result in widespread leaching and nitrate pollution of underground water tables.

Despite the large number of improved crop varieties released each year; global yield improvement for many crops has slowed. This is illustrated by recent CIMMYT experiments which have indicated that the rate of increase in wheat genetic yield improvement has declined with time (Sayre et al. 2008), further contributing to the production/economic dilemma faced by many farmers.

In view of the above limitations, recent investigations have sought to show the way to a more sustainable form of agriculture, which has been termed Conservation Agriculture. CIMMYT's long-term Conservation Agriculture (CA) trials have clearly demonstrated that new, improved wheat and maize varieties can achieve their genetic yield potential only with sound cropping systems management (Govaerts et al. 2006a). Information from these investigations is presented below.

33.2 Toward Sustainable Management of Cropping Systems

In recent years, many concerned farmers have begun to adopt and adapt improved crop management practices that lead towards the ultimate vision of sustainable farming. The term Conservation Agriculture has been used over the past decade to distinguish this more sustainable agriculture from the narrowly defined 'conservation tillage' (an oxymoron since the goal is to reduce or eliminate tillage). CA removes the emphasis on tillage and addresses an enhanced concept of the complete agricultural system; it involves major changes in many aspects of the farm cropping operation. Appropriate CA technologies encompass crop production systems that combine the following principles:

- Marked reductions in tillage
  - Goal – Zero-till or controlled-till (including strip till and the in-furrow soil disturbance associated with reshaping permanent raised beds) planting for all crops.
- Retention of adequate levels of crop residues on the soil surface
  - Goal – Sufficient residue on the soil surface to protect the soil from water run-off and erosion, increase infiltration, improve water productivity and enhance sustainability.
- Use of beneficial crop rotations
  - Goal – Economically viable, diversified crop rotations which moderate weed, disease and pest problems.
- Improved farmer perception of the potential for immediate economic and livelihood benefits.
  - Goal – Combined farm production sustainability and profitability.

These basic cropping practices define an overall approach to soil and crop management that is applicable to a wide range of crop production systems. None-theless, to facilitate farmer adoption of CA, specific management components (such as weed control tactics, nutrient management strategies and appropriately-scaled implements) need to be developed through adaptive research with active farmer involvement, under a range of agro-climatic conditions and production systems.

Successful farmer adoption of the CA practices necessitates altering the traditional farming practices of many generations, especially those of small- and medium-scale farmers in developing countries. The change in mind-set, needed not only by farmers but also by scientists, extension agents, and policy makers, may be the most difficult aspect to achieve. It is often difficult to explain to farmers the rationale supporting the adoption of the basic CA tenets beyond the potential to diminish production costs by reduced tillage. They also need to be made aware of the importance of sustainability problems linked to tillage and removal of residues.

In practice, the movement towards CA and a more sustainable production system normally comprises a sequence of actions. For example, (1) adoption of reduced or zero tillage, (2) retention of adequate levels of crop residue on the soil surface, then (3) selection of appropriate crops, cultivars and rotations. In most situations, (2) and (3) represent the most challenging aspects of the transition (Derpsch 1999).

Obviously, the fourth listed CA principle above (economic and livelihood benefits) represents a common aim not unique to CA but it *must* guide the evolution of suitable CA technologies. While farmers may recognise serious sustainability issues on their farms, the adoption of CA needs to be driven by economic advantage (see also Chap. 7).

33.3 Reasons to Invest in Conservation Agriculture

The benefits of CA occur at global, national and regional society levels, as well as at an individual farmer level. Some benefits begin almost immediately, others develop over time; the pace often depends on the relevant agro-climatic production system (Sayre 1998; Derpsch 1999).

The benefits (adapted from Bradford and Peterson (2000)) include:

33.3.1 Short-Term Benefits

- savings in costs from reduced traction and labour requirements for land preparation
- reduced turn-around time between crops, which improves timeliness (harvest today, plant tomorrow) when weather and field conditions allow immediate sequence cropping
- increased water infiltration into the soil and reduced run-off due to protection of surface structure by the surface-retained residues
- reduced soil erosion through decreased water runoff
- reduced evaporation of soil surface moisture as a result of surface-retained residues
- less frequent and less intense crop moisture stress due to this increased infiltration and reduced evaporation
- moderation of soil temperatures, especially the extremes of high soil surface temperatures.

33.3.2 Medium- to Long-Term (5–10 Year) Benefit

- increased soil organic matter, resulting in improved soil structure, cation exchange capacity and thus nutrient availability, and water-holding capacity (see also Chap. 14)
- enhanced carbon sequestration in the soils with reduced release of CO_2 to the atmosphere
- more efficient nutrient utilisation and cycling
- increased biological activity in both soil and aerial environments, leading to opportunities for biological control of pests and diseases (see also Chap. 6)
- increased and more stable crop yields reduced risk of crop failure (see also Chaps. 39 and 40).

33.4 Long-Term Experiments in Conservation Agriculture at CIMMYT

33.4.1 Rainfed Cropping Systems

In 1990, CIMMYT established a long-term, rainfed cropping trial at El Batan, Mexico, which is representative of the rainfed highlands of central Mexico. Agriculture in these highlands is mainly found in temperate, sub-humid, high valleys (1,500–3,000 m asl), between 16° and 24°N latitude. Rainfed cropping predominates, with mean annual rainfall of 350–800 mm (600 mm at El Batan). This occurs during a 4–6 month summer wet season followed by a dry and frosty winter. Farm size in the region tends to be small to medium-scale. Crops are dominated by maize but also include wheat, barley, beans, oats and potato, all planted at or just before the onset of the summer rains. Most rain events are intense afternoon storms but significant dry spells can stress crops at any time during the cropping season. The soil is bare for much of the year since almost all crop residues are removed directly for fodder, or are grazed, or burned. Fields are tilled frequently, using mainly small, tractor-drawn disc ploughs, harrows and cultivators, although draught animals are still common. Sloping fields, combined with heavy tillage and lack of ground cover lead to rain runoff and extensive erosion. This results in the loss of precious water and soil and a gradual 'wearing down' of production potential.

The trial aims to compare the long-term effects of CA-based tillage, crop residue management and crop rotation, with the local, commonly used tillage-based practices, for both wheat and maize production. Other practices such as weed control and nutrient management are as locally recommended.

The trial results confirm the benefits of CA for farmers in this region and show how the three main CA practices interact (Govaerts et al. 2005, 2006a, b, 2007a, b). Wheat and maize grain yields over a 10-year period (1996–2006) are presented in Figs. 33.1 and 33.2. Each year, in all treatments, new recommended wheat and maize cultivars have been used and all other management practices applied at recommended levels. The best CA practice provided continuously higher and more stable yields for both wheat and maize than the traditional one. The results show that use of the current, tillage-based practices, with crop residue removal, on these already degraded soils, does not deliver the maximum yield response to, or full return on the investments into developing new cultivars. Similarly, other inputs, in particular rainfall, are not being efficiently utilised. An important part of the yield benefit from residue retention is from the reduction of soil moisture evaporation.

Figures 33.3 and 33.4 illustrate the potential economic benefits (returns above variable costs) for farmers from appropriate CA technologies. There were highly significant differences in the economic returns between the common farmer practices and the CA-based practices for both wheat and maize. This indicates the clear

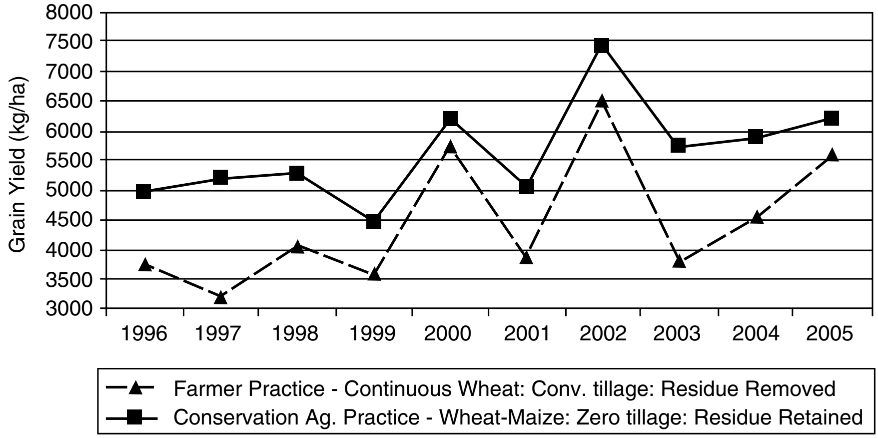

Fig. 33.1 Comparison of rainfed wheat yields for most common farmer practice versus the best conservation agriculture practice at El Batan, Mexico from 1996 to 2005 (Year by Management Practice LSD (0.05) = 207 kg/ha)

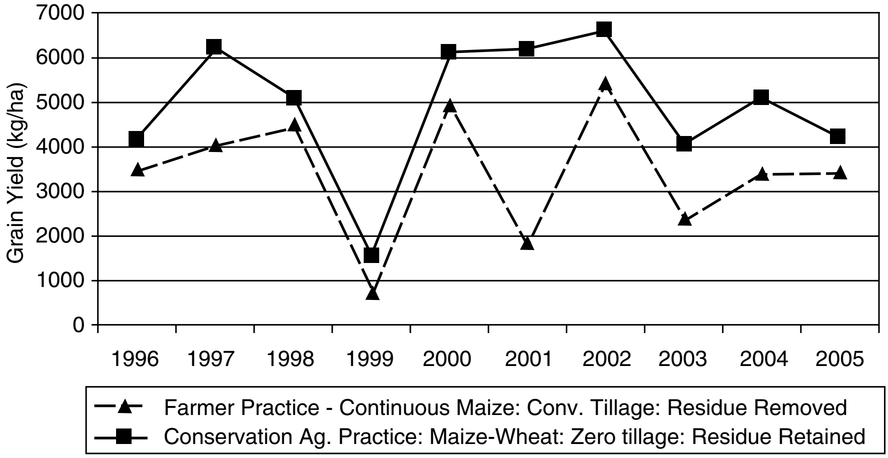

Fig. 33.2 Comparison of rainfed maize yields for most common farmer practice versus the best conservation agriculture practice at El Batan, Mexico from 1996 to 2005 (Year by Management Practice LSD (0.05) = 239 kg/ha)

economic advantage, especially to small and medium-scale farmers in a developing country setting, if they have the means to adopt appropriate CA technologies.

33.4.2 Irrigated Cropping Systems

CIMMYT has also conducted similar long-term trials in the irrigated areas in north-west Mexico, mainly in the Yaqui Valley in the State of Sonora. While this book is about rainfed agriculture, the importance of irrigated agriculture in many developing

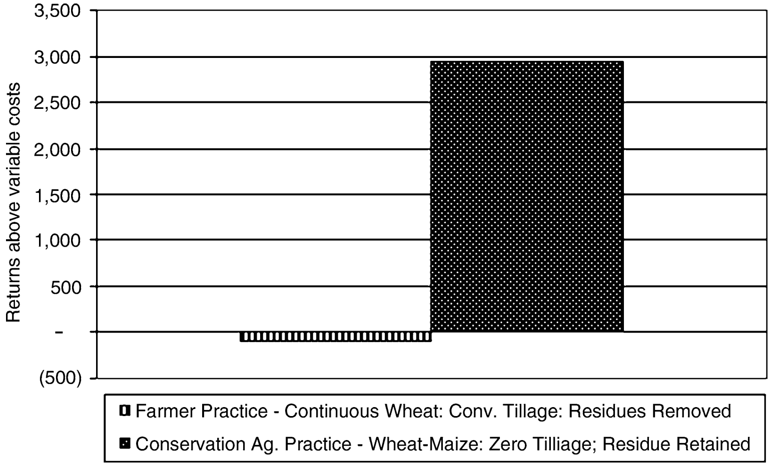

Fig. 33.3 Average returns above variable costs in Mexican pesos/ha/year (1996–2005) from rainfed wheat for most common farmer practice versus the most promising Conservation Agriculture technology at El Batan, Mexico (10.5 pesos = 1 US dollar)

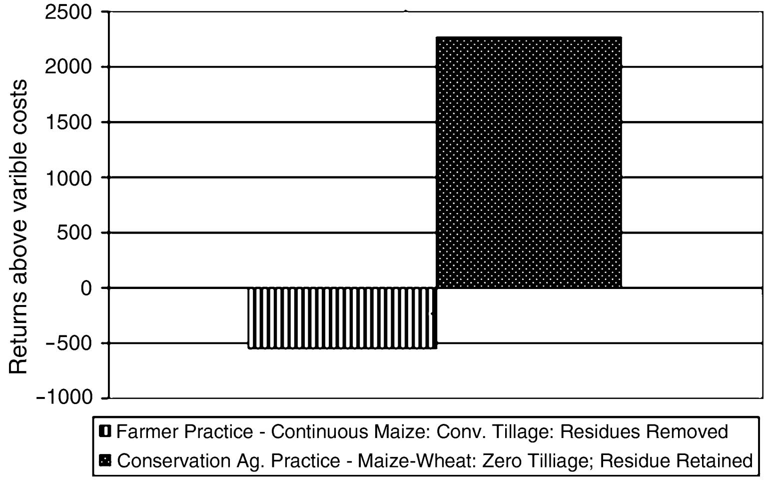

Fig. 33.4 Average returns above variable costs in Mexican pesos/ha/year (1996–2005) from rainfed maize for most common farmer practice versus the most promising Conservation Agriculture technology at El Batan, Mexico 10.5 pesos = 1 US dollar

countries warrants mention of these experiments. Further, they provide information complementary to that discussed above for the rainfed trials.

Farming in Yaqui Valley is mechanised. Farm size ranges from less than 10 ha to several hundred. Over the past 25 years, more than 95% of the farmers have changed from the conventional technology of planting on the flat with basin/flood irrigation, to planting on raised beds. This applies to all crops, including that most widely grown – wheat. Irrigation water is delivered by furrows between the beds.

Wheat yields for the Yaqui Valley have averaged over 6 t/ha for the past several years. Farmers growing wheat on beds obtain about 8% higher yields, with nearly 25% lower operational costs as well as irrigation water use, than those still planting conventionally on the flat, using border/basin flood irrigation (Aquino 1998).

Most farmers currently practice conventional tillage, by which the beds are destroyed after the harvest of each crop by several tillage operations, before new beds are formed for planting the succeeding crop. This tillage is often accompanied by burning of the crop residues, although some maize and wheat straw is baled for fodder and, when turn-around-time permits, some crop residues are incorporated during tillage (Meisner et al. 1992).

However, there has been intense farmer interest in the development of new production technologies based on CA principles, with marked reduction in tillage and retention of crop residues. These changes should lead to reductions in production costs, improved input-use efficiency, more rapid turn-around-time between crops and more sustainable soil management, while also allowing continued use of the less expensive gravity irrigation system (Sayre and Moreno 2007). A long-term experiment was initiated in 1992 to compare existing farmer practice (tilled beds with residues incorporated) with the practice of using no-till on permanent raised beds. In the latter, three residue treatments were also compared (Fig. 33.5).

Wheat yield trends differed between the irrigated and rainfed trials. In the rainfed production systems in central Mexico, zero till with residue retention and crop rotation provided the most benefits in grain yields (Fig. 33.1), due mainly to more efficient rain water use. Under the irrigated conditions in the Yaqui Valley, no major

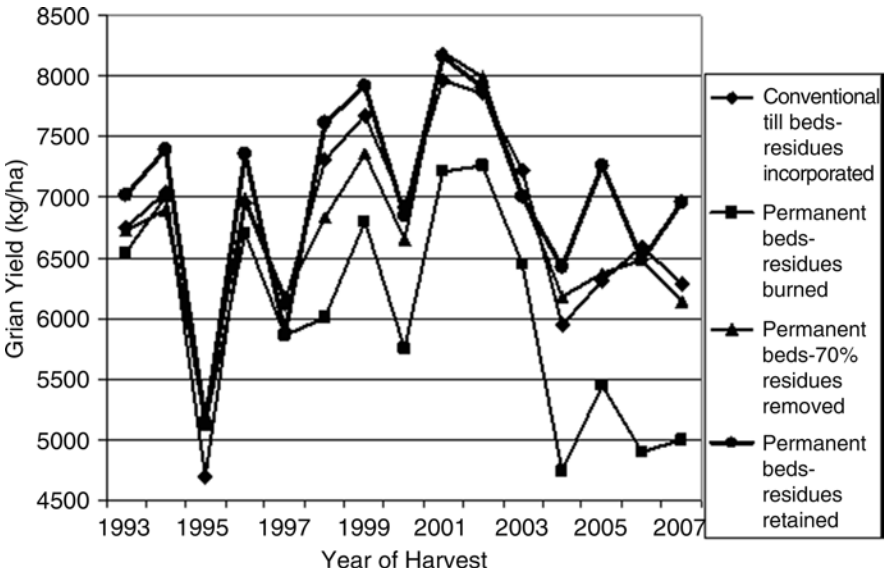

Fig. 33.5 Effect of tillage and residue management over15 years on wheat grain yields with optimum management in the Yaqui Valley, Sonora, Mexico

differences in wheat yield were observed among the contrasting tillage/residue management practices for the first 5 years (involving ten crops, since soybean or maize crops were planted each summer in rotation with wheat). This lack of differences may have been due to the masking effect of irrigation on the capacity of residues to reduce soil moisture evaporation. However, from 1998 onwards, wheat yield was markedly lower for the permanent raised-bed treatment where all summer and winter crop residues had been continuously burned. The other three treatments gave similar yields to each other. This leads to the conclusion that, under irrigation, removing all residues negatively affects factors other than moisture supply, including soil physical, biological and chemical properties associated with sound soil health, and is an unsustainable practice.

There are many examples from rainfed production conditions where farmers using zero till planting without retaining adequate surface residues have failed to achieve satisfactory results; however, there are few clear examples of this occurring under gravity-irrigated conditions, since so few attempts to develop appropriate CA technologies have been made for surface irrigated production systems. The CIMMYT results for both rainfed and irrigated experiments certainly reinforce the near axiom that adequate retention of surface residues is required for the sustainable, long-term use of zero till planting systems.

33.5 Extent of Farmer Adoption of Conservation Agriculture in Developing Countries

The rate of the adoption of Conservation Agriculture has been increasingly rapid over the past 20 years, after rather slow development during the previous two decades. Pioneering farmers had to deal with issues of markedly reducing tillage operations while attempting to zero till seed into surface-retained crop residues.

Derpsch (2005) has estimated that there are approximately 96.5 million hectares worldwide of crops grown with zero-till-based CA technologies (Table 33.1),

Table 33.1 Estimated Area under CA Zero-till (ha) 2004/2005 (Adapted from Derpsch 2005)

Country	‘000 ha
USA	25,304
Brazil	23,600
Argentina	18,269
Canada	12,522
Australia	9,000
Rest of the South America	3,035
Indo-Gangetic-Plains	2,800
Europe	450
Africa	400
China	100
Others (rough estimate)	1,000

although some may be on the way towards CA rather than operating true CA. About 90% of this total area is located in five countries—USA (26% of the total area), Brazil (24%), Argentina (19%), Canada (13%) and Australia (9%). Most current adoption of CA involves relatively large commercial farms using heavy tractors and large-scale equipment (especially seeders). More than 96% of the total area under CA is in rainfed production systems, involving mainly wheat, maize and soybean At least 50% of the world total area under CA is devoted to wheat production, with substantial areas planted to maize, soybean, canola, sorghum, sunflower and grain legumes in several countries.

Current levels of CA in developing countries are low and poorly documented but include farmers in North Africa, western, central and southern Asia and China. China now devotes considerable resources to developing CA for both rainfed and irrigated production systems. Outside of these areas, there has been insignificant CA adoption in most developing countries, and the use of CA for irrigated conditions, especially gravity-based water delivery irrigation systems, is negligible in nearly all developed as well as developing countries. Although small farmers in general have been slow to adopt CA, there are some well-documented examples of adoption. In South America, there are an estimated 200,000 ha of permanent CA on small farms in Brazil, especially in the states of Parana, Santa Catarina and Rio Grande do Sul, as well as a considerable area in Paraguay (Derpsch 2005). In Ghana, by 2002, there were more than 100,000 small farmers producing rainfed maize using CA, and pockets of adoption of rainfed CA on small farms have been reported in several other countries (Ekboir 2002).

Over the past 15 years, CIMMYT agronomists have been cooperating with national agricultural research institutions in several developing countries to help catalyse CA technology development and farmer adoption. The outcome in Bolivia has been rapid adoption of CA, particularly for the rainfed wheat, soybean and maize production systems in the lowland, eastern areas bordering Brazil. In northern Kazakhstan, development of appropriate CA seeders and technologies has offered potential to both intensify and diversify the rainfed wheat–fallow systems (P. Wall, CIMMYT CA agronomist, personal communication).

33.6 Implications for the Future

Agricultural research and technology transfer budgets continue to decline, in real terms, for most national and international agricultural research centers. Unfortunately, a common response to declining budgets has been to reduce disproportionately the allocation to agronomy and crop management studies so as to lessen budget reductions for plant breeding. However, unless the widespread, on-farm soil degradation is arrested and the process reversed, resources used to develop new germplasm will be largely ineffective. New crop cultivars will not be able to achieve their yield potential or provide better economic returns. Rather, there will be diminishing returns from all kinds of inputs, accompanied by increasing costs.

There is, therefore, need for a new revolution based on integrated CA farming systems that include improved varieties as a component.

One of the major lessons learned from experience is that, to achieve the complex system changes leading to widespread adoption of Conservation Agriculture, farmer experimentation and adoption must be stimulated by many coordinated activities conducted through collaboration between local partners: farmers, governmental and non-governmental institutions and international research centres.

These co-coordinated activities include: community awareness programs; farmer, researcher and extension agent training; on-farm participatory demonstration plots; on-farm and on-station strategic research combined with well-developed adaptive research; equipment development and evaluation; stimulation of local production of adapted equipment combined with provision of opportunities for the establishment of machinery service providers; and support for farmer-to-farmer exchange and study tours. Regular monitoring and evaluation of advances and farmer perceptions, and the adjustments to respond to these help ensure a dynamic and successful development process.

The understanding of farmer perceptions related to zero/reduced till systems combined with residue retention which can lead to limitations to adoption will permit the analysis of the effects of policy (at community, district, regional and national levels). Therefore discussions with policy makers to identify potential policy shifts needed to encourage the adoption of sustainable agricultural practices can be more useful. An example is the decision by the Government of India to provide price subsidies to farmers towards the purchase of zero till seed drills Because of the multi-faceted approach, activities are better concentrated in a few, defined locations rather than being lower intensity efforts on a wide scale. This will help reduce the initial lag phase of adoption, and these hubs will serve as platforms for expansion to the surrounding areas. This has been well demonstrated by the initial use of fields of innovative farmers by the Rice-Wheat Consortium to extend CA-based zero till seeding practices to farmers in South Asia. Adoption in over 2 million hectares occurred exponentially over a period of 10 years (see Table 33.1).

In the rainfed areas, full adoption of CA will increase rainfall use efficiency. However, this involves changing the common practice of residue removal for livestock feed. Although the value of crop residues as fodder is widely recognised and relatively easy to assess, the value of residues for soil protection and improvement has not yet been widely quantified in most countries. This requires analysis of the agronomic and economic trade-offs between the use of residues for fodder, and their use for soil protection and improvement. The production of alternative fodder sources would be a relevant possibility to consider. The goal of residue management in CA is to optimise the balance between the amount of residues retained for soil protection and improvement and the amount removed for other economic uses such as livestock feed. However, little empirical information is available to determine the optimal level of ground cover to guarantee soil benefits.

Future strategic research will have to concentrate on production system × genotype interactions (especially tillage/residue management × genotype interactions) and the physiological basis of yield potential in different management systems.

Historically, the availability of new, improved varieties has facilitated wider adoption of new crop management practices. Similarly, innovative changes in crop management have facilitated wider adoption of new varieties. However, little has been done to maximise the synergies that can be obtained from plant breeders and agronomists working together, to take full advantage of the higher yield potential cultivars in association with appropriate CA technologies (Cook 2006) (see also Chap. 26). Other strategic research will need to focus on nitrogen cycling, water use efficiency, phytopathology and integrated pest management, development of multi-crop, multi-use implements and the adaptation to and mitigation of the effects of climate change through CA.

Primitive rainfed farmers used to manage their crop production systems sustainably. Pre-Colombian agriculture in Mexico was based on zero till, stick-planted, multiple-intercropped systems based on maize, beans and cucurbits. Crop residues, especially maize stalks, were left in the fields. When the Spanish conquistadores arrived, they introduced the plough and draft animals (horses, mules and bullocks) to pull the ploughs and consume the crop residues. Immediately, soil erosion and soil degradation became chronic problems and, until recently, 'modern agriculture' based on ever more efficient tillage instruments and ever increasing use of inputs such as fertiliser and pesticides has attempted to rectify these problems. The proper application of the tenets of Conservation Agriculture, however, offers farmers the opportunity to achieve sustainable cropping systems again while preserving the high yield levels associated with modern agriculture. If done properly, CA adoption can also make more efficient use of agricultural inputs, enhance water productivity and help mitigate potential climate change associated with GHG emissions. More importantly, however, it offers farmers new prospects to improve the economic viability of farming operations.

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Chapter 34
Using Conservation Agriculture and Precision Agriculture to Improve a Farming System

Mark Branson

Abstract Conservation Agriculture and Precision Agriculture can improve farm efficiencies and the environment in rainfed farming systems. Along with benefits that include reduced soil compaction through controlled traffic systems, Conservation Agriculture (CA) involves carbon farming (undertaking specific farming practices in order to sequester carbon and maybe obtain tradable rights in that carbon). Precision Agriculture (PA) matches the agronomy of broadacre cropping, including fertiliser application, with field variability, by using GPS technology and on-the-go sensors. Application algorithms are being developed and economics need to be defined for rainfed systems. This chapter describes how CA and PA can improve farm efficiencies and preserve the environment.

Keywords Carbon farming • Conservation agriculture • Precision agriculture

34.1 Introduction

Achievement of a high level of agricultural productivity, profitability and sustainability rely not only on agronomic, plant breeding and economic gains but also on appropriate management at the levels of the farm system and individual fields. Some of the critical challenges at these levels are to:

1. prevent soil erosion and other degradation and further, to improve soil fertility and structure
2. make efficient use of rainfall—the most common limiting factor
3. manage spatial variability in soil conditions and in the incidence of weeds, plant diseases and insect pests.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_34,

Two of the most important methodologies currently applied to meet these challenges are ‘Conservation Agriculture (CA)’ and ‘Precision Agriculture (PA)’.

34.1.1 Conservation Agriculture (CA)

Conservation Agriculture (see also Chap. 33) is concerned principally with the conservation of soil and the improvement of ‘soil health’. It is often defined by four principles:

1. Use of minimum or no-tillage, to reduce the breakdown of soil organic matter and soil structure
2. Use of suitable crop (or crop–pasture) rotations which help prevent the buildup of plant disease organisms, reduce the incidence of insect pests and weeds and help combat salinisation, acidification and nutrient imbalance.
3. Become farmers of Carbon by growing as many high carbon content crops such as cereals as possible, or add a carbon source to the soil such as animal manures, to build the carbon content in the soil. The crop residues need to be fully maintained in order for the soil carbon content to be maximized.
4. Maintaining continuous cover of the soil surface by crop and pasture residues. This protects the soil against wind and water erosion, increases rainfall infiltration, reduces the loss of soil moisture by evaporation and increases soil organic matter when the residues decompose.

Soil health is also concerned with ‘soil fertility’. In its most general sense, this includes maintenance and improvement of soil structure which allows aeration and drainage; organic matter content; water holding capacity, soil pH and soil nutrient status. Farmland is usually variable in such properties, as well as in other characteristics such as the soil profile of texture and depth. All these contribute to the variability of crop yield potential within and between fields. Efficient management of such variability entails variation of inputs to the system to avoid both too little or an excess that is wasteful and may harm the environment.

34.1.2 Precision Agriculture

Precision Agriculture is a means of identifying variability in a field and matching inputs to it. Variability may be seen in crop yield, various soil characteristics and the incidence of weeds, plant disease and insect pest damage. It usually requires field testing to determine its cause and how to deal with it. Then a range of new and relatively sophisticated techniques may be used to apply varying rates of inputs for such operations as planting, soil amelioration, and pest control, as well as for monitoring outputs of grain yield and quality. By implication, PA also involves more precise timing of operations in relation to the weather, and to crop needs.

Taken together, CA and PA provide the potential to increase markedly the efficient use of rainfall, soil resources and farmer inputs. In the process, they improve the possibility of attaining productive, economic and ecological sustainability.

34.2 Applying Conservation and Precision Agriculture

Farmers have traditionally dealt with variable agricultural land by fencing according to soil type, and treating each field as an individual unit with constant inputs applied across it. However, as farmers strive to increase efficiency, machinery size and field size have increased. The adoption of PA on this scale has been made possible by the dramatic reduction in the cost of GPS equipment in recent years; this has allowed farmers to access yield mapping and to see the yield variation actually occurring on their farm. PA can allow farmers to balance management with land capability to improve profitability and protect environmental resources (Wells 2005).

Technologies used include spray guidance systems, auto-steering and controlled traffic systems, variable rate controllers and provision of detailed information about fields by satellites, yield monitors and survey equipment.

This process involves collecting many layers of spatial information, and processing with appropriate computer software.

A simple way of approaching PA is to look at two different types of problems:

1. **Problems involving factors that can be changed readily.** Such changes include applying gypsum to overcome sodicity, lime to counter acidity, nutrients to overcome deficiencies and chemicals to combat pests. Variable rate technology can be used in all these instances.
2. **Problems involving factors that cannot be altered readily.** Examples include soils with different water-holding capacity (such as those with spatial variations in texture and depth), where variable rate technology can be used to adjust input rates to the potential of the soil.

34.2.1 Balancing Nutrients and Matching Them to Crop Requirements

Matching nutrients to crop needs is difficult, particularly for nitrogen (N)—also discussed in other chapters of this book.

34.2.1.1 Nitrogen

The challenge is to manipulate N availability to match crop demand at all stages of growth. Timing also affects the risk of loss from leaching and denitrification, a risk which increases with the time between application and uptake by the crop.

Split N application (part at sowing and the remainder during the growing season) better matches N availability with crop demand, and can allow in-crop adjustment according to seasonal growing conditions.

Changing to a no-till system can temporarily reduce the soil N available to the crop as it is 'tied up' by bacteria decomposing high-cellulose crop residues. This available soil N needs to be monitored through soil testing. During the year, a model[1] of N mineralisation based on tillage practice, rainfall and temperature may be used to estimate the amount of mineralised N available to the crop during the year. This portion of N can vary widely from year to year, field to field, and zone to zone within the field; and hence is difficult to calculate.

New technologies based on chlorophyll monitoring and remote sensing in conjunction with top dressing procedures show promise but it is still difficult to define appropriate N application rates. The amount of nitrogen taken up by the plant from the soil can also be estimated by comparing a nitrogen-rich fertilised strip with the field average using a Greenseeker® sensor (see later).

The rate of N application required for a section of field can be calculated by adding the total N removed by the most recent crop to any deficit that existed prior to that crop (from historical data, yearly, deep soil N testing). The amount of N removed from the field has to be calculated from crop yield and protein content. Yield maps show yield variation across the field, and with the aid of a protein sensor, protein variation can also be mapped. By combining these two sets of data, total N removed can be mapped.

34.2.1.2 Phosphorus and Potassium

Phosphorus (P) and potassium (K) requirements are easier to predict because of their greater stability in the soil. There are numerous models available that provide P recommendations based on soil tests, soil types, crop type and expected yield (see also Chap. 5).

Farmers have traditionally used a blanket approach to P application according to overall yield expectations, and thus have been building up different levels of phosphorus across a field because yield variation removes different amounts of P.

To address this, farmers in Europe and the United States started a campaign of grid soil sampling, but this proved too expensive. Only two companies[2] still advocate this system using 1 ha grids for measurement of P, K and pH.

While SOYL agree that their system might not be very precise, they maintain that the maps provided enable the farmer to profit by using varying rates of nutrient. Over 151 farms, they claim an average annual benefit of twice the cost, with P being a major component. The variation of P, K and Mg (magnesium) in fields that have been using this system for 10 years has been reduced—with more soil nutrient samples falling in the optimum range.

[1] Australian examples include PIRSA's N Calculator, and CSIRO N Fertiliser Calculator.

[2] Including SOYL which is the biggest precision agriculture company in the UK.

Chris Dawson, Secretary of the International Fertiliser Association and head of the Precision Farming Alliance in the UK, suggests that an adequate grid size for P and K would be 40 m^2, and a better method would be for P and K to be put on at replacement rates from the previous year's yield maps (C. Dawson, 2005, personal communication). This has been used in Australia for a few years, and is gaining acceptance when P and K levels in the soil are acceptable for maximum yield.

Constant multiple geo-referenced[3] soil tests should be done by the farmer or a consultant every 5–10 years to monitor how this method is affecting P and K levels, and to track the availability of P and K in the system. For example, over a number of years, no-till with stubble retention will increase the amounts of available P and K.

Where farmers have been applying animal manure to supply nitrogen they often forget about the equally available phosphorus, potassium and trace elements. Fertilising with manures in this case may need to be stopped or greatly reduced to avoid excessive levels or lessen leaching into the local waterways.

34.2.1.3 Other Soil Limitations

Other soil limitations that can be overcome by precision agriculture include soil acidification through liming, sodicity using gypsum, and salinity by lowering the water table.

Many areas in the world have problems with soil compaction, and few are addressing it. Compaction can result from a plough pan or from wheeled traffic. A compacted soil suffers a loss of structure, restricts root access to soil water and nutrient supply, and is more prone to erosion and waterlogging. Water infiltration and soil aeration are reduced, as is the biological activity in the soil. Soil compaction is estimated to cost Australian agriculture up to Australian $850 million a year in lost production (Whitlock 2005).

Equipment wheels may cover more than 85% of the field area in a given season in a minimum-tillage, grain-growing system and around 50% in a no-till system. A single pass of traffic can decrease yields by 12–17% (Webb et al. 2004). However, under Controlled Traffic (CT), wheels are confined to permanent lanes taking up about 15% of the field area (SAGIT 2004) (see also Chap. 39).

34.3 Precision Agriculture

34.3.1 Precision Agriculture—The Technology

34.3.1.1 Yield Monitors

The ability to monitor yield variation in a field is critical to understanding soil variation and matching inputs to crop requirements. Crop yields may be monitored

[3] Located by GPS reference points.

in real-time during the harvest process, with most new grain harvesters having a yield monitor as a standard item. Once calibrated, the yield monitor can provide a continuous record of yield over the field. When this information is combined with a GPS unit, a yield map can be produced that documents the spatial variability in that field in that particular year.

The accuracy of the yield monitors from the factory settings are around 2–5%; a higher level of accuracy can be obtained with calibration on multiple loads, at different flow rates.

Grain yields estimated by yield monitors are adjusted to account for differences in grain moisture and are reported at standard grain moisture. Most systems estimate grain moisture from a continuous measurement of the electronic conductivity of the grain at a given temperature, and so incorporate a grain temperature sensor.

Machine make and model presets include the ‘time-delay’ calibration, i.e. time taken to move grain through the machine from the front of the harvester to the grain flow and moisture sensors. This figure varies between 6 and 20 s depending on the type of harvester used, and must be accounted for to get ‘geographically-correct’ grain yield and moisture maps. Harvest data are downloaded to a personal computer each night.

34.3.1.2 Protein Sensors

There is a need to record protein ‘on-the-go’ along with yield ‘on-the-go’ because of its relationship with N usage (nitrogen removed is the product of yield and protein percent). Examples of commercial protein sensors are Cropscan 2000H and the Zeltex AccuHarvest On-Combine Grain Analyzer.

Cropscan 2000H: This system takes a reading every 6 s, and measures protein and moisture using NIR (Near Infra Red) technology similar to the testers used at commercial grain-receiving sites. Cropscan 2000H consists of an NIR spectrometer, a remote sampling device, and a remote PC display and controller. The spectrometer and the PC controller are mounted inside the harvester cabin, and are connected to a sampling device fitted to the final clean grain auger in the header bin by fibre optic cables. Protein and moisture are computed and sent to the PC Controller where the data can be displayed as a moving average, bin average, a trend plot or even as on-the-go field protein or moisture maps. Grain yield and GPS signals can be fed to the PC controller allowing yield maps to be calculated, so the complete field maps can be displayed and stored.

AccuHarvest On-Combine Grain Analyser: This sensor was developed by the Australian Centre for Precision Agriculture, in conjunction with growers in Conservation Farmers Incorporated, in collaboration with Zeltex Inc. and the Swedish Institute of Agricultural and Environmental Engineering. The grain protein sensor is mounted on the harvester’s clean-grain elevator. Depending on the harvester’s ground speed, the sensor automatically samples grain four or five times per minute. Some hardware and software modifications have been necessary for it to work in the dry, dusty Australian conditions.

34.3.1.3 Soil Mapping with Electrical Conductivity

Soil properties changing across a field can cause marked variation in the yield potential of a particular crop; PA can map these changes in soil condition. Aerial photos of bare soil, using different wavelengths and other remote sensing techniques have been used to map soil changes; but looking at the surface of the soil has only limited application as most soil properties correlated to yield are at deeper levels.

For accurate information, direct sampling of the soil on a grid is best but requires at least four samples per hectare, with sampling at various depths. Except for initial survey this sort of information is too expensive to collect and, in most cases, has been abandoned in favour of cheaper methods.

Electro Magnetic Induction and Soil Electronic Conductivity[4] techniques are favoured because they can penetrate the soil to different depths and identify areas of contrasting soil properties. These methods effectively measure electrical conductivity (EC) of the soil at different depths, and are combined with a GPS to log precise locations across the surveyed area. These data can then be processed to produce a map that indicates soil variability in the root zone across the field. This map provides the foundation for a sound understanding of where soil properties may be varying in a field and their agronomic significance. (see also Sects. 4.4 and 4.6)

Factors which can affect the EC reading in the soil are: moisture content, soil texture (especially clay content), electrolytes in the soil solution and soil bulk density. The clay content of the soil is especially important as it determines water holding capacity and is a key ingredient of productivity. The concentration of electrolytes in the soil solution, i.e. salinity, is important because of its potential to reduce productivity. Compacted soils will have a higher soil bulk density, and hence the EC reading might be able to pick up compacted areas if other factors do not dominate.

Because a number of factors can affect the EC reading, 'ground truthing' by soil sampling must be used to determine any relationships between EC and the actual soil profile characteristics.

The map provides a guide to where soil samples should be collected by indicating where the trends in conductivity exist, therefore inferring a change in soil profile conditions. Soil samples (collected close to the time when the survey was conducted) are used to analyse the soil chemical and physical properties in regions delineated by the map.

Three examples of systems that are able, directly or indirectly, to measure 'on the go' Electronic Conductivity are Geonics EM-38, the Verris Soil EC Surveyor 3100, and the GEOCARTA. These operate as follows:

Geonics EM38: This is an Electro Magnetic Induction sampler that emits an electromagnetic signal. It passes down through the soil profile, generating a second magnetic field in the soil that varies depending on the soil properties. The second magnetic field

[4] There are two techniques used to measure soil EC in the field: electromagnetic induction (EM) and contact electrode. See Glossary.

strength is detected by a receiver on the EM38 measuring the apparent electrical conductivity (ECa) of the soil profile. The energy field extends vertically from the instrument for a distance of approximately 1.5 m and horizontally for about 75 cm.

Verris Soil EC Surveyor 3150: This is a series of four discs which are pulled through the soil. One pair of counter-electrodes injects a known voltage into the soil, while the other counter-electrodes measure the drop in that voltage, effectively measuring the soil electrical conductivity (EC) at two depths (0–30 and 0–91 cm) simultaneously.

GEOCARTA ARP: This uses similar technology to the Verris sensor, but has six disks and measures voltage at three depths simultaneously (0–50, 0–100, 0–200 cm). It operates on 12 m swathes, and can travel up to 20 km/h to survey 100 ha in a day. From the data and soil sampling, the ARP can generate various maps for texture, soil depth, stone content, and phosphorus content. From the EC maps at different soil depths, a potential yield map can be generated for nutrient budgeting; however, soil test verification is required to determine what soil factors are determining the EC values (Fig. 34.1).

More methods of on-the-go soil sensing have been developed, and although some have been commercialised and may replace EC sensors in the future, they currently hold a small part of the market. These include: sub-surface soil reflectance sensors, microwave sensors, ground-penetrating radar, soil mechanical resistance profilers, soil-penetrating noise sensors, air permeability sensors, and electrochemical sensors.

Fig. 34.1 The GEOCARTA ARP from France

34.3.1.4 pH Mapping

In 2005, there were two commercial platforms for on-the-go pH testing—the Verris pH Manager from USA and the then yet-to-be-named on-the-go Soil pH and Lime Requirement Measurement System (SpHLRMS) developed by the Australian Centre for Precision Agriculture, the Swedish Institute for Agricultural and Environmental Engineering, and Computronics Holdings Limited of Perth, Australia.

Verris Soil pH Manager: The Verris pH Manager automatically collects and measures a soil sample every 10–12 s. A sampler brings the soil sample core into contact with an ion-selective pH electrode, and after 8–10 s of stabilisation period, the pH reading is logged on the Verris instrument, and another cycle is started (Fig. 34.2).

Verris manufactures a Mobile Sensor Platform (MSP), which combines both the Verris EC Surveyor 3150 and the Soil pH Manager into one platform, and so pH and EC data can be obtained simultaneously. Verris are working on an improved MSP that would measure potassium (K) and nitrate (NO_3), as well as buffer pH.

Soil pH and Lime Requirement Measurement System (SpHLRMS) (Buffer pH Sensor): The buffer pH Sensor uses a tine to loosen the soil to be sampled. The sampling mechanism consists of a self-propelled 30 cm waved spinning disc that throws up soil from the top 10–20 cm layer. The soil goes through a fan to a cyclone at approximately 30 m/s to be pulverised and then sieved. A measured volume of soil is mixed with analytical solution, and the pH is measured and logged. The sensor also provides lime requirement estimates.

Fig. 34.2 The Verris pH sampler shoe

A second prototype is being developed to improve accuracy and to reduce sampling interval from 27 to 13 s (Taylor et al. 2005).

34.3.1.5 Elevation Maps

Elevation is a vital layer in PA for providing elevation, slope, and aspect maps, and thus for understanding the influences of topography on water infiltration and yield variation based on direction of slope.

Elevation can be obtained by averaging Differential Global Positioning System (DGPS)[5] maps over a number of yield maps, with the popular 2 cm RTK GPS systems providing a higher level of accuracy.

34.3.1.6 Remote Sensing

Photography has been used for aerial surveillance for well over a 100 years, with cameras being strapped to everything from tethered balloons to carrier pigeons in the mid-1800s. During World War I, airplanes were used to carry cameras for military purposes. By the 1940s, the USA Soil Conservation Service was routinely collecting aerial photographs, primarily for soil surveys. Since that time, there have been considerable advances in remote sensing technology such as colour-infrared photography, digital cameras, thermal infrared sensors, and satellite imagery.

Aerial views coupled with the farmer's field knowledge can greatly enhance a farmer's ability to make informed management decisions. Examples of beneficial information obtained from basic remote sensing include: soil type changes, early detection of weeds, problems in crop establishment, moisture stress in a crop, farm equipment patterns including compaction, crop lodging and crop disease.

New advances in remote sensing include determining the nitrogen status of the crop by using a series of different wavelengths in different ratios to provide recommendations for nitrogen application.

A common approach used by researchers to assess vegetative health within agricultural fields is the calculation of vegetative indices. These indices are calculated by mathematically manipulating or calculating ratios of the infrared reflectance in a digital image with the red reflectance, resulting in a new indexed image. This indexed image is composed of numerical values that represent the relative condition of a crop, i.e. plant biomass and health. The most popular of these indices is the Normal Difference Vegetation Index (NDVI) equation.

$$\mathrm{NDVI} = \left(\left(\mathrm{Nir} - \mathrm{red}\right) / \left(\mathrm{Nir} + \mathrm{red}\right)\right)$$

where

Nir = Near Infrared Reflectance
red = Red reflectance

[5] See Glossary for explanation.

The output of this process is an image showing the variation of plant condition throughout the field, where red indicates areas that are the healthiest (or most biomass) and pink the least healthy. There are many other indices used in agriculture depending on the information required. As with any field image, ground-truthing of what is happening in that particular spot in the field is essential.

34.3.1.7 Satellite Imagery

Satellites orbit up to 700 km above the earth, capturing information from sensors focused on a particular area of the earth's surface. Satellites have an advantage in their ability to provide images throughout the growing season—cloud cover permitting.

Different types of satellites capture different information, at different spatial resolution, and for differing costs. Spatial resolution is defined by pixel size. Some satellites (e.g. Quickbird, IKONOS) provide high-resolution images with 0.6 m pixel sizes whereas others (e.g. Landsat 5) have a coarser resolution of 30 m. The smaller the pixel size the higher the cost of acquiring the imagery. Higher resolution pixel size usually means the sensor needs to be nearer to the ground.

The image obtained needs to be Georeferenced, Orthocorrected,[6] and corrected for atmospheric variations; the cost increases with additional corrections.

Satellite images show the spatial variability of the growth and health of a crop, which, after ground truthing, can be used for various purposes in Precision Agriculture. These might include identifying potential problems such as disease incidence, plant establishment, weedy patches and soil zones needing different management.

FARMSTAR: In France, EADS Astrium (European Aeronautic Defence and Space Company), the second largest aerospace company in the world, is testing the FARMSTAR program which is used by French, UK and hopefully Australian farmers to aid crop decision making.

Farmstar which started as collaboration between EADS and the wheat institute of France has now been operating for 10 years. In 2005, France had 6,000 farmers using it on 180,000 ha for whole-field agronomy, but only 30 farmers used it for Variable Rate Fertilising.

Farmstar measures the chlorophyll content of the crop, which is correlated with the nitrogen status of the crop, and the Leaf Area Index (LAI) which is highly correlated (90%) with the canopy status. From this, EADS can estimate plant population, biomass and nitrogen status, and so inform the farmer/adviser of the tiller density and risk of lodging, and recommend N rates for numerous stages of the crop's life. Because the acquisition pixels are at 20 m grids, nitrogen rates can be recommended for different parts of fields.

For each field, Farmstar needs to know the field boundary, variety sown, sowing date, sowing density, and the types of soil.

Figure 34.3 illustrates the French wheat package that includes three acquisitions. GS 26 (Zadock Growth Stage 26 with a GAI (Green Area Index of 1), GS 30 and GS 39.

[6] See Glossary.

Growth Stage:	GS26	GS30	GS32-33	GS39
Approx date:	Mid-February	Late-March	Late-April	Early May
Crop Architecture:				
Maps delivered to grower:	•Shoot Density •1st Nitrogen •GAI (1)	•Fertile Tiller Density •Main Nitrogen •GAI (2)	•Lodging Risk (2nd PGR)	•Final N •GAI (3)

Fig. 34.3 Farmstar's 2004 wheat package for Europe

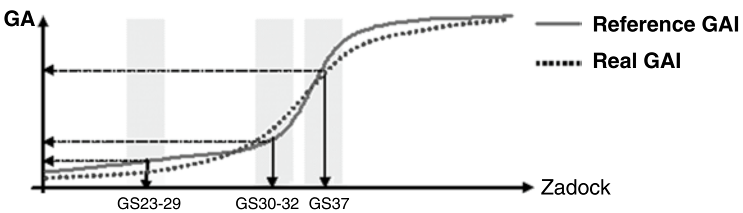


Fig. 34.4 A graph representing the use of Green Area Index (GAI) for recommending N application rates, in order to manipulate GAI, at three key growth stages

From this information, nitrogen rates are recommended, and a lodging risk map provided in time for the second Plant Growth Regulator (PGR) spray. At the first acquisition, they provide a nitrogen budget from the amount of nitrogen that has already being absorbed by the crop. Also from the first acquisition, they are able to tell if there are any bad weed areas, detected as an abnormally high biomass for the growth stage of the crop (Fig. 34.4).

Farmstar information is used to correct Green Area Index (GAI) using nitrogen when the crop falls outside the optimum yield response GAI curve. Wheat provides optimal yield when GAI development is close to the theoretical GAI growth curve.

The Co-operative Epis-Centre who uses the Farmstar program as part of their Precision Agricultural package estimates net gains of Australian $50–100/ha.

GEOSYS: The second satellite company based in France is Syngenta's company, GEOSYS. This company was a split from EADS, and hence has similar services and operates in France, UK, and the USA.

They offer an online service where crop information is put on the web; the farmer pays an annual subscription to have access to the satellite image at any time of the year. With the package, a software programme allows the farmer to enter the field information required to generate nitrogen recommendation maps from the Leaf Area Index (LAI) gained from the satellite. These can be used by a variable rate controller for variable rate applications.

34.3.1.8 Aerial Photography

Aerial photography offers the same service as the satellite information but can provide better resolution by being closer to the crop. It can swap sensors and use multi-spectral or the better, but more expensive, hyper-spectral sensor.

Research is being done into hyper-spectral sensing identifying different weeds, including distinguishing ryegrass from other plant species. This information will be of great benefit in the control of herbicide-resistant annual ryegrass.

34.3.1.9 Ground Sensing of Crop Performance

Ground sensing may the most promising option for PA as it may allow on-the-go management decisions. It also allows for multiple acquisitions to be made in a single year, and does not have the problems caused by cloud cover. In this system, a sensor is mounted on a vehicle or trailer, to gather reflected light back from the crop. The necessary light source may be the sun, or operates from the sensor.

Using a controlled traffic or tramline system is an advantage as it allows for more precise location of repeated measurements, and allows measurements to be taken in an advanced crop without running over and damaging it. Most of these sensors operate in real time, but a GPS in the system allows the sensed information to be mapped.

Yara N Sensor: The Yara N Sensor has been available for the longest period. In 2005 there were over 200 sensors being used in Germany and, in 2008, about 650 throughout the world (Fig. 34.5).

Fig. 34.5 The Yara N Sensor mounted on a Househam self-propelled boomspray

An optical sensor mounted up above the cabin of the tractor, sprayer, or other mobile vehicle, measures and analyses the sunlight reflected by the crop, and corrects for ambient light conditions. The sensor measures biomass and chlorophyll content of the crop in a similar way to the Farmstar and Geosys satellite systems. These measurements are then used to adjust application of chemicals such as for variable N fertilising, application of fungicides (according to differences in biomass), application of growth regulators (according to differences in biomass), and application of plant desiccants They also allow more efficient harvest protein prognosis, and other markers.

The N sensor recommends and applies a variable rate of N according to the plant density and chlorophyll content.

Many trials in Europe have shown that this system has increased wheat yields by about 3.2% and is environmentally friendly (Yara 2008). It also creates an even protein content and quality (screenings and weight) of the grain, and thus simplifies harvesting.

An estimate of likely economic benefits in a 450 mm annual rainfall district of South Australia in 2008

Assumptions: APW wheat yielding 4 t/ha at Australian $250/t.	
Costs: Combine, Australian $55/ha. N application, 60 kg/ha @ Australian $1.45/kg N.	
Yield increase (3% = 0.12 t/ha)	$30.00
Fertiliser savings (10% reduction = 6 kg/ha)	$8.70
Increased Combine performance (15%)	$8.25
Reduced lodging risk (avoid 2% of the field)?	$2.55
Benefit per hectare per year	**$49.50**

In summary, the N sensor and variable rate application can give a 100% return on investment with about 300 ha of wheat in a single year.

In Australia, the Southern Precision Agriculture Association (SPAA) is experimenting with one system to determine weed populations and more profitable methods of weed control (Heap and Trengrove 2008). At the cost of Australian $34,000, a large area of grain would be needed to make it pay.

A major problem arises from using the sun as the active light source, as it can be used only when the sun is high—between 10 a.m. and 4 p.m. during winter in Southern Australia.

A new Active Light Sensor (ALS) has been developed and sold by Yara since 2006; this uses the same technology as the old model, but has its own light source for crop reflectance. Hence it is able to work at any time of day, avoiding the problems with the previous model operating only when the sun is high. In 2009, the Australian-based PA company Topcon will take over the manufacturing of the ALS, and will be the distributor outside of Europe. Topcon's ALS "Crop Spec" have two separately mounted modules that are still placed up high on the tractor or self-propelled sprayer. At a mounting height of 3 m, the ALS would scan 6 m of crop. At about $25,000 the Topcon "Crop Spec" Sensor is better priced for the Australian market.

N-Tech—GreenSeeker® Sensor: This was developed at the Oklahoma State University and produced by NTech of Ukiah, California.

The GreenSeeker ® emits its own light source to measure the reflectance of specific wavelengths of light (red and near-infrared) off the crop canopy. Thus it is not restricted by the sunlight hours. The computer system then calculates NDVI as a measure of crop above-ground biomass and growth rate. The In Season Estimated Yield (INSEY) is then used to estimate the yield potential of the crop, and hence optimum application of fertiliser.

A small amount of fertiliser—enough to cover requirements for a low-rainfall year—is applied at seeding time, and the sensor is used to determine later applications of N for crop needs. Over a small area of the field, N is applied at a rate high enough not to be limiting. This N-rich strip is compared with the rest of the field to show whether top-dressing is needed.

This has been used in experiments at the Indian Head Research Farm, Canada (see Chap. 19, Lafond et al. 2004) (Fig. 34.6).

Greenseeker® RT 200: This system is designed for variable rate application of inputs. It has six sensors mounted across a urea boom, or boomspray, to scan 3.6 m of crop in one pass. Economic benefits are likely to be achieved by either maintaining yields with less N inputs or increasing yields with the same amount of N, by redistributing N placement. Profits of Australian $25–50/ha have been achieved in trials in winter wheat crops in Oklahoma (Ntech Industries 2008).

There may be advantage in defining a background layer of Management Zones and using the RT 200 to apply variable amounts of nitrogen according to the yield potential in the different zones (see later).

GreenSeeker® RT 100: This model is used for scanning the N-rich strip (Fig. 34.7), to work out a standard rate for each field or zone, using a representative area of the field or zone. The software works out a nitrogen recommendation for that zone.

Crop Circle ACS-210 Plant Canopy Reflectance sensor: This is a new active ground sensor developed by Holland Scientific Inc, of Nebraska USA, released in 2004. The crop circle sensor provides classical vegetative index data such as Normalized Difference Vegetation Index (NDVI),[7] as well as basic reflectance information from plant canopies. It has its own patented light source which simultaneously emits visible

Fig. 34.6 The N-Tech, RT 200 with 6 Greenseeker® sensors mounted across a self propelled boomspray in Virginia, USA

[7] See Glossary.

Fig. 34.7 The N-Tech GreenSeeker® RT 100 being used to measure an N-Rich strip in Tarlee, South Australia

and near infrared light (NIR) from a single LED light source. Thus both visible and the infrared light bands illuminate the same area of plant canopy. Serial data produced by the sensor can be easily captured using a laptop PC, PDA or other data acquisition devices for later analysis.

A new multi sensor kit has been developed where up to eight sensors can be fitted to a boom for Variable Rate work. This has been trialed in Europe and is a commercial product. The European distributor suggests that four sensors would be adequate for the author's farm, and they use their own algorithms tied to growing green leaf area for their nitrogen recommendations (Fig. 34.8).

34.3.2 Data Analysis

Precision Agriculture generates a lot of information; for example, the data set of a single field may comprise 5 years of yield maps, and EM survey, elevation, satellite images and NDVI scans. All this information has to be integrated in such a way that it can improve management decisions.

Fig. 34.8 The Crop Circle ACS-210 being used to measure the NDVI in barley in South Australia

Most countries are moving down the path into Zonal Management, in which the Australian Centre for Precision Agriculture (ACPA) has been a world leader. Management Zones are areas of a field which, over time, show differences which are mainly related to yield. These differences could be linked to differences in soil type, slope, or a combination of factors. The real challenge to using management zones is to determine what is driving a difference, which in most cases requires ground truthing.

There is debate about the degree of manipulation, smoothing or interpolation of data. Terry Griffin and Jess Lowenberg-DeBoer at Purdue University in Indiana, USA believe that data should be 'cleaned up' to remove bad data[8] before analysing it, but do not like interpolating data because it can introduce potential errors.

The ACPA prefer cleaning up the data and then kriging (a statistical technique for interpolating data) to produce a number of potential management classes, and setting out sampling points within each class for the farmer to explore what may be causing the variability seen in the data layers (Whelan 2005).

Some typical trends seen in using Management Zones are shown in Figs. 34.9 and 34.10.These are from a nitrogen experiment on canola in 2004, in the field 'Top D' on the author's farm.

The summary of results by Dr B. Whelan of ACPA of two trials in 2003 and 2004 indicated that:

> In Top D, the classes (zones) respond in terms of total yield over the field in the order 3>1>2 (except in 2003 with field peas, where 2 out-yielded 1). In the soil tests prior to

[8] The conventional terminology for data which is not real, such as data collected at the end of a harvest run where the harvester is emptying out or the cutting width is reduced but the yield monitor is calculating yield on a full comb width.

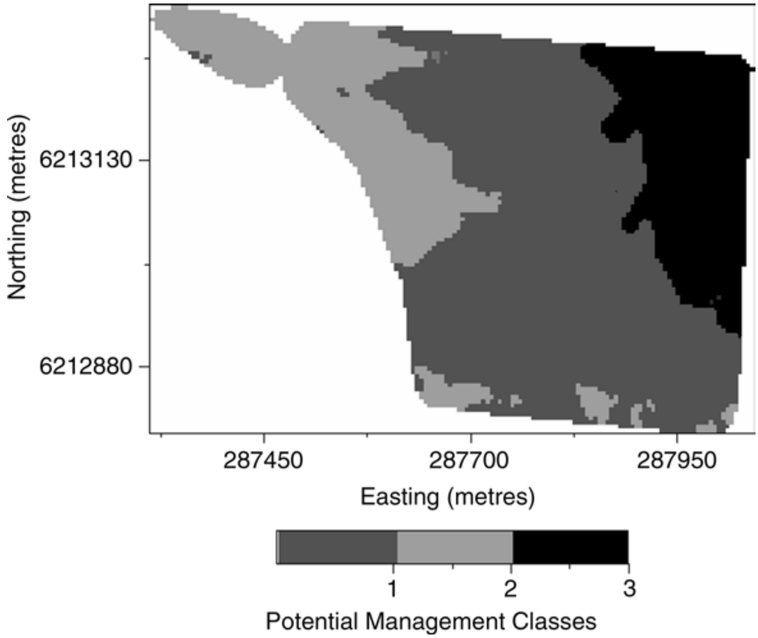
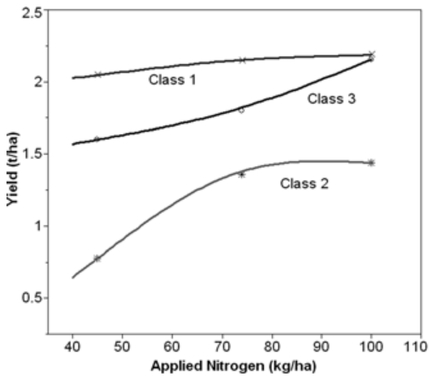


Fig. 34.9 Potential management zones created from data collected for field 'Top D'



	2004	
	Yield Max. (kg N/ha)	Economic Opt. (kg N/ha)
Class 1	100 +	77
Class 2	90	85
Class 3	100 +	100 +

Fig. 34.10 2004 Nitrogen rate trial results for three classes of land from the field 'Top D'. The responses to applied nitrogen are shown in the Graph and the maximum yields and economic optimum rates of nitrogen application, in the table

planting field peas in 2003, the soil nitrate was similar in Classes 1 and 2 and one third less in Class 3. The field peas yielded 0.7, 1.7 and 2.0 t/ha for Classes 1, 2 and 3 respectively. This gave the soil total available N prior to sowing canola in 2004 as 58, 84 and 73 kg N/ha. The better-yielding peas had increased the soil N in 2 and 3, but it seems that water availability must have been limiting, as Classes 1 and 3 were well enough supplied with N. Class 3 looks like it could have used higher rates of N in the canola in 2004.

The defining of management zones is a complicated statistical process and the farmer will either have to receive training in the process, or have the information processed by a consultant.

Chris Dawson of Chris Dawson Associates (C. Dawson, 2005, personal communication) suggested that, while Zonal Management in a field is a good idea, caution needs to be used when using Yield Maps, as these can vary greatly according to the characteristics of the season in which they were produced. To overcome this, Chris suggests that a large database of yield maps be compiled, and the farmer pick similar analog years to the season they are experiencing, and put these years through the statistical process to create management zones more in tune with the present season. By doing this, the management zone produced should be more accurate for the season the farmer is experiencing, especially where the water holding capacity is the main driver of yield in the management zones. A large database of numerous years' results would be needed to achieve good results.

The need for new software to analyse the data further, and produce yield maps for the benefit of the farmer has been recognized; and such software is being developed.

The list of possible inputs is large, so that which ones are varied in a field will depend upon the likely level of financial gain.

In the areas of UK and USA where rainfall is not usually limiting, the aim is to even up a field with the inputs. Seeding rates may be varied to make up for variable establishment rates, while fertiliser, plant growth regulator, and fungicide rates could be varied according to the measured needs of the crop.

In Australia and other areas that are rainfed, similar techniques are used to optimise the inputs and maximise the yield potential of established Management Zones. With herbicide resistant weeds occurring in patches, increasing seeding rates may allow the crop to out-compete resistant weeds.

Phosphorus removed from the soil can be replaced at rates determined from the P content of the previous year's harvest and the yield map. This helps even up the available phosphorus in the field, optimising its use. If the farmer considers that phosphorus is adequate, he needs only to assume a small loss factor to the environment; if phosphorus needs to be built up, this loss factor allowed for can be increased. The loss factor is the amount of P that is removed from the soil through erosion, leaching and other environmental losses. This calculation is not only economically sound, but also reduces the chance of phosphorus leaching into waterways—which is environmentally unsound.

The process of producing a phosphorus replacement map is simple.

1. Collect yield map for the paddock from the previous year's data.
2. Clean yield map to take out bad data created by the harvesting process.
3. Create two to three yield zones across the paddock using a simple GIS computer package. The software that comes with the yield monitor can be used to do this.
4. Obtain the average yield from each zone.
5. Apply a formula of P or K replacement plus a factor for P or K lost to the environment each year. This factor varies depending on whether P or K in the soil

needs to be increased or reduced. For wheat after a pea crop, the author uses the following formula:

$$\text{P replacement} = (\text{Pea Yield t/ha*\%P in Pea grain}) + \text{P loss factor. i.e.}$$
$$\text{P replacement} = (2.1 * 3.9) + 2 = 10 \text{ kg/ha of P.}$$

6. Convert this value to a fertiliser rate, i.e. if using DAP in the above example, P rate/P % in fertiliser (20 for DAP)*100, i.e. 10/20*100 = 50 kg/ha DAP.
7. From the zoned map, replace the average yield with the new fertiliser rate value.
8. Save in the format that the Variable Rate Technology (VRT) controller uses.
9. Place the file in the VRT controller's programme.
10. Sow the paddock with the VRT programme operating.

The best features of going through this process are that, in dry years or droughts, the rates of phosphorus application are reduced, benefiting the cash flow.

34.3.3 Disease Management

In South Australia, levels of inoculum of soil-borne disease, such as crown rot, can be correlated with different management zones. With this information, it may be possible to improve soil sampling for soil diseases, and hence to target pesticides and cultural control to the zones affected. In addition, the economics between the zones might differ with the economic advantage of high pesticide rates greater in zones of high yield potential (Heap and McKay 2005). It has also been found that there is two to five times less crown rot in the inter-row than in the seed row. Therefore where root disease levels are expected to be high, it would be beneficial to sow in-between the previous year's rows to reduce the effect of the root disease on current yield. With the recent use of very accurate autosteer systems on the tractor or implement and a very accurate GPS, some planting systems are able to place seed between the previous year's cereal stubble, maximising this benefit.

34.3.4 On-Farm Trials

This is one of the real benefits of having a harvester equipped with a yield monitor.

By placing input trials in a single zone, and having a yield monitor on the harvester to collect the yield data, the farmer has the capability to run input trials to fine-tune the farming system for the soil and climate. When one uses traditional statistical methods in analysing the data, one must either place the comparative trial in a single management zone where the environmental variability is kept to a minimum, or replicate by blocks across the field to account for field variability.

Terry Griffin and Jason Brown from Purdue University in Indiana, USA, have a different method of running on-farm trials. They put large well placed treatments across all field zones, and use spatial analysis to analyse the data. Spatial analysis methodology assumes that all treatments are directly related to each other, and hence that this is a better method of analysing yield data because of the common connection with the environment (T. Griffin, 2005, personal communication).

The SST company uses their SST Toolbox® program to compare varieties and other inputs on a whole-field level, but this needs a very large database. Opti-Crop from Kentucky USA run extensive trials in the Opti-Crop business, but they encourage their farmers who have yield monitors to run properly constructed trials on their own properties.

In Australia, SPAA recommends that on-farm trials be conducted within yield zones in order to minimise the effect of variable environment. They have a protocol in place to get the most benefit from conducting on-farm trials.

34.3.5 The Economics of Precision Agriculture

A recent economic study (to 2006) into Precision Agriculture was done by the Southern Precision Agriculture Association (SPAA) on southern Australian farms. Rainfed farming systems showed an average annual benefit of Australian $19/ha. This was a sample of 14 advanced PA farmers who had adopted PA techniques over a number of years. GPS guidance, autosteer, yield mapping and variable rate (VR) equipment were the main PA technologies evaluated for their financial impact on each business. Over all the farms, the investment in PA technologies averaged Australian $44/ha (SPAA 2008).

34.4 Controlled Traffic Systems

Controlled traffic confines soil compaction and crop disturbance by wheeled traffic to permanent 'tramlines' or tracks in fields. This is achieved by matching the wheel widths of the tractors and farm equipment and the operating widths of the farm equipment. The width of the farm equipment should be multiples of one, two, three or four times the width of the planting equipment, so that all wheeled traffic can be confined to the permanent wheel tracks. The harvester can be in the system with the proviso that the farmer decides whether it will cause significant compaction under the expected soil conditions at harvest time. The benefits of controlled traffic include greater efficiency (reduced inputs, easier access when wet and easier driving using guidance systems), better yield and value (less compaction and crop damage) and more agronomic opportunities (relay crops, fertiliser placement, post-emergent fungicide banding) (Webb et al. 2004) (see also Chap. 39).

Traditionally, tramlines have been kept bare but, with the problems of herbicide-resistant weeds and potential erosion in Australia, various methods, including bare tramlines, fuzzy tramlines, and sown tramlines, have been developed.

1. **Bare tramlines**. Bare tramlines are not sown, and provide a firm compacted zone for the machinery to run on. They are visible driving through the crop, and there is no crop damage during any post-planting operation. The plants on either side of the tramline compensate in yield through accessing the extra sunlight and soil moisture, and the overall benefit more than compensates for the area lost to bare wheel tracks. Opti-Crop in the USA advocate diverting the seed and fertiliser from the missing row into the two rows on either side, using an electronic set-up. However, herbicide-resistant weeds may grow in and escape from the tram-line. Although the tramlines can be sprayed with non-selective herbicides, this could bring its own resistance problems, e.g. glyphosate-resistance which is potentially the biggest threat to a winter-dominant, rainfed farming system. Herbicide resistance occurs when the same chemical group is applied to the same weed population over a number of years; surviving resistant weeds set seed and dominate the weed spectrum after a number of years, causing major problems to the farming system (Fig. 34.11).
2. **Fuzzy tramlines**. Fuzzy tramlines are made by taking out a tine where the wheeled traffic will go; seed is dropped but only pushed into the ground at a shallow depth. These tramlines provide some guidance and compete against any weeds germinating in the tramline, but there are difficulties in incorporating trifluralin in this system.
3. **Sown tramlines**. Sown tramlines are made by sowing the row normally, or on a modified tine, so the seed is placed at depth, and the trifluralin is incorporated by the soil throw. A sown tramline is often difficult to distinguish from the rest of

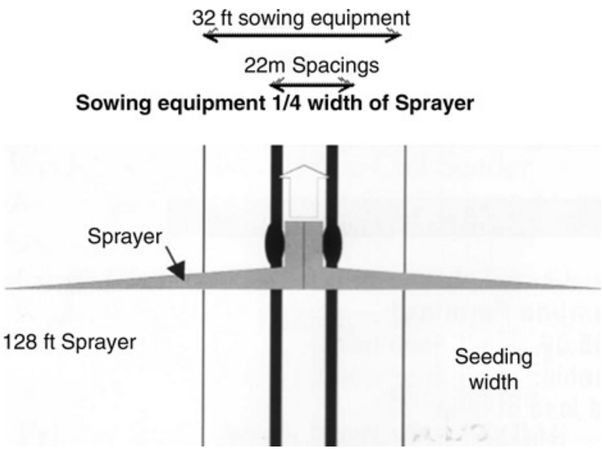


Fig. 34.11 The controlled traffic set-up at ‘Clifton’ South Australia

the crop, and usually requires an Autosteer tractor to operate correctly. Over the first few years, the tramline firms up. This makes it unsuitable for the crops to grow, leading to the bare tramline system.

To operate a controlled traffic system effectively, a guidance system is recommended. This may be mechanical, such as marker arms, or electronic, such as video or global positioning systems (GPS). It provides for more accurate driving to minimise overlap and also to set up and maintain the controlled traffic lines. These lines can be curved, or straight up and back. Curved lines may lead to wider tracks because towed machinery lags behind the tractor. Up-and-back traffic lines are recommended unless the farmer is using tractor-mounted sprayers and spreaders, specialised steered trailing boomspray or spreaders, or self-propelled four-wheel steering equipment.

Accurate driving and the matching of machinery operational widths are essential to precision farming, the same GPS equipment being suitable for variable rate applications of fertilisers and herbicides.

Table 34.1 lists some different ways of providing guidance for a controlled traffic system. The farmer has to decide the level of accuracy needed and this may depend on the size and layout of the farm, the degree of accuracy required for various operations (boom spraying needs less accuracy than planting equipment), and cost of putting the system on the machinery.

The benefits include a 3–10% reduction in input costs from less overlap, through more accurate driving, easier driving by using a guidance system, and with Autosteer, less driver fatigue. The compacted tramlines also allow for earlier access for operations such as planting and spraying in wet conditions, and allow for night-time spraying—important for areas where the days are too windy. CT systems are estimated to reduce fuel use by up to 25%. Fuel and fertiliser savings alone could translate to substantially less greenhouse gas emission for each tonne of increased grain production (Webb et al. 2004).

The more expensive Real Time Kinematic (RTK) guidance (Table 34.1) gives repeatable 2 cm accuracy, and allows a new suite of agronomic opportunities. These include (1) the ability to sow in-between stubble rows, which can increase the

Table 34.1 Guidance systems, approximate costs (AUD) and accuracy (October 2005)

	Cost	Accuracy	Accuracy
Guidance method	Australian $	(long- term, stable over time)	(pass-to-pass, 15 min apart)
Camera	1,500–2,000	50 cm	50 cm
Permanent wheel tracks	5–10/ha	30 cm	30 cm
Marker Arms	1,000–12,000	30 cm	30 cm
Visual GPS guidance (Light BAR/screen)	10,000	1 m	30 cm
Sub-metre auto-steer (Satellite/marine beacon)	21,000	1 m	10–15 cm
10 cm auto-steer (Satellite Omnistar HP)	31,000	10 cm	5 cm
RTK 2cm auto-steer (Base station on farm)	50,000	2 cm	2 cm

second cereal crop yield by reducing root disease two- to fivefold; (2) improving the efficacy of soil-applied herbicides; and (3) facilitating the stubble handling of the planting equipment. The RTK system also allows the use of in-between-row shielded sprayers with non-selective herbicides to improve weed control.

Band spraying with fungicides, targeting only the crop is particularly useful in crops with low biomass, such as chickpeas, or where a fungicide is required early in crop development before canopy closure.

However, although the tractor may be driving to an accuracy of 2 cm, the trailing implement may creep, especially if the land is sloping, and the planting implement tends to follow a path of least resistance. These problems can be reduced by using combinations of three-point linkage, hydraulic rams and even a camera focused ahead, e.g. the Robocrop® system.

34.5 Conclusion

Much pressure is coming onto agriculture throughout the world with the general population demanding that farmers be more environmentally accountable and sustainable. Conservation Agriculture and Precision Agriculture go a long way in addressing such public concern, while improving farmer's profits. The ever-increasing cost of inputs is giving an economic imperative for farmers to be more efficient in their operations and more precise in their use of chemicals and fertilisers.

Conservation Agriculture involving No-Till, Controlled Traffic and Carbon Farming, which includes full stubble retention and growing high-carbon crops, has over time shown itself to improve soil health, with less erosion, higher water-holding capacity, and greater retention and cycling of nutrients. CA leads to less reliance on inorganic fertilisers when compared to more conventional farming systems. All these attributes have favourable effects on farms profits and, equally important, on the environment.

As Precision Agriculture is a rapidly developing industry, new technologies are being constantly researched and released. It will be up to researchers, advisers and farmers to find what is relevant to their situations economically and environmentally. The future in PA will be in simple on-the-go, plug-and-play sensors that are easy to operate and do their job without much grower input. Outside of these tools, a PA industry needs to be developed to where a farmer can give information to a PA specialist adviser, who will process it and hand it back to the farmer in a form that can be placed into a VR controller, from which the job is done.

PA tools that have benefit today include making phosphorus replacement maps from last year's yield maps, optimising the use of phosphorus-based fertilisers, which not only is economically sound, but environmentally leads to less chance of P being leached into waterways. Also the new on-the-go ground remote sensing tools such as the Yara N Sensor, Topcon Crop Spec, Greenseeker, and Crop Circle—even though expensive—have the ability to optimise the use of nitrogen in pre-determined yield management zones, producing a profit, while helping the environment with less nitrogen escaping into the air and leaching into groundwater and waterways. These sensors, which map green leaf areas, can under certain circumstances map weeds and target them with herbicides or increased crop densities. These PA techniques are only examples of what can be done in improving the whole farming system.

PA has the potential to achieve profitable, CA-based rainfed farming systems with economic and environmental sustainability. This is achieved through more efficient use of scarce or costly inputs (water, labour, fuel, fertilisers, sprays and other chemicals), with less waste, and less contamination of the environment. It also provides flexibility for the farm system to respond to changing conditions, through accurate monitoring and decision making on timing and rates of action and inputs.

The major benefit of PA to the broader community is the reduction in chemicals released into the environment. European trials have indicated at least one third less nitrogen is leached using on-the-go nitrogen sensors over conventional nitrogen application methods. There needs to be more research in this area in the major grain-producing countries.

In the future, farmers will have available simple, relatively inexpensive, easy-to-use equipment to enable them to supply the optimal amount of chemicals and nutrients to the crops and to be able to measure and record the results of any application.

It is an exciting, but challenging, time to be in agriculture; if rainfed farmers adopt Conservation Agriculture and Precision Agriculture techniques, they will improve their whole-farm profits over an extended period, while at the same time preserving the farming environment.

Acknowledgement The author would like to acknowledge that this chapter is based of a report on his 2004 Scholarship Report for the Australian Nuffield Farming Scholars Association, titled ‘Using precision and Conservation Agriculture to Improve Farm Profits and the Environment’.

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Chapter 35
Risk Management Strategies and Decision Support Systems in Agriculture

A Study of Risk Management in Rainfed Farming Systems in Queensland, Australia

Nam Cao Nguyen, Malcolm Wegener, and Iean Russell

Abstract Rainfed agricultural production systems in a semi-arid climate operate under high risk. While weather variability is the major source of risk over much of Australia, other sources of risk include finance, markets, human resources, and changes in government policy. Most farmers employ a range of strategies to manage these risks. A comprehensive risk management program has to take many complex interactions into account and decision support systems (DSS) have been designed (as their name suggests) to offer assistance in making some of these decisions. However, DSS are not widely used by farmers as they often address only part of the risk management problem and may do that in a way that is too complex for many farmers to understand. In addition, many farmers believe that their tried and tested strategies for managing risk are satisfactory. For better adoption, each DSS should be easy to use and provide local information. The use of DSS to stimulate discussion and appreciation of the complexity of managing risk by farmers and students of agriculture suggests that 'discussion support' might be a more appropriate term. After a series of interactions with a group of rainfed cropping farmers in south-west Queensland, a decision support tool ('Key to dryland planting decisions') for rainfed farms in south-west Queensland was developed. It uses Lucid3 software to capture the timing and logic of the decision-making process and structures the process to select preferred crop planting options for both summer and winter planting periods from a wide range of possibilities.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_35,

Keywords Risk • Risk management • Decision support systems (DSS) • Rainfed farming systems • Rainfall uncertainty • Soil moisture • Planting decisions • Interactions

35.1 Introduction

We live in a world of uncertainty. While we always try to make our plans with great consideration and anticipation of all likely events happening, every decision-maker still faces risks regularly. Risk is an inevitable part of farming life.

In this chapter, we define risk, following Hardaker (2000), as a two-dimensional concept that includes the chance of achieving a bad outcome as well as the variability of all outcomes. It is the converse of stability (Hardaker 2000).

The following two sections address the background to risk management in agriculture and decision support systems applied to risk management in farming. This is followed by a report on a case study of risk management in rainfed farming systems in Queensland.

35.2 Risk Management in Agriculture

Agriculture involves a higher level of risk and uncertainty than many other comparable activities (e.g. manufacturing) because of the inherent variability of the natural environment in which farming is conducted and the unstable commodity markets in which farm products are sold. Farm production involves a relatively long time-period between production decisions and the harvesting or marketing of the product (Mishra 1996).

For several decades, agricultural economists have sought to understand farmers' decision-making behaviour when confronted with risk, and they have been interested in developing tools to assist them in this.

35.2.1 Farmers' Attitudes Towards Risks

Farmers operate in a multi-attribute environment or system in which many forces, choices, preferences, and events influence their behaviour and performance. Gaynor (1998) claimed that the farmers' 'factory floor' is subject to all the variables of manufacturing—for example, performance of equipment and personnel, quality and supply of inputs, prices of inputs and products—as well as the variables of weather, soils, diseases and genetics.

Most farmers are risk-averse with respect to decisions that may affect their income. They prefer a smaller gain which is certain to a larger gain which is uncertain, and seek to avoid risk through various risk management and risk-sharing mechanisms (McLeay et al. 1996; Anderson and Hazell 1997).

However, the individual farmer has to decide which risks and which part of those risks to share. These decisions therefore depend on the farmer's attitude to risk and perceptions about the nature of the risks; the costs involved in risk sharing; the size of the potential loss and the probability of it occurring; the correlation between different sources of risk; other sources of indemnity; and the farmer's financial state (Barry et al. 1995; Harrington and Niehaus 1999).

Because farmers vary in their attitudes towards risk, risk management cannot be viewed through a 'one size fits all' approach. Different farmers confront different situations in different ways, and their preferences toward risk and their risk-return trade-offs have a major effect on decision-making in each given situation.

35.2.2 Sources of Risk Faced by Farmers

Farmers often have to make decisions, of varying importance, under conditions of imperfect knowledge; and to deal with important factors influencing farm profitability that are beyond their control. Indeed, risk exposure varies substantially from farmer to farmer. Whether a strategy to cope with risk is adopted, and what elements it includes, does depend on how those risks are perceived subjectively by the individual. Risk perception varies from farmer to farmer, depending for instance on the farmer's own experience and on the degree of his/her risk-aversion.

The primary sources of risk faced by farmers include *production risks*, *market risks*, and *financial risks* (Goucher 1996)—to which should be added *institutional risk*, and *human resource or personal risk* (Kay and Edwards 1999; Burgaz 2000).

Hardaker et al. (1997) differentiated between *business risks* and *financial risks*. Business risks include production risks, which are related to the unpredictable nature of the weather and to the uncertain performance of crops and livestock, and price risk, which refers to uncertainty of prices for farm inputs and outputs. In addition, business risks include personal risks, such as illness or death of those who operate the farm, and institutional risks that originate from uncertainty about the impact of government policies on farm profits. Financial risks refer to the risks related to the way a farm is financed.

In various surveys, the five categories of risk that have been identified have been ranked according to their importance to farmers.

In the Netherlands, price risks were perceived as the most important source while financial risks were the least important (Meuwissen et al. 2001). New Zealand farmers felt that market risks were very important and the human risk associated with accidents or health problems were moderately important (Martin 1996). In Texas and Kansas, farmers, agricultural lenders, and agribusiness representatives listed price variability, yield uncertainty, and input cost changes as the three most important sources of risk, followed by changes in environmental regulations and unforeseen litigation (Ker and Coble 1998; Knutson et al. 1998).

However, American beef producers identified drought and cattle price variability as their greatest concerns, followed by extremely cold weather and disease. Less important were land price variability, availability of rented pasture, and labour availability (Hall et al. 2003).

35.2.3 Risk Management Strategies Available to Farmers

Risk in farm management is an area that is receiving more attention than it did previously. Farmers have been operating for some years in an environment where new risk management tools or strategies are being developed rapidly (Coble and Barnett 1999). As farms in most countries become larger, more capital, labour, and management inputs are used and this can create more risks related to financial and human resources. Increasing regulations are creating more legal and environmental responsibilities leading to greater institutional risk and adding different dimensions to other previously existing sources of risk. Increasing involvement by farmers in international trade in agricultural products and the forces of globalisation have also created more price risk for farmers worldwide. All of these sources of risk combine to make farming a rather precarious business, and so constant effort is required to minimise the exposure to risk on the farm.

Potential activities that can be used to manage risk have been classified into production, marketing, and financial risk management strategies (Sonka and Patrick 1984; Patrick and Ullerich 1996), although now institutional and human resource risks can be added to the list. Hardaker et al. (1997) believed the most important strategy to be based on maintaining *flexibility*, and that is still largely true. Strategies that can be adopted by farmers include flexibility in the management of assets, products, markets, costs, and time; dealing with environmental, institutional, and human resource risks, which are now more prominent, may require more specific action.

Meuwissen et al. (1999) distinguished two types of *risk management strategy* including those concerning on-farm measures, and those involving risk-sharing with others. *On-farm strategies* concern farm management and include selecting products with low risk exposure, choosing products with short production cycles, diversifying production programs, and holding sufficient liquidity to overcome downturns in prices, production, or other adverse effects. Farm management strategies to reduce the risk of environmental damage may restrict the level of inputs such as farm chemicals likely to cause environmental damage or avoidance of dangerous products and practices that could cause risk to human health. *Risk-sharing strategies* include production and marketing contracts, vertical integration, hedging on futures markets, participation in mutual funds, and insurance.

Farmers can adjust the enterprise mix (*diversification*) or the financial structure of the farm (the mix of *debt and equity capital*), while access to strategies such as insurance and hedging can help reduce their farm-level risks. *Off-farm earnings* are a major source of income for many farmers that can help stabilise farm household income. Harwood et al. (1999) also recommended maintaining *financial reserves and leveraging.*

After the 1996 Farm Bill was passed in the USA, operators in the largest gross income categories (more than US$250,000 annually) were most likely to use hedging, forward contracting, and virtually all other risk management strategies, whereas operators with less than US$50,000 in sales were less likely to use forward contracting, hedging or diversification (USDA 1996). Keeping cash on hand, for emergencies and for 'good buys', was the most frequently used strategy for every size of farm in every region.

Risk management strategies commonly used by a high proportion of readers of the national magazine *Farm Futures* included using government farm programs, diversifying into both crops and livestock, planting varieties with different maturity dates, contracting inputs to lock in a favourable price, buying crop insurance, and using crop-share rental arrangements (Harwood et al. 1999). In contrast, beef producers in Texas and Nebraska perceived that understocking pasture and storing a hay reserve were the most effective drought management strategies. Adjusting stocking rate, weaning calves early, and reducing the breeding herd in times of drought were ranked as slightly less effective. Purchase of hay during drought was ranked as the least effective strategy (Hall et al. 2003).

Dutch livestock farmers considered that risk-sharing strategies were more important risk management strategies than on-farm strategies. Producing at lowest possible cost, and buying business and personal insurance were regarded as the most important. Although, on average, price risk was perceived as the major source of risk, risk-sharing strategies to deal with this were not considered as important (Meuwissen et al. 2001).

Many Canadian farmers had strategies such as production contracts in place for managing risk; about one-in-five participants reported using options and futures. Other strategies included producing commodities that were marketed at different times of the year, or buying and selling throughout the year (AAFC 1998).

New Zealand farmers used a range of production, marketing, and financial risk management strategies; some strategies appeared to be favoured by farmers in all industries, others seemed to be industry specific, and some were universally unpopular. The mix of strategies employed seemed to vary by farm type (Martin 1996).

In summary, management of risk is an important activity for farmers worldwide. While many strategies for managing risk are conceptually possible, the management task facing farmers is to choose a combination of risk management strategies that best suits the unique conditions of their particular farming systems and their personal circumstances.

35.2.4 Risk Management Strategies Used by Australian Farmers

Most farmers in a Queensland survey (Ralston and Beal 1994) favoured storage of produce as a way to manage the risk associated with fluctuating prices. In addition, marketing through grain pools was highly favoured by broadacre crop farmers and mixed farmers, while forward selling was practised by crop farmers, mixed farmers, and fruit and vegetable growers.

Because many Australian agricultural commodity producers do not generate large cash incomes and are in a reasonably sound equity position, many see little value in expenditure on price risk management (Kingwell 2000). Wynter and Cooper (2004) found that some South Australian wheat farmers used a number of strategies (e.g. cash sales, pools, forward contracts, futures and options) each year to reduce the risk of price fluctuations; however, most wheat growers still relied instead on pool managers to price their grain.

The use of seasonal climate forecasting when calculating planting areas for irrigated cotton in the northern Murray Darling Basin of Australia can minimise risk by helping farmers to adjust planted areas and lead to significant gains in gross margin returns (Ritchie et al. 2004). However, the way farmers responded to seasonal climate forecasts was dependent on several other factors including their attitude towards risk. For many cotton producers in Australia, price risk management was an important part of farm business management, but adoption of these practices was influenced by a range of demographic, agronomic, and biophysical factors, as well as the individual personality of the farmer (Adam et al. 2006).

35.3 Decision Support Systems in Agriculture

Decision support systems (DSS) have been developed to help farmers deal with decisions involving complex interactions in agricultural systems.

35.3.1 Decision Support Systems in Australian Agriculture

There are a number of definitions of decision support systems (DSS) used to cover the range of products that have been developed. They range from any kind of decision aid, whether computer-based or not, to complex computer-based system involving complex modelling (Finlay 1994) and are fairly tolerant of whether the problem is more or less structured (Cox 1996). Lynch et al. (2000) called these systems 'Intelligent support systems'. Meinke et al. (2001) considered that a DSS could refer to any approach using simulation-based information, including software products, and dissemination of such information via printed or web-based media.

Guidelines for designing a DSS have been suggested by various Australian authors including Dillon (1979), Malcolm (1990), Hamilton (1995), Cox (1996), McCown (2002a) and Lynch (2003). As a consequence, the number of attributes that are regarded as essential for the development of a successful DSS has increased as the evolutionary process has unfolded.

McCown (2002b) reported that developing DSS in the 1980s and early 1990s was an exciting adventure with the optimism of modellers seeming to grow in proportion to advances in personal computing technology. However, the increase in computer ownership by farmers has not resulted in more widespread use of DSS.

35.3.1.1 Reasons for Poor Adoption of DSS in Australian Agriculture

By the turn of the century, lack of success in implementing DSS in agricultural decision-making in Australia was evident (McCown 2001); McCown, Hochman, and Carberry concluded:

> Although there are cases of local successes, as a field of agricultural research, DSS work is in a state of crisis…. As laudable as the idea of computerised scientific tools to aid farmers' decision making may be to some researchers, persistent lack of demand by farmers for DSS cannot be ignored (McCown et al. 2002, p. 1).

Others have commented on the slow rate of adoption of DSS by farmers in Australia and warned against agricultural DSS representing an abdication of professional responsibility and a failure of accountability (Cox 1996). Unfortunately, despite much effort to encourage their adoption, the unwelcome fact is that the use of agricultural DSS by managers of farms has been low (Carberry 2004). Attributes that apparently dissuaded use of DSS included phobias about using computers, tedious data entry, complicated set-up processes, lack of software support, lack of technical interpretation and application, and lack of local relevance (Nelson et al. 2002).

35.3.1.2 DSS and Computer Ownership

Contrary to expectations, the use of DSS in management of contemporary family farms has not grown with computer ownership (Ascough et al. 1999).

The ownership of personal computers among farming households increased greatly in recent years and a 2004–2005 survey found 56% (72,828) of Australian farms used a computer as part of their business operations (ABS 2006). However, it seems that desktop and even laptop computers do not fit easily into the farm workshop or the cropping paddock where many decisions are made (Hayman 2004).

Bryant (1999) reported that, in Australian farming, it is often the women on family farms who are responsible for record keeping (largely for tax purposes) while men make most of the operational and tactical decisions using their memory or simple analyses with pen and paper as their only aid. While greater use may now be made of electronic spreadsheets for analysis, it is believed that this rather simple approach to decision-making is still common, and past records are not used as much as they could be for decisions relating to the future.

35.3.1.3 Mismatch Between DSS Developers and End-Users

The notion that the adoption of DSS was limited by availability, or fear, or dislike of computers should logically be dismissed in the twenty-first century (Robinson 2004), while the lack of end-user involvement is more important (Armstrong et al. 2003).

Hayman and Collett (1996) pointed out that there was a mismatch between (a) the understanding of risk by farmers dealing with farm level business risk with clever, but relatively simple, intuition and (b) the detailed specification of risk used by scientists to model relatively constrained agricultural production systems at paddock level using complex formal analysis. Brennan and McCown (2003) argued that agricultural economists saw farm management practice from the 'outside', rather than from the 'inside' of the management system as farmers did.

The development of many DSSs was driven by the suppliers, and the product often had little relevance to intended users (Newman et al. 1999). DSS mostly focused on the production component of the farming system and failed to address the subjective/social dimensions of the management system (McCown 2001). Malcolm (2004) believed that adoption might be enhanced by the extensive involvement of the potential users in the initial development of the tool (through participatory learning approaches), along with intensive investment in education of the direct users.

Decision makers have an important role in model development because they are capable of providing feedback concerning design issues, relevance, needs, and perceptions. End-users who are involved in the development of DSS applications are able to gain greater insights into the problems they are facing (McGill 2001), and they differ, sometimes critically, from professional model developers in their perceptions of the biophysical aspects of the real world or the model (Robinson and Freebairn 2000).

Freebairn et al. (2002) noted that simple, single-issue decision support tools or models have several advantages over larger models—including speed and cost of development, accessibility, ease of use, and transparency. However, the disadvantages of such simple tools include less comprehensive representation of processes, less flexibility, and reduced ability to include complex interactions. They are unable to capture the complex, inter-related processes that are identified with most farm decision-making.

In spite of this, there are many relatively simple decision support tools in use by service providers and experienced managers (Armstrong et al. 2003), and making models and modelling tools simpler can make them more usable, understandable, and effective (Freebairn et al. 2002).

In rainfed crop production, we found that farmers' decision-making was largely based on on-farm measures such as moisture conservation, product diversification and marketing strategies and consideration of whether they would become involved in risk sharing with off-farm institutions. Thus simple models had many deficiencies in regard to handing the complex issues involved in simultaneously dealing with production, marketing and institutional risks, while the scientists' creations were considered 'partial, opaque, unstable, and not-adaptive' (Ridge and Cox 2000).

35.3.1.4 Future Development of DSS

By the mid-1990s, R&D funding bodies realised that investment in the development of DSS to improve agricultural practices had been largely wasted because these products had not been widely taken up by producers (Cox 1996).

Robinson (2005) noted that only recently had DSS developers recognised that they are competitors for farmers' time (and other resources), and that this means that new systems must be more efficient, effective, and more accessible than the decision support to which farmers already have access (such as from advisors or neighbours). The high level of 'indigenous knowledge' and generally competent management of enterprises by farmers and their advisors in extremely risky environments creates a situation in which it is very difficult to develop a successful DSS.

Nevertheless, confidence about the future of DSS was being maintained (McCown 2002a). Some scientists have suggested that crop–weather simulation models and their outputs are the starting point rather than the end point to decision making under uncertainty (Woodruff 1992) and, indeed Hammer et al. (2001) have suggested that DSS should signify 'Discussion support' rather than 'Decision support' because of their capacity to generate useful discussion among farmers about planting and crop management decisions in variable weather environments.

35.3.2 Modeling Applications in Australian Agriculture

Models used to simulate farming systems can be classified as biophysical models and economic models (Wegener 1994). Biophysical models can be and have been used to describe almost any aspect of the agricultural production system while models that have an economic orientation can be broadly classified as including those used to achieve economic efficiency in the allocation of resources and those used for risk analysis. In general, these risk analysis models help to identify risk-efficient farm plans from a range of alternatives with specific resource constraints.

Kingwell (1987) noted that simulation models of parts of farming systems in Australia have been constructed starting in the 1970s and 1980s. These models emphasised biophysical or biological relationships; some dealt with the interactions among various parts of the farming system, but they often ignored economic considerations and the management goals of farmers. However, models which included economic and managerial aspects of farming systems, e.g. Davis (1974), and Ockwell and Batterham (1982), often ignored important biological considerations and generally treated the complex biology of farming systems rather simply (Kingwell 1987).

The MIDAS (Model of an Integrated Dryland Agricultural System), a whole-farm mathematical programming model jointly describing biological, managerial, financial, and technical aspects of the dryland farming system, was developed in the mid-1980s (Kingwell and Pannell 1987). MIDAS did not originally address risk but a modified version MUDAS (Model of an Uncertain Dryland Agricultural System) was developed to do that. MUDAS was a discrete stochastic programming version of MIDAS that dealt with seasonal and price variability as well as with farmers' attitudes to income risk (Kingwell et al. 1991). This model has been used to assess the value of seasonal forecasting (Petersen 2001) together with farmer's attitudes to risk (Kingwell 1994) and crop selection (Kingwell et al. 1993).

At the field and farm level, discussion support tools based on simulation analyses have been available for some time to provide objective assessments of management alternatives for specific crops and locations (Keating and Meinke 1998). At the regional scale, studies to develop drought and land condition alerts have been undertaken (Carter and Brook 1996), while preliminary studies aimed at commodity forecasting at the national scale have also been conducted (Stephens 1996). The use of seasonal weather forecasting techniques to manage risk at the farm scale has been reported by many authors including Marshall et al. (1996) and Hammer et al. (2001). A number of other studies, e.g. Rimmington and Nicholls (1993) and Meinke and Hammer (1997), have analysed associations of agricultural system outputs with seasonal weather forecasts. At a generic level,[1] the RAINMAN program allows farmers or anyone affected by rainfall variability to generate their own localised probabilistic seasonal rainfall forecasts (Clewett et al. 2003).

Some decision support systems have included an attempt to address seasonal weather variability in a dynamic way. For example, SIRATAC (Hearn et al. 1981) and WHEATMAN (Woodruff 1992) have been part of research, development, and extension programs that have facilitated social interaction between researchers and farmers (Nelson et al. 2002). Meinke et al. (2001) described the use of participatory systems simulation approaches to increase profits and reduce risks in crop production enterprises.

Crop-weather simulation models have now been developed for most crops, and some are described in detail by McCown et al. (2002). CSIRO researchers have developed a range of decision support tools for extensive and semi-intensive agriculture in southern Australia (Moore et al. 2004).

The most comprehensive model of this type in Australia is APSIM (Agricultural Production Systems Simulator) which was developed to simulate biophysical processes associated with crop growth and development for a wide range of crops in response to daily weather inputs and soil conditions. These models can therefore generate yield estimates for a range of farming systems, and are particularly useful where there is interest in the economic and ecological outcomes of management practice in the face of variable weather inputs (Keating et al. 2003) (see also Chap. 37).

35.4 A Case Study of Rainfed Farming Systems in Queensland

This study in south-west Queensland investigated the sources of risk, current management strategies, and the attitudes of farmers towards risk management. This was followed by investigations into the feasibility of developing a program to improve the risk management abilities of local farmers, or a decision support system to help them make better decisions at crop planting time.

[1] This program can be used anywhere in Australia for which historic data is available.

Table 35.1 Mean seasonal and annual rainfall, and temperatures for selected centres in the study area

Centre	Summer (Oct–Mar) rainfall (mm)	Winter (Apr–Sept) rainfall (mm)	Mean annual rainfall (mm)	% Summer rainfall	Mean daily max temp °C	Mean daily min temp °C
Booringa Shire: Mitchell	382	186	568	67	27	12
Bungil Shire: Roma	394	205	599	66	28	13
Waroo Shire: Surat	379	201	579	65	28	13
Balonne shire St George	327	190	517	63	28	14
Waggamba Shire: Goondiwindi	385	236	622	62	27	13

35.4.1 Farming Systems and Farming Systems Research in the Study Area

The climate of the Balonne–Maranoa region of south-west Queensland has been described as sub-humid to semi-arid warm temperate (Reid et al. 1990). Low rainfall, high temperatures (Table 35.1) and high evaporation result in inadequate soil moisture for reliable crop production in most years; however, both summer and winter crops can be grown successfully if sufficient moisture is stored in the soil before planting to provide a buffer against moisture stress (Robinson 2004). Grain growing and beef cattle raising are the predominant farming activities in the region (Fig. 35.1).

This study was undertaken as part of the Western Farming Systems (WFS) project conducted by QDPI&F[2] staff in the region. The vision for the WFS project was to improve research outcomes and farm decision making by fostering a partnership between the farming community and the research project team, and encouraging all parties to learn from each other. Each season, QDPI&F staff in the region held a series of discussion meetings with groups of local farmers to assess how the crops in the area had performed; it was at one of these meetings that the possibility of conducting the risk management project was discussed.

In the past, the use of crop simulation modelling in the area had been restricted to an assessment by Hammer et al. (1987) who used simulation modelling to assess average wheat yields and annual variability of yield at various locations in south-west Queensland. The results from their study indicated that crop yields were sufficiently high and consistent to support a permanent grains industry in the area. Probert et al. (1996) simulated soil conditions and crop yields for several treatments in a field experiment at Warra, adjacent to the study area. The APSIM model used in those simulations satisfactorily reproduced the accumulation of total soil water

[2] Queensland Department of Primary Industries and Fisheries.

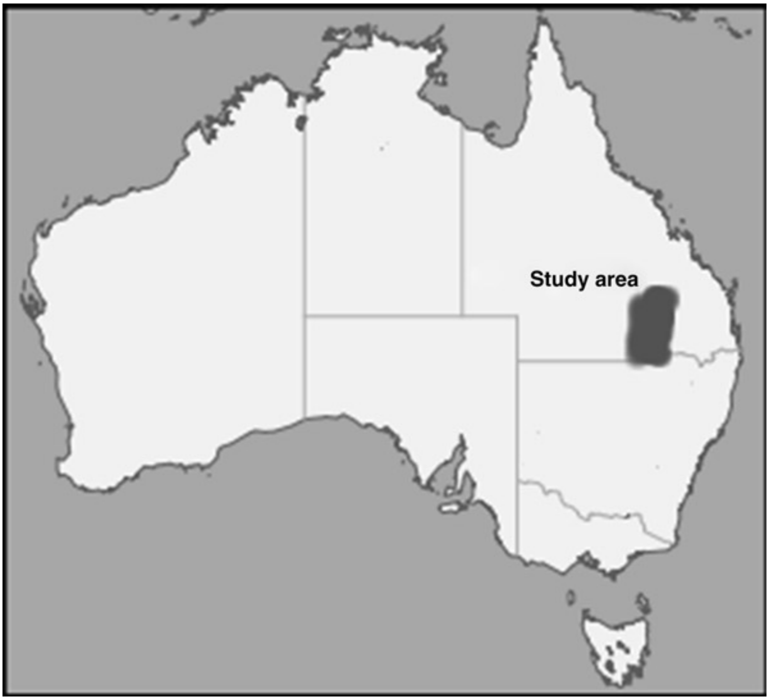

Fig. 35.1 Study area—Queensland, Australia (Source: modified from Nguyen (2007))

and total soil nitrate during the summer fallow periods. Other simulation experiments have defined likely benefits from new farming practices, such as reduced tillage and ley farming (Connolly et al. 1998) which are currently under trial in the Balonne–Maranoa region.

35.4.2 The Study

For the sake of brevity, this section only reports key results of the study. Detailed results have been reported in other papers (Nguyen et al. 2005, 2006a, b, 2007a, b); and a comprehensive report of the study is presented in Nguyen's Ph.D. thesis held at The University of Queensland (Nguyen 2007). These publications can be accessed via the following link: www.uq.edu.au/uqresearchers/researcher/nguyennc.html.

35.4.2.1 Preliminary Interviews

In 2004, some semi-structured interviews were conducted with five researchers from state and federal agricultural institutions, and with a group of crop/livestock farmers from the study area, to develop a better understanding of the risk management problems they faced.

The researchers interviewed understood that few formal 'tools' such as models, or information derived from modeling, were used by farmers to manage risks. They suggested that several risk management strategies being used by Queensland rainfed farmers included maintaining a high level of equity, keeping overhead costs low, reinvesting profits into the farm business, diversifying activities, using conservative nitrogen fertiliser rates combined with the use of long fallows to accumulate soil moisture prior to planting.

The farmers interviewed suggested that risk was difficult to identify. "Getting the timing right" (with respect to farming operations) was emphasised as the essential strategy in risk management and making decisions. Timeliness was clearly important as one farmer stressed: "Every time it rains, it brings income opportunities". Another farmer added: "Sometimes doing the right thing is not as important as doing it at the right time". Experience and preferences were considered important in decision making, especially for decisions regarding crop planting. Generally, production risks were mentioned as the main type of farming risk—driven by weather variability. Other sources of farming risk (e.g. financial, marketing, and institutional risks) were mentioned, but the main concerns were what to grow and when to plant.

35.4.2.2 Focus Group Discussions

The main objectives of the two focus group[3] discussions held in Roma (centre of the study area) were to explore the issues involved in risk management more closely, identify what risks farmers face, and learn how they deal with them. In addition, it was hoped that we could assess farmers' needs in relation to risk management and decision support tools and learn how these needs might be met.

Weather variability (which contributes to production risk) was considered the most important source of risk, but other risks including those associated with financial arrangements, government policy, and product marketing were also mentioned.

The range of strategies that these farmers used to manage the various sources of risk included conservation of soil moisture, zero till planting, and enterprise diversification (running cattle or sheep as well as growing crops). Much attention was given to managing the agronomic package (soil moisture, variety, cropping options, planting windows) and concern was expressed about the need to educate young farmers appropriately. Conservation of soil moisture was the most important priority for these dryland farmers, and "getting the time right" was emphasised as the essential element in risk management and making decisions. With regard to managing financial risks, good business management was a relevant strategy, and interest rates were regarded as controllable. It was generally acknowledged that marketing

[3] Total 16 participants selected from a list of farmers representative of the area by QDPI&F staff.

should be “left to experts”; however, only part of farm produce should be sold at any one time. Diversification and generating off-farm income were other risk management strategies. Managing the risk of changing government policies was considered to be “outside their control”.

In summary, the focus group discussions revealed that soil moisture management and crop choice were the topics of most concern to these farmers, and the research team concluded that it would be useful if participants had a tool that could help them assess how much water was stored in the soil and understand how to use it most effectively. This involves choosing the most appropriate crop at planting time to make most effective use of available soil water. It appeared that some decision support tools could be useful to these farmers to help them assess crop planting options in this very risky farming environment.

35.4.2.3 Expert Survey

Questionnaires about designing decision support systems (DSS) and their adoption by farmers were emailed to 23 DSS specialists working in universities and research and extension organisations in Australia. The intention was to gather their experience and to ask for suggestions about developing a decision support system for farmers in the study area.

Generally, respondents agreed that the issues which had been identified (soil moisture and crop choice) were critical to managing risk in rainfed farming systems but many reasons were given to explain the slow uptake of DSS by farmers. It was noted that farmers can make good decisions without using a DSS, and many farmers are not computer-oriented—although not all DDS are computer-driven. The dominant reason given for this failure to take up the technology was that most DSS are not well designed and are too complex, while farmers deal with the issues that concern them in different ways to researchers. Many DSS were regarded as too general and not specific to each farmer’s own circumstances. Farmers are often short of time to learn how to use a DSS, and these products have not been well marketed.

The future prospects for the development of DSS for Australian farmers were regarded as poor, as had been predicted in the literature (Hayman 2004). Nevertheless, some experts optimistically believed that useful DSS would be adopted, consistent with the conclusions from well-known DSS specialists (Hammer et al. 2001; McCown 2002b; Robinson 2004). While currently-available DSS might not meet the needs of farmers, it was thought that they could meet the needs of undergraduate students in universities who needed to learn about and understand farming systems.

To improve the adoption rate for DSS, the specialists recommended that widespread and serious problems need to be addressed—rather than trivial issues. The products developed should be location-specific, with strong support from initial users. Relevance, simplicity, effectiveness, and low cost were regarded as key attributes, and products other than computer-based programs should be considered. Most importantly, end-users need to be closely involved in the development of any DSS.

Although the prospects for the development of DSS are generally predicted to be poor, new DSS having appropriate attributes and developed according to suggested pathways could still be widely accepted. Farmers' personalities and their attitudes towards risk management and decision making will play an important role in deciding the adoption rate of DSS, but the intergenerational change underway in Australian farm ownership must also influence the pattern of adoption of computer-based management aids (Plowman et al. 2004; Foskey 2005). As younger and better-educated managers take over farm businesses, DSS might play a greater role in farmers' decision-making processes.

35.4.2.4 Decision Support Systems Workshops

Workshops were held to introduce several risk management and decision support tools to the group of local farmers who had indicated their willingness to participate in this part of the study. These tools included *Howwet?* and *Howoften?* (Freebairn et al. 2002), *WhopperCropper* (Cox et al. 2003), and *Yield Prophet* (GRDC 2005). The main objectives for these workshops were to improve farmers' knowledge about soil moisture management, to provide them with knowledge to help them make better planting decisions, and to assess the usefulness and usability of these tools, as a guide to the design of a planting decision support tool.

Workshop participants identified nine pieces of information essential for making planting decisions. These included stored soil moisture, soil conditions (soil type, texture, profile), the length of the planting window, climate outlook, crop rotation, weeds present, financial situation, and disease incidence. All of this information did not need to be memorised and could be obtained from external sources (e.g. QDPI&F Crop Notes). Participants also listed many other factors that influence their choice of summer and winter crops.

Any tool to assist with planting decisions should include the main cropping options of wheat, chickpeas, and sorghum, but pasture, barley, sunflower, lablab, and mungbeans were also mentioned.

The participants felt that attending the workshops had improved their ability to choose which crops to plant and when to plant them. They had a better appreciation of factors influencing crop choice, and had learned to analyse different starting conditions and seasonal weather forecasts.

35.4.2.5 Seasonal Climate Risk Workshops

Two workshops were conducted to discuss the 2006 winter climate forecasts and crop outlook. Other objectives were to present the latest findings in climate research in regard to the Southern Oscillation Index (SOI) and the Madden–Julian Oscillation (MJO) and to discuss various issues including soil water, nitrogen, and climate risk with participants (22 farmers and seven consultants).

Participants at these workshops listed the climate indicators/tools that they were using and discussed their usefulness. They considered that the best indicator of crop performance in the coming season was soil moisture in the field at planting time. Generally, participants agreed that the problem with weather forecasting tools was that "accuracy needs to be improved".

Most workshop participants said that they based their planting decisions on historical data and their 'gut feel' to make a planting decision. They look upon the planting decision as something that is akin to an art. Only a couple of participants said that they had used one or more of the available tools (such as WhopperCropper) to assist their decision making, while the others claimed various reasons that prevented them from using decision support tools.

Generally, participants stated that decision support tools could not make the decision for them; however, they would like the tools to produce information, or some guidelines, that they could use as a basis for making their own decisions.

35.4.2.6 Designing a Decision Support System

After this series of interactions with the farmer group, a decision support tool ('Key to dryland planting decisions') for rainfed farmers in south-west Queensland was developed. It uses Lucid3 software (CBIT 2006) to capture the timing and logic of the decision-making process and to structure it to select preferred crop planting options for both summer and winter planting periods. It also takes into account many of the factors that were identified by the farmers as influencing their decision. A description of the use and application of the tool can be viewed on the Internet (Nguyen et al. 2007), and it can be used without cost.

The developers (and authors of this chapter) had been 'working closely' with a volunteer group of farmers from the Roma area through the whole process of assessing the need for the tool, through the design of it, to its initial testing. The farmers contributed significantly to the input data that were used to build the tool. Input data applicable to the study area were also included from other sources.

The tool was developed to be 'very simple' and 'quick-to-use'. Even users with very low-level computer skills can use the tool. In addition, most of the input data for the key were either provided by local farmers or collected from the QDPI&F website. Therefore, it can be assumed that these data were relevant and applicable to the study area. This enables the key to be 'location specific'.

At a follow-up workshop, a participant said "This is a tool which is very much needed in dryland farming systems", while others said that it was "a fairly easy program to use with the basic information that may be helpful".

A prototype has been produced that could be developed further by one of the institutions involved in the WFS project.

35.5 Conclusion

Most farmers are risk-averse and they often use 'rules of thumb' in making their management decisions—which tends to limit them to a range of options that they have used before. Experience and preferences (based on precedent) were regarded as important elements in their decision-making process. Obviously, managing risk in agriculture does not necessarily involve avoiding risk. It involves finding the best available combination of risk and return, given the farmer's capacity to cope with a wide range of outcomes. Indeed, most farmers combine many of the different strategies and tools available to them. In other words, they rely on a mix of strategies to manage risk.

By following the principles advocated for the development of DSS likely to be used by farmers, the authors were able to produce an aid to making planting decisions for rainfed farmers in south-west Queensland. Limited testing within the scope of funds and the time available with the group of farmers who were involved in its development suggested that the tool met the farmers' need for a quick, simple way to assess summer and winter crop planting options during the planting window.[4] A prototype has been developed that should be tested further across rainfed farming areas of Queensland.

Acknowledgement The authors are grateful to Professor David Pannell and the editors of this book for their suggestions and constructive comments on the draft of this chapter. We would like to thank Ms. Katherine Snars and Mr. Richard Routley for their assistance in conducting the initial meeting with the farmers. We also thank Dr. David Freebairn, Mr. Norman Gurner, Mr. Howard Cox, and the WFS project team (including Mr. Nick Christodoulou, Dr. Daniel Rodriguez, Mr. Allan Peake, and Ms. Lexie Donald) for their contributions to the various workshops. Our sincere thanks also go to Dr. Geoff Norton and Mr. Matt Taylor for their help and advice with the Lucid3 software. All of the farmers, researchers, and other experts who participated in this study are acknowledged for being involved so willingly in the preliminary interviews, focus group discussions, survey, and workshops. This study had financial assistance from an International Postgraduate Research Scholarship (IPRS) at The University of Queensland and the WFS project.

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Part IV
Research, Extension and Evolution in Rainfed Farming Systems

Part IV deals with farming situations where research, development and extension (RDE) are combined.

Chapter 36 discusses the progression from the earlier ‘component systems approach’ to agricultural research and development to the more recent ‘participatory systems’ approach where participants include not only policy makers and researchers but also farmers, consultants and commercial company representatives. Others in the community are involved in planning and evaluating RDE programs.

Chapter 37 provides an example of present-day participatory systems RDE in which researchers, farmers, and consultants work together to solve local farming problems and improve the performance of their farming systems.

In contrast, Chap. 38 moves to subsistence agriculture in Tanzania where science, research and modern technology play virtually no part in agricultural production. Here, development is strongly linked to, and often held back by, local culture and tradition. The chapter explains some attempts (successful and unsuccessful) to improve farming and farming systems under these conditions.

Chapter 39 shows the impressive progress made in economies where full use is made of science, research and modern technology in the development and adoption of no-till and conservation farming. It provides details and describes progress of this revolution in soil management.

Progress in use of no-till is much slower in developing countries where resources, education and training are lacking. This is shown for the West Asia–North Africa (WANA) region in Chap. 40 despite widespread research and results supporting the use of conservation agriculture.

Chapter 36
The Emergence of 'Farming Systems' Approaches to Grains Research, Development and Extension

David Lawrence

Abstract A systems approach is needed to understand and manage a 'farm'. Research, development and extension (RDE) professionals should therefore understand 'systems approaches' to ensure their work is relevant and supports farm managers to adapt to change. Participatory systems approaches, such as Farming Systems RDE, have been used in developing countries but are now emerging in developed economies, including Australia. These modern approaches place farmers and their advisers within the boundaries of the farming system and represent an increasing proportion of national RDE funding, despite a scarcity of data to support their effectiveness in developed economies. Evaluations are now providing evidence of the impact of systems projects and their ability to address issues that have eluded traditional Transfer-of-Technology approaches. However, these evaluations conclude that systems approaches are not simple blueprints for success and must be developed to meet local conditions. Practitioners must first understand the underlying concepts of systems, diversity, participation and learning. Ultimately, scientists and farmers must learn to participate together at high enough levels to learn from each other and so fully utilise their diversity of expertise and resources.

Keywords Farming systems • Participation • Diversity • Learning • Research • Development • Extension • Transfer-of-technology

36.1 Introduction

Chapter 1 concludes that a systems approach is needed to understand and manage a 'farm'. Consequently, research and extension professionals must also recognise and understand 'systems approaches' to deal with the complexities of farm

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_36,

management. Research must be relevant, value the knowledge of farm managers and support decisions to make farms and agriculture in general more productive and sustainable.

36.1.1 Transfer-of-Technology Approaches to Research, Development and Extension

Research Development and Extension (RDE) has a long history of innovation to produce more food for the world. This RDE has traditionally been conducted within the Transfer-of-technology (ToT) paradigm, that is, research has been conducted in controlled settings and the results *extended* to the farming community to use on their farms. Consequently, agricultural extension developed and became a process to provide information, opportunity and persuasion to gain the voluntary 'adoption' of new practices that were often developed in a different environment (Bloome 1991). Each innovation is expected to 'diffuse' throughout the community as it is 'adopted' by other farmers (Rogers 1983).

This ToT approach to RDE has achieved rapid use of technologies that have direct financial benefits, minimal complexity, acceptable risk, and that are easily integrated into existing practices (Marsh 1998). However, this approach to innovation has been less successful when issues are complex, or when people have different understandings of the problem situation (Ridley 2005; Vanclay 2004). For example, farmers may place value on different factors to scientists and may not recognise the same problems; or they may recognise a problem but need specific information about it for their own situations; or they may require different solutions to those prescribed. This is most common where there are no apparent 'win-win' technological solutions, or where there are competing land-use decisions that must balance productivity and environmental concerns in modern farming landscapes (Ridley 2005).

In these complex or conflicted situations, the traditional ToT approach to RDE, creating awareness of new research findings and technologies, may fail to translate this awareness into understanding, or to transcend community barriers to achieve change (Blacket 1996). Consequently, most reviews of agricultural RDE have concluded that ToT approaches alone are inadequate to deal with our modern agricultural systems (Packham 2003; Russell et al. 1989).

In Australia, this realisation has created debate for the last decade amongst RDE agencies and funders about the role and effectiveness of extension, and agricultural RDE in general (Coutts 1994; Hamilton 1995). The debate is directed by the reduced importance of agriculture in the economy of developed countries, subsequent reductions in public expenditure for agricultural RDE and a focus on services with community benefits rather than the direct 'private' benefits that traditional advisory services emphasised (Black 2000). These factors reinforce the need for continued innovation in RDE to support improvements in farming practices with potentially reduced public resources. RDE agencies have typically responded to this need by proposing more participation by farmers and the wider community in the RDE process (Vanclay and Lawrence 1995; Dart 2005).

36.1.2 Participatory Approaches to Research, Development and Extension

Agricultural scientists have historically wanted to maintain precision and control in their research until a new technology was ‘ready’ for farmers to ‘verify’ and use (Stroud and Kirkby 2000). Indeed, research that gives reliable results is also valued by farmers and the wider community. However, participatory RDE is proposed in order to help farmers and scientists learn together to conduct more relevant research and to pool their experiences, to consider the practical aspects of implementing innovations (McCown 2001a). For example, grains research highlighted the need for higher nitrogen fertiliser rates in northern Australia, but many farmers required assistance through extension to understand how to make their fertiliser decisions and assess these decisions in a variable climate that may produce good and poor outcomes in any season (Henzell and Daniels 1995; Lawrence et al. 2000).

This focus on participation and learning in agricultural RDE is not just an Australian phenomenon. It has emerged globally as international development agencies grapple with the notion of sustainable development and the possible trade-offs between ecological, economic and social sustainability (Dixon 2003; Gibbon 2003). Australian theorists draw upon international experiences to support the use of ‘Farming Systems’ approaches, such as ‘Farming Systems Research’ and ‘Participatory Action Research’ (Carberry 2001; Guerin and Guerin 1994; McCown 2001a; Petheram and Clark 1998; Ridley 2005):

- **Farming Systems Research (FSR)** provides a diagnostic process, and an approach to research and development that uses a range of methods to elicit a better understanding of farm households, their decisions and decision-making processes (Collinson 2000). The biophysical structure of a farm is not omitted from this process but is included as part of an overall focus on improved farm management decisions and practices.
- **Participatory Action Research (PAR)** is action research in which scientists, farmers and their advisers become collaborators to jointly plan, act, observe and reflect on their research (Zuber-Skerritt 2000). Consequently, PAR produces knowledge and modifies situations *as part of* the research process in contrast to the predominant ‘policy research’ of the ToT paradigm that produces knowledge before it is modified in practice and extended (McCown 2001b; Onquist 1978). Opportunities to contribute to the planning and interpretation of research will encourage inter-dependent rather than independent activities. However, PAR must avoid the ‘lowest common denominator’ that may result from forcing consensus on each aspect of each person’s activities (Lawrence 2006).

Early Farming Systems Research was developed within International Research Centres in the 1960s, as their technological solutions were recognised as inappropriate for the priorities and circumstances of small farmers in developing countries (Packham 2003). These farmers often lacked the expertise or capital to apply the proposed new technologies (Gibbon 2003). Even today, planting crops in rows and using herbicides for weed control present challenges for some poor rural villagers

(Lawrence et al. 2007). Farming systems approaches have since evolved and taken a broader and more socially sensitive perspective. Key developments have been:

- getting off research stations and conducting on-farm research in farmers own paddocks to make the research more relevant to local contexts with all their constraints;
- using PAR to facilitate farmer participation and learning in the planning and interpretation of RDE activities (Dixon 2003; Pretty 1995).

Consequently, modern Farming Systems RDE has become a participatory process that may incorporate any type of inquiry considered appropriate by the participants, be they methodologies from applied social, economic or biological science, hard science or even basic science in which the details must be planned by experts (Petheram and Clark 1998). Such 'Farming Systems RDE' projects now use a significant proportion of Australian national research and development funding and have recently accounted for 20% of the Grains Research and Development Corporation's annual budget of over AUD $110 million (Lovett 2003).

Yet, participatory farming systems approaches are not complete blueprints for success. Farming systems researchers must first understand the underlying concepts of these approaches and their limitations to plan and use the most effective RDE methods for their own systems (Packham 2003). This challenge and a scarcity of data to support the effectiveness of participatory processes in Australia may explain the continued dominance of the ToT paradigm in most RDE agencies, despite its perceived limitations (Carberry 2004; Guerin and Guerin 1994). Indeed, even in 'participatory' farming systems projects, the way that scientists and farmers participate varies from groups of farmers running trials that involve local advisers, to formal programs run by technical specialists who seek farmer participation to contribute and evaluate ideas from research stations, models or farms (Petheram and Clark 1998).

This chapter aims to explain how systems thinking, participation, and learning—the enduring elements of modern participatory Farming Systems RDE (Gibbon 2003; Packham 2003; Petheram and Clark 1998); may be used in multi-disciplinary (diverse) projects with scientists, farmers and their advisers. The chapter also draws upon experiences from Farming Systems projects in the grains industry of northern Australia (Lawrence 2006) to highlight some potential benefits and challenges of using the participatory systems approaches in a developed economy.

36.2 Systems and Systems Thinking

'Systems' and 'systems thinking' are key concepts in Farming Systems approaches. These terms are now ubiquitous in the FSR literature. However, they have also been devalued, as people often neglect to clarify what they mean by them (Checkland 1992; Packham 2003). This section builds on the definitions provided in Chap. 1 to review the changing meanings of 'systems' and how 'systems thinking' has been applied during the evolution towards modern systems approaches.

36.2.1 Defining ‘Systems’

Dyer (1993) defines a system as *an assembly of components connected together in an organised way; the components are affected by being in the system and are changed if they leave it. The assembly of components does something, and the assembly has been identified by a human being as being of interest* (p. 408). As such, systems thinking can be described as considering a part in detail while keeping the whole in focus (Mant 1977). However, systems are also situations perceived by people (Flood and Jackson 1991) and are ultimately constructs of the mind (Packham 2003). Choosing the system of interest, its boundaries, and the level of detail are subjective and value-laden judgments (Hayman 2001). Consequently, research agronomists may focus on optimising biophysical relationships whereas a farm manager may also have to balance economic and social pressures and select practices with less than optimal technical solutions. An obvious example is cash flow problems precluding some farm managers from applying optimal fertiliser rates to maximise their returns. As discussed in Chap. 1, it is therefore critical to draw a clear and transparent boundary around the system of interest for a particular purpose.

Three lines of systems thinking are evident in the ways agricultural researchers define systems (Hayman 2001):

1. ‘hard systems’ approaches from the natural sciences to understand and describe a phenomenon
2. ‘hard systems’ approaches from the applied sciences of management, engineering and operational research to discover how to manage it
3. ‘soft’ systems approaches from the social sciences to explore people’s different perspectives of the phenomenon.

These lines of systems thinking reflect the evolution of Farming Systems RDE already described. Early FSR was based on natural sciences and a hard systems approach in which scientists helped farmers by identifying the optimal farming systems and combinations of practices for them to use (Checkland 1985). This approach provides a more detailed description of the farming phenomenon by considering the external and wider systems factors that influence it, but the emphasis remains on improving scientists’ understanding (Bentley 1994).

The second line of thinking emphasises management and operational research to use the outcomes of research efficiently. It aims to understand how to implement the subsequent recommended practices.

Finally, the third line of thinking aims for greater farmer participation and encourages a soft systems approach to understand and improve farming rather than to optimise inputs and outcomes. This acknowledges that scientists, farmers and others may have different perceptions of situations, and that these perceptions may drive their individual farming decisions. Indeed, farmers are part of the farming system and Farming Systems approaches must provide a better understanding of their perceptions and values to be effective. Ultimately, farmers are not an external influence and must be considered within the boundaries of the farming system if RDE is to improve farm management (Christodoulou 2000).

36.2.2 Placing People Within Farming 'Systems'

This evolution of systems thinking reflects the increasingly broad framing of farming systems. The modern participatory Farming Systems RDE being developed in Australia extends beyond biophysical issues to include farm management issues and the social aspects of agricultural practice, such as labour requirements and information networks (Hamilton 1995). The participatory Grains RDE projects developed in northern Australia since the late 1990s have provided increased opportunities for farmers and their advisers to participate together in the development and strategic management of projects. The vision of these projects has been to develop farming systems that have benefited from farmers, advisers and researchers exploring together options for improved economic and environmental sustainability (Carberry 1997). This recognises that agriculture is a complex social process, not just a complex, diverse and risky technical activity (Scoones and Thompson 1994). People are part of farming systems and their views cannot be ignored.

36.2.3 Increasing Diversity with Participatory 'Farming Systems' Approaches

Participatory approaches will implicitly increase the diversity of people involved. This diversity (Lawrence 2006) may be described in terms of the group's:

1. *demographic diversity*—age, gender, location
2. *organisational diversity*—employer, hierarchical status, occupation
3. *informational diversity*—knowledge, experience, skills
4. *values diversity*—attitudes and beliefs about the group's vision and aims.

Farming systems projects that involve farmers, their advisers and a multidisciplinary range of RDE scientists will increase the opportunities for learning from the additional skills and knowledge available (Tziner and Eden 1985). However, such diverse work groups do not always lead to improved learning and performance. Indeed, the potential cognitive benefits of increased knowledge and skills are typically overwhelmed by the negative relationships and consequent conflicts that arise (Williams and O'Reilly 1998).

Ultimately, the impact of a participatory farming systems approach depends on how well project members deal with their diversity and potential conflict, that is, how team members participate with each other. Project teams, but especially project leaders, must therefore understand the key notion of participation to conduct effective Farming Systems projects.

36.3 The Notion of Participation in Farming Systems Projects

Stakeholder participation in the RDE process has become an underlying tenet of the modern Farming Systems approach. However, directives from RDE funders for a range of scientists and farmers to work together in teams will not guarantee cooperation (Johnson and Johnson 1997). Managers of Farming Systems projects must understand participation and use appropriate methods to encourage the participation of both farmers and scientists in RDE.

Farming Systems approaches in Australia aim to increase participation between the research and extension disciplines, participation between the different RDE agencies involved but, above all, they aim to increase farmers' participation in RDE processes. This aim has wide support (Black 2000) because *the idea of citizen participation is a little like eating spinach: no one is against it in principle because it is good for you* (Arnstein 1969). However, the extent to which farmers and scientists participate with each other may not match the rhetoric. This paradox arises because RDE agencies both need and fear people's participation. They need people's agreement and support, but fear that this wider involvement is less controllable, less precise, and so likely to slow down planning and progress (Pretty 1995).

The contrasting emphasis placed on both the need for participation and the fear of its consequences underpins the two major views on how to use participation in farming systems projects. Both of these views involve people in the planning and implementation of RDE programs. They differ in that:

1. one regards participation as a means to increase (RDE) efficiency, the central notion being that if people are involved, then they are more likely to agree with and support the new development or service
2. the other sees participation as a fundamental right, in which the main aim is to initiate mobilisation for collective action, empowerment and institution building (Pretty 1995, p. 1251).

The efficiency view predominates in agricultural RDE projects. So, while most projects say participation is part of their work, for local farmers this may simply mean having discussions or providing information to the RDE agencies—not sharing in major project decisions (Guijt 1991). Consequently, the term 'participation' should not be accepted without appropriate clarification.

Pretty's (1995) typology of participation is the most widely used in agricultural RDE. This typology, as outlined in Table 36.1, identifies seven types of participation that develop in RDE projects. These range from manipulative and passive participation where farmers are told by agencies what is to happen, to interactive participation and self-mobilisation in which farmers take initiatives largely independent of the RDE institutions.

There is a lack of farmer influence in the first four types of participation in Table 36.1. In these, farmers are essentially passive recipients of information in

Table 36.1 A typology of participation in agricultural research, development and extension

Typology	Characteristics of each type
1. Manipulative participation	Participation is simply a pretence with 'people's' representatives on official boards who are unelected and have no power.
2. Passive participation	People participate by being told what has been decided or has already happened. It involves unilateral announcements by administrators or project management without any listening to people's responses. The information being shared belongs only to external professionals.
3. Participation by consultation	People participate by being consulted or by answering questions. External agents define problems and information gathering processes, and so control analysis. Such a consultative process does not concede any share in decision-making, and professionals are under no obligation to take on board people's views.
4. Participation for material incentives	People participate by contributing resources, for example labour, in return for food, cash or other material incentives. Farmers may provide the fields and labour, but are involved in neither experimentation nor the process of learning. It is very common to see this called participation, yet people have no stake in prolonging technologies or practices when the incentives end.
5. Functional participation	Participation is seen by external agencies as a means to achieve project goals, especially reduced costs. People may participate by forming groups to meet predetermined objectives related to the project. Such involvement may be interactive and involve shared decision-making, but tends to arise only after major decisions have already been made by external agents. At worst, local people may still only be co-opted to serve external goals.
6. Interactive participation	People participate in joint analysis, development of action plans and formation or strengthening of local institutions. Participation is seen as a right, not just the means to achieve project goals. The process involves interdisciplinary methodologies that seek multiple perspectives and make use of systemic and structured learning processes. As groups take control over local decisions and determine how available resources are used, so they have a stake in maintaining structures or practices.
7. Self-mobilisation	People participate by taking initiatives independently of external institutions to change systems. They develop contacts with external institutions for resources and technical advice they need, but retain control over how resources are used. Self-mobilisation can spread if governments and non-government organisations provide an enabling framework of support. Such self-initiated mobilisation may or may not challenge existing distributions of wealth and power.

manipulative and passive participation, informants in consultative participation, or paid labourers. They have no direct control over decisions, and these types of participation may best be called types of non-participation (Arnstein 1969). Such participation may have no positive lasting effect on people's lives (Rahnema 1992). For example, subsidies to encourage more sustainable farming practices may not guarantee their continued use once the subsidies are removed.

'Self-mobilisation' (No. 7 in Table 36.1) is needed for sustainable development because it develops the capacity for on-going change in the farming community (Pretty 1995). However, two other types of participation may bridge the gap between the forms of 'non-participation' and 'self-mobilisation'. The first, 'functional' participation (No. 5) gives farmers the opportunity for joint decision-making, but only after external agencies have made the major decisions. Consequently, farmers are still participating to meet the pre-determined needs of the RDE agencies. For instance, farmers may participate to decide the key research questions for research projects to address. This may be most beneficial when the needs of the RDE agencies and farmers are not in conflict (Flood and Jackson 1991). However, 'interactive' participation (No. 6) views participation as a right and uses the diversity of participants in joint analysis to develop action plans for sustainable development.

This book on Rainfed Farming Systems asserts that a systems approach is needed to understand and manage a 'farm'. This chapter highlights systems approaches that have developed in agricultural RDE over the last 50 years to better support farm management. They have evolved to become more participatory and to include people within the boundaries of the farming system. This trend recognises that universal technical solutions are rarely adopted without adaptation and that farmers must ultimately develop solutions for their own situations. Consequently, modern farming systems approaches propose participatory processes that support researchers, extension workers, farmers, advisers, and other community members to learn from each other, and develop a capacity for on-going adaptation on farms.

The following case study shows how greater farmer participation can improve the efficiency of RDE and support major changes in local farming practices. However, understanding 'participation' and developing RDE processes that include joint analysis of problems and equal decision-making power for participants remain major challenges for sustainable development.

36.4 Case Example: Farming Systems RDE in the Northern Grains Industries of Australia

This case study discusses three Farming Systems projects in the northern grains region of Australia.[1] This region extends across 1,000 km from the Emerald district of central Queensland, south to Dubbo in central New South Wales. Rainfall ranges from 500 to 700 mm, with 60–70% falling in summer. Summer rainfall dominance over winter rainfall increases from south to north. Mixed farming systems of broadacre crops with beef in the north and sheep in the south predominate. Cropping is based primarily on vertosols—deep, clay soils that can store between 100 and 200 mm

[1] Further information on this region can be found in Chap. 25.

of soil moisture during fallows to improve the reliability of cropping. Grain production is based on sorghum, winter cereals and increasing areas of summer and winter grain legumes.

The **Western Farming Systems project**, the **Eastern Farming Systems project** and the **Central Queensland Farming Systems project** were each initiated in 1995 with the common goal of sustainable development. They aimed to develop more profitable and sustainable farming systems across the northern grains region through a partnership between local RDE agencies, farmers and commercial agri-business. However, for sustainable development this partnership aimed to improve understanding of issues, and application of technologies by farmers. It also aimed to improve RDE processes for learning between scientists and farmers that would improve their capacity for on-going change on farms.

The projects were supported by several State and Federal RDE agencies and the Australian Grains Research and Development Corporation that collects industry levies to fund RDE. These projects attempted to engage the grains industry across large areas. For example, the Eastern Farming Systems project area contained over 4,000 farmers with more than 2 million hectares of cultivation for grains production. Project members were located across each project area to engage with local farmers and their commercial agronomic advisers.

The projects spanned the research, extension and management disciplines. Each project involved up to 20 men and women at up to 10 locations that were often hundreds of kilometres apart. These staff provided technical expertise in broadacre crops, pastures, soil fertility, soil conservation, animal husbandry, economics, and crop simulation modeling. Activities spanned a wide range of methods and methodologies: traditional small-plot field experiments; large-scale participatory on-farm research with farmers; group-based learning and training activities with farmers and commercial agronomists; and the development of decision-support tools using crop simulation models to assess future scenarios (Martin et al. 1996). Participation of farmers and commercial agronomists was formalised. For example, the management committee of the Eastern Farming Systems project comprised eight people: a representative of each of the four participating RDE agencies, and a farmer or commercial agronomist representative from each of the grain industries' four research advisory committees in the region. This project management committee was responsible for strategic planning and provided all participants with direct decision-making power through reviews of the project and its core activities every 6–12 months.

Similarly, each of the project's on-farm research activities required that the project team and participating farmers develop specific research questions from their general 'issues' of interest, and review results annually with these farmers and the wider team. To clarify participants' knowledge before developing a research question, each participant was asked to document (Lawrence et al. 2007):

1. What is your issue?
2. Why is it important to you?
3. What do you already know about it?

4. What else do you want to know?
5. What is the most critical information you want to know?

An iterative process for the group to consider and discuss the specific object of the research, the boundaries of the research, and the likely measures needed led to general issues being refined to increasingly specific research questions. For example (Lawrence et al. 2007):

- Issue: Earliness in Bollgard® (Heliothus-resistant) cotton
- Question attempt one: Is the earliness of Bollgard® cotton affected by early season insect damage?
- Question attempt two: What is the effect of early-season insect damage on the earliness of Bollgard® cotton in the St. George district?
- Question attempt three: What is the effect of early-season sucking insect damage on the time to maturity of Bollgard® cotton in the St. George district?

This focus on shared research questions and annual reviews provided opportunity for all participants to contribute their knowledge and insights (Lawrence 2006).

36.4.1 Project Evaluation

An explicit evaluation of these projects confirms that their 'systems approach' has advanced beyond rhetoric to enhance participation, support learning and improve the on-ground management of issues that have eluded traditional RDE (Lawrence 2006). The activities of each project directly involved between 300 and 800 farmers and commercial agronomists as participants. The evaluation showed that a majority of participating farmers believed the projects have 'improved how research and extension was done'. Much of this improvement was attributed to:

- the project teams providing increased opportunities for farmers to participate in the planning and review of activities
- the subsequent learning that helped farmers understand key agronomic principles and make more informed management decisions.

Furthermore, participatory on-farm research supported farmers to test general agronomic principles and practices such as nitrogen budgeting on their farms. The evaluation data show that 49% of farmers categorised the projects' impact on their knowledge of key technical issues as moderate, while 23% categorised this impact as large. These data suggest that the projects' emphasis on increased participation to support learning was successful.

This increased technical understanding and the project teams' support to apply this knowledge to authentic decisions had a major impact on participants' farming practices. Across all three projects, most participants (80%) believed they had improved their farming practices and that their farming had become more sustainable (77%) and more profitable (74%) as a result. The following evaluation data from the individual projects demonstrate how they have improved management of four key issues with on-farm practices that traditional RDE had been unable to achieve:

- **Minimising soil erosion with the use of zero tillage and controlled traffic in central Queensland**—The proportion of participating farmers' land under zero tillage (i.e. using herbicides rather than cultivation to control weeds and to maintain stubble and so reduce erosion) rose from 24% in 1996 to 77% in 2001. The number of participating farmers using zero tillage over this period rose from 48% to 95%. The increased proportion of land under controlled traffic to reduce compaction and improve the efficiency of paddock operations has been equally impressive, rising from 7% in 1996 to 53% in 2001. Again, the number of participating farmers using controlled traffic rose from 17% to 66%.
- **Nitrogen management in western Queensland**—The proportion of farmers using nitrogen fertilisers rose from 28% in 1995 to 72% in 2000, and their average application of nitrogen rose from 23 to 38 kg N/ha over this same period. These dramatic changes were pivotal in ensuring farmers matched their soil nutrients supply to the needs of summer and winter cereal crops as soil organic matter levels declined with long-term cropping in the region.
- **Ley pasture management in central Queensland**—The proportion of participating farmers using legume ley pastures to reduce the decline in soil organic matter and improve soil fertility increased from 20% in 1995 to 33% in 2000. Further, the surveys suggested that these impacts would continue as 60% of these farmers intended using ley pastures in the future. There had been no suitable legume species available in one region until the Central Queensland Farming Systems project team of scientists and farmers developed on-farm practices to improve management of the grazing legume, butterfly pea (*Clitoria ternatea*). In the space of 5 years, this little-used species was being grown by 21% of participating farmers' in the region. This has been a great advance for managing soil fertility in this mixed farming region as it provides an alternative to nitrogen fertilisers.
- **New crops and rotations in western Queensland**—Surveys show that the area of traditional crops (wheat, barley and sorghum) grown by farmers in the marginal cropping areas of western Queensland increased by 25% between 1995 and 2000. Yet, the area of other crops, such as canola, chickpea and mungbean increased by 560% and the proportion of participating farmers growing legume crops increased from 28% in 1995 to 48% in 2000. This diversification was a major achievement that has long been sought by RDE agencies to ensure more diverse, flexible and resilient cropping systems that were not based solely on cereal grains.

These four issues are important for sustainable grain production in the northern grains region and confirm the beneficial impacts of the farming systems projects on farming practices. These data show that RDE was improved by replacing passive participation and informal consultation with explicit farmer consultation to influence decision-making and support participatory learning between farmers and scientists.

Decision making was not shared equally and the project teams still had the final say. However, the data confirm the earlier assessments by farmers that the projects had improved their knowledge on key technical issues and had improved the profitability and sustainability of their practices.

Farmers recognised the increased participation and considered the subsequent RDE more relevant and effective. However, consultation does not ensure farmers' opinions are taken into account. Some farmers became frustrated when they felt their opinions were discounted in significant decisions. At times, some team members used consultation to manipulate on-farm research trials to meet their known personal interest. Indeed, an influential team member barely 'camouflaged' his participatory intent when he suggested that because the project's farmer groups were now working on all the scientists' priorities, they could let "*two new groups (of farmers in the project) identify their own issues…(and) go down the 'proper' approach of talking, talking, talking…let me know when the snow falls (lots of laughter)*." Despite such cynicism, each project provided increased opportunities for farmers to engage in real planning and decision-making of specific activities. Indeed, farmers' endorsement of the beneficial impacts of these processes on farming practices attested to the success of the projects.

Finally, these evaluations and subsequent whole-farm economic modeling of the three farming systems projects have compared farm profits and returns from using these new technologies earlier than they would have without the projects. The analyses show a direct benefit of up to $6 and a subsequent increase in economic activity of $11 for every $1 invested in the project (including labour costs, overheads, trial work and workshops). These analyses excluded any economic consideration of improved sustainability. Subsequent provision of a third round of funding, from 2007 to 2010, indicates that these rates of return are sufficient for the participating RDE agencies and industry funders.

36.4.2 Constraints to Using 'Farming Systems' Approaches

These evaluation data confirm that the farming systems projects increased participation and learning amongst the scientists and farmers. The diversity of project members' knowledge, interests and belief in participatory or transfer-of-technology paradigms of RDE provided many opportunities to learn from each other. However, this same diversity also constrained participation. Participation between scientists and between scientists and farmers broadened as individuals became part of a larger network, gained awareness of others' activities, consulted specialists in other agencies, and were exposed to different ideas on how to conduct RDE. Yet, levels of participation in the projects failed to reach 'interactive participation'—the sixth level of Pretty's typology of participation—or the ideals of joint analysis and equality of decision-making in project planning (Pretty 1995). Participation was enhanced but remained largely 'participation for better adoption' of the outcomes sought by RDE agencies rather than participation to empower all participants and support sustainable development.

Participation was observed to progress from the past isolation and passive approaches towards more consultation and functional involvement. However, there remained little joint analysis of problems or outcomes across the projects. The projects largely employed ‘hard’ systems analysis in a series of parallel multi-disciplinary activities for farmers. They did not become inter-disciplinary teams that sought multiple perspectives and reframing of problems through structured learning processes (Pretty 1995). Some teams-within-teams in each project developed interactive participation but these communities-of-practice typically attracted participants from their own organisations, with similar values and RDE paradigms. Indeed, their mostly positivist perspectives apparently constrained participation between these communities as each applied the ‘best’ methodology—their own—and passively informed others of their progress. This behaviour reflects the traditional transfer-of-technology paradigm of agricultural RDE.

This understanding may be valuable to develop new projects that progress further towards the potential of participatory systems approaches by:

- recruiting key staff with the understanding and experience in participatory processes
- developing a shared vision with clear roles and responsibilities for each organisation and its individual staff
- co-locating staff with major time commitments in the project area
- developing structured processes to support participation and learning opportunities for all staff.

However, the extent to which the current project teams can address these constraints and participate more effectively remains to be seen, as peoples’ long-held values, paradigms and worldviews are very resistant to change (Dick and Dalmau 1999).

36.5 Conclusions

Systems approaches in agricultural RDE have developed over the last 50 years to better support farm management and help farmers integrate the available knowledge and technologies on their farms. Initial hard-systems analyses developed optimal technical solutions for farmers but failed to gain the desired ‘adoption’ because they failed to account for individual farmer’s differing priorities and circumstances. Farming systems approaches have since evolved and taken a broader, more socially sensitive perspective. Key developments have been:

1. Conducting more research on farms, rather than on research stations, to make it more compatible with local contexts
2. Facilitating greater farmer participation and learning in the planning and interpretation of RDE activities.

Consequently, modern farming systems approaches propose participatory processes that support scientists and farmers working together, learning from each other, and developing an on-going capacity for change on farms.

Three projects in northern Australia confirm that more participatory systems approaches can improve learning and farming practices in a developed agriculture. Indeed, systems approaches have helped grains RDE to utilize more effectively the diversity in the knowledge and resources of farmers and scientists. Participation within each project team and between the teams and participating farmers was increased. This helped farmers and scientists improve their understanding of technical issues, the farm management and research processes, and each other's perceptions and priorities. RDE was subsequently more relevant and rigorous, and helped participants make more informed decisions for their own situations. There was a wide consensus amongst participants that a Farming Systems approach had improved grains RDE, and improved the profitability and sustainability of farming systems.

Highly participatory approaches are unlikely to replace traditional RDE in Australia in the foreseeable future. Participatory methodologies that use transfer-of-technology and other approaches, as appropriate, may be desirable. The diversity of participants and the prevailing transfer-of-technology paradigm in Australian agriculture makes a completely interactive participation in grains RDE difficult to envisage. The challenge that remains for RDE staff is to understand participatory processes better, and learn to determine appropriate processes with the levels of participation that will support learning in modern farming systems (Ellis et al. 2005).

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Chapter 37
Farmer Decision-Making in Rainfed Farming Systems

The Role of Consultants, Farming Systems Groups, and Decision Support Systems in Australia

William (Bill) Long and Ian Cooper

Abstract This chapter reviews how farmers in Australia gain information and make decisions about their rainfed farming systems. It examines the roles of consultants, farmer groups and decision support systems (DSS) in assisting farmers as their systems adjust in response to changes in their external environment. A specific DSS, Yield Prophet®, is discussed in terms of its development in conjunction with two farming systems groups and their consultants.

Keywords Consultants • Decision support systems • Farming systems groups • Yield Prophet®

37.1 Introduction

The way farmers gather and use information to modify their farming practices has changed significantly since the late 1980s. In many parts of Australia provision of information to farmers has shifted away from State Departments of Agriculture, largely to the private agribusiness sector.

It is estimated that more than 50% of farmers in Australia now use specialised *farm consultancy services* to assist them with farm production, marketing and management issues. These specialised consultants, or 'information brokers' play a vital part in farm decision making and act as a 'filter' for the huge amount of information that is available to the farming community. Their role is wide and varied; it ranges from sifting through the agronomic information available and reporting and advising

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_37,

on all aspects of farm management, to acting as a facilitator, trainer, mentor and/or coach to assist in building, developing and maintaining the farm business.

Alongside the evolution of private sector advisers has been the development of *farming systems groups*. These groups access funding from many sources to conduct local research and demonstration trials, field walks and training activities. In most cases, the success of the farming systems groups is the result of the efforts of a few ‘champions’ within the organisation who have the passion and drive to make changes in their farming community. In many cases, one of those champions within the group is a farm consultant.

Methods of access to and availability of new and relevant farm business information have improved considerably in the last decade. Most farmers now use computers and Internet services to seek information relevant to their farm business. Computers are primarily used to keep financial and physical farm records. However the Internet also provides weather forecasts, information on grain marketing and selling and means of purchasing machinery, equipment and supplies (Brennan et al. 2007).

While computers provide a tremendous and expanding new resource for gathering information, using this information appropriately on farm provides challenges. For instance, as computer technology developed, scientists saw the computer as a tool to deliver research outcomes and decision support systems, to assist decision making around specific farm business questions. Researchers and their funding bodies have invested considerable effort into developing computer based *decision support tools* to aid farm decision making. However, the direct use of decision support programs by farmers has been slow to occur, although their uptake by consultants for use with farmer clients has been more successful (Brennan et al. 2007).

In spite of advances in computer technology and decision support tools, *information gathering* is still done via a number of traditional methods. The farm consultant plays a significant role in providing information through a range of processes. The support offered by consultants has increased the speed of adoption of new technology.

This chapter reviews some of the ways in which farmers gather and use information to make decisions. It also discusses the development of farm consultancy services and farming systems groups. It uses a case study approach to examine the development and use of a decision support tool, Yield Prophet®, by a farming systems group and supporting consultants.

37.2 A Changing Farming System

Farming systems are constantly changing. Farmers and their advisers are continuously presented with new products and new technology to improve profitability (Chap. 7) along with changes in input and product prices, government policies (Chap. 12) and climate (Chap. 4).

Crop water use efficiency has increased significantly over time (Chap. 28), with yield gains attributed to improved varieties, better nutrition, improved weed control, reduced root and leaf disease levels and more efficient use of water through such practices as no-till and earlier planting dates. Since the mid 1980s, an unprecedented increase in choice of inputs such as pesticides and fertilisers has increased the complexity of farm decisions. For instance, with the specific nature of pesticides, there is a risk of applying the incorrect product or applying the correct product at an inappropriate rate, with the consequence of significant crop damage. In their quest to increase productivity, farmers have quickly recognised the benefit of seeking specialised help in using these products.

Tillage practices have changed dramatically. For instance, since the mid 1990s, pre planting cultivation practice has been replaced with single pass planting operations (no-till) across much of Australia. This has brought about the need to develop new means of applying pesticides and fertilisers (see Chaps. 34 and 39) At the same time, weeds were developing resistance to a range of herbicides (see Chap. 8).

New crop types were also being introduced into the farming system. In southern Australia, crops such as lentils[1] offered farmers much higher profits than other pulse crop types and knowledge through experimentation was required in order to grow such a crop. Other industries were also evolving at the same time. For example, oaten hay production was developed to supply high quality hay to the Japanese dairy market. This new market provided farmers with not only another profitable crop, but also an opportunity to control herbicide resistant ryegrass populations (by mowing to reduce seed carry-over) that threatened to degrade crop production systems.

In addition, market deregulation in Australia and volatility in grain pricing added another dimension to farm decision making, increasing the complexity of decisions that must be made in order to remain profitable and viable.

37.3 Information Transfer in Rainfed Farming Systems

37.3.1 Technology Adoption Process

In the past, farmers have been labelled as ‘conservative’ and ‘slow to adopt new technology’. Often there has been a long ‘lag phase’ between research outcomes and uptake of the new research results. Given some of the information delivery processes used in the past and still being employed in some cases today (journal articles, other printed media, field days), it could be argued that the fault in poor adoption lies in the hands of the deliverer and not the farmer recipient of that information.

[1] See Glossary for botanical names of crops.

Increasingly, through participatory research processes involving farming systems groups and consultants, researchers are engaging with the end user in the design, analysis and implementation of experiments. The engagement of farmers at all levels of the research and extension process is ensuring faster uptake of the technology than has been experienced previously (Collinson 2000).

Coutts et al. (2005) identified key extension models that farmers use to engage in new technology. These include:

- facilitation, where groups are enabled to achieve their own education and training needs.
- technological development, for example the development of decision support systems (DSS) tools to assist learning and education on a topic.
- training, where specifically designed programs and workshops are delivered to targeted groups.
- information which individuals and groups can access from a distance at a time that suits them, for example Internet and website information.

Consultants and farming systems groups have played an increasingly important role in some or all of these processes, to improve managerial, technological, social or environmental aspects of farming systems.

37.3.2 How Do Farmers Make Decisions on Changes to Their Farming Systems?

The way in which farmers make decisions can range from simple to extremely complex processes. While many of the decisions are made in order to improve the economic position of the farm business, a number of them are influenced by a range of social and psychological factors. McGuckian and Rickard describe these processes in more detail in Chap. 30.

Farmers work in an environment where multiple variables with different risk profiles and complex interactions impact on their businesses (Gibb 2009). Gibb goes on to report that:

> Good farm managers appear to have a mysterious capacity to make 'best bet' decisions and implement them in a timely way. On closer analysis, they actually follow rules to achieve their success. Some of these rules are;

- Identify the critical variables and don't be distracted by non critical variables. Experience, observation and a comprehensive 'world view' contribute to identifying the key items quickly. Smart farmers listen to 'experts' but don't follow them blindly because they know experts only ever see part of the 'big picture'.
- Act quickly and decisively. More often than not, the good options disappear quickly.
- Make near ideal decisions rather than analyse a situation 'to death' and as a result, miss an opportunity that depended on getting the timing right.

Gibb argues that management skill comes down to the ability to make good decisions in a timely manner. Due to the unpredictable nature of the environment in which farmers work, it is impossible to make the best/most profitable decisions all the time. A decision that turns out as such is therefore a best-bet decision that turned out to be the best possible, with the wisdom of hindsight.

Most of the argument for change is directed at the economic benefits derived from that change. Information delivery has so often been targeted at the economic benefit, in order for change in practice to occur. Environmental drivers for change are also targeted but often with a financial or economic incentive. Social benefits have largely been overlooked in information delivery and yet they are very important features in decision making processes.

The social dimensions of decisions are often not acknowledged or understood by farmers nor taken into account by extension workers and researchers. However they are fundamental to the farming family's decision to be farmers; and the social benefits derived from specific decisions can sometimes override economic or environmental benefits. Farming is a serious and professional business where the business owners are motivated strongly by social drivers (see Chap. 30).

Decisions differ in the level of difficulty (see Chaps. 12 and 30). Many daily decisions are simple, with one easily identifiable right answer. Decisions become complicated when there are a range of factors involved in the decision making process; but there is still generally, one right answer. Complex decisions require analysis of a range of input factors which can result in several or in fact many outcomes. Decision support tools such as Yield Prophet® play a role in complicated and complex decision making by simplifying some or many of the information input steps in this process (Yield Prophet® uses data input by the grower and the APSIM computer model to generate regular reports of projected yield outcomes, together with the impact of crop type and variety, sowing time and nitrogen fertiliser, given the rainfall received (Long and Hunt 2007).

Farmers and their advisers constantly use heuristics (mental shortcuts or 'rules of thumb') to simplify the decision making process. Farmers, like any decision maker, do not have infinite resources or time to devote to gathering and analysing information.

Farmers frequently use intuitive decision making processes in managing the farm business. Rickards (2009) describes 'intuitive thinking' as "a process by which our subconscious finds links between current situations and past experience and knowledge." Intuition allows us to make quicker decisions because it bypasses rational processes.

Intuition allows us to bypass rational processes but for decisions to be good, our intuition depends on the quality of our past experience and knowledge. Therefore, the more farmers experience, read, discuss and think about a particular subject, the better is their intuition. Despite having gaps in information, intuition enables a decision to be made.

Even when farmers make a conscious effort to make decisions using a logical, rational process, there is often a need to make simplifying assumptions and accept limits on the availability of information and the thoroughness of the analysis.

In addition, most farmers have not received any formal training in research skills or decision analysis and are therefore ill equipped to collect an exhaustive supply of information on a subject for analysis. Farmers, like many other managers, make decisions that are 'good enough', using only some of the overwhelming amount of information available—Simon's (1955) '*satisficing principle*'.

The amount of information being generated from research efforts is immense. Information is readily available from many sources. Farmers often complain that there is too much information available and find it difficult to keep abreast of and process information that is relevant to them. Farm consultants assist farm managers with managing this information overload.

37.4 The Development of Farm Consultancy Services

Farm consultants now have a wide and varied role in building, developing and maintaining the farm business. Llewellyn (2007) reported that farmers who used a consultant were two to three times more likely to adopt and continue to use new technology than those who didn't.

37.4.1 Types and Roles of Consultants

In a report to the cooperative venture for capacity building, 'Making the most of Agricultural Consultants in your Farm Business', Coutts et al. (2007) reported:

> There is a wide range of private consulting being undertaken in rural Australia. Most consultants to agricultural enterprises focus on business and technology management with some inroads into marketing, human resources and succession. Roles range from provision of advice, to facilitating change and providing training.

In a review of national extension and education, Coutts et al. (2005) estimated there were in excess of 1,300 private agricultural consultants operating in rural Australia. Furthermore Stone's study of agribusiness (2005) concludes that "agribusiness has largely supplanted the previous government extension role … increasingly it is undertaking R&D work and can act as an information conduit from farmers back to researchers and decision makers".

Coutts et al. (2007) found that producers use private consultants primarily because they can provide a professional, 'independent', opinion on management decisions. Most farmers find their consultants by 'word of mouth' recommendation. The farmers who benefited most from their consultants were those who were clear about their goals and expectations and had a high level of involvement in the consultant's activities.

Stone (2005), in his report to the Cooperative Venture for Capacity Building, defines agribusiness as a person or organisation that generates income from the sale of a product and/or a service which facilitates the decision making of a farmer or land manager. In his report, he examines the role of agribusiness in the meat, livestock, dairying, wine, grain, horticulture and sugar industries in southern QLD and Northern NSW.

Today's agribusiness includes consultants, trainers, accountants, producer organisations, farmer directed groups, resellers and their product suppliers, privatised or semi-government organisations, banks, marketers and seed companies. All of these people work to support farmer decision making in exchange for payment, either directly as a fee for service or indirectly through costs of service being built in to the supply of products or services (Stone 2005).

Stone goes on to describe 'innovative' farmers as those who operate in a globally focussed business environment and concentrate on 'doing business'. This group relies heavily on 'honest brokers' who are mostly 'fee for service' providers and have no pecuniary interest in the advice provided. He further suggests that farmers view the 'honest brokers' as consolidators of information and value their advice as one professional to another.

Information is increasingly being provided by farmer-directed groups, which seek out information and deliver it according to group and member preferences. Innovative farmers are wary of resellers and believe their advice often has 'strings attached' Farmers will use resellers as a second opinion to help confirm decisions.

Age and experience of advisers is important and innovative growers are wary of advice given by those who have not served a '10 year apprenticeship' or who lack 'life experience' This is likely to result in a human capital crisis within a few years as there are not enough advisers to service the demand.

Traditional farmers are having real trouble accessing advice as they are not willing to pay. Free advice from Government services has been reduced significantly in many regions. The role of resellers is important to this group of farmers as they either don't recognise that they are paying for the advice in the price of products or simply chose to ignore that the costs are built in.

There is also belief within the agribusiness sector that Research and Development Corporations should be funding agribusiness-driven research programs as it is the agribusiness that is more closely in touch with farmer needs.

37.4.2 Reasons for Using a Consultant

> Primarily, producers use private consultants because they can provide a professional, external opinion on management decisions on agricultural enterprises (Coutts et al. 2007)

The consultant role is, in reality, wide and varied. Coutts et al. (2007) suggested producers identified that the most important benefits of using a consultant were to have someone:

- who helped provide peace of mind
- who helped the farmer make management decisions

- who was able to stand back and look at the business as an independent observer—with whom the farmer was able to discuss the business and develop ideas
- from whom the farmer could obtain advice that is independent of government bodies, or commercial firms (e.g. seed or chemical merchants)
- from whom the farmer could gain help in learning to operate the business successfully.

Consultants are valued by farmer clients for providing information relevant to their needs, for their availability during busy times and for their good communication skills.

The consultant often plays a role in each of the steps of the decision making process. One of the major roles of the consultant is to collect data and information and filter and edit that information to suit the farmer's needs. After presentation of the data (which is done in various ways) the consultant is also engaged with the farmer in making the decision, followed by a review of the result which contributes to the database of information that is in the farmer's mind to assist in similar decision making processes in the future. Thus, the consultant is engaged in all phases of the 'learning cycle' of plan → action → observation → reflection → modified plan.

Such an interactive approach is not always adopted. Some farmer–consultant relationships are more dependency based, with the consultant making the majority of the decisions regarding crop inputs, on behalf of the farmer. Farmer growth in understanding of this aspect of the business is therefore limited by the degree to which this task is undertaken for him. Such dependency does, however, allow the farmer to focus attention on other aspects of the business and is a preferred option for some farmers.

The farm consultant now and in the future, will play a significant role in organising learning activities and ensuring that the adoption of new technology is rapid and effective.

However, not all farmers use consultants. Little, if any research exists into the motivation forces behind farmers' use of consultants. Maybery et al. (2005) in categorising farmers into economic, lifestyle or conservationist types may offer a clue in answering this question, the hypothesis being that farmers who are striving for improved financial returns are more likely to employ a consultant to lift production and profitability than those who farm as a lifestyle choice or are focussed on farm conservation issues.

37.4.3 Consultant–Client Relationships

Most farmers and their consultants have a very good relationship, in most instances, closer than with any other service provider. As the consultant is involved in many of the day to day, on-farm decisions regarding crop husbandry practices, communication between the farmer and consultant is regular. Owing to the nature of farm work, this communication often occurs after normal working hours—a fact appreciated by farmers, many of whom place high importance on accessibility to consultants outside of the normal working times.

For a relationship to endure, it is important that the farmer and the consultant get along well together and have similar personalities, values and beliefs. Further, most farm consultants live in the community in which they work. They then interact with clients not only professionally but also socially, which reinforces the relationship.

37.4.4 The Development of Farming Systems Groups

Several farming systems groups have been in existence for over 25 years, having begun as research and demonstration sites for new herbicides and crop and pasture varieties. Farming systems groups as they exist now have largely developed and evolved since the mid 1990s. Such groups have identified local and regional issues that require investigation. They engage with researchers and advisers to identify needs, conduct research, demonstrations and training. For these purposes, they access funding from many sources. In most cases, the success of the farming systems groups is the result of the efforts of a few 'champions' within the organisation who have the passion and drive to make changes in their farming community. In many cases, one of those champions within the group is a farm consultant.

It is estimated that there are 60 farming systems groups across Australia, which are actively involved in both field trials and extension activities. There are many other information sharing groups that are not directly involved in trial and demonstration activities and are more focussed on information sharing through regular group meetings. These groups vary from small groups of only a few local farmers to large state and national based groups with membership of over 1,000 farmers, consultants and industry representatives. They conduct many training activities throughout the year, supported by replicated field trials.

37.4.5 The Development and Use of Decision Support Systems

In order to support farmers in the decision making process, scientists have invested considerable time, effort and research dollars into the development of computer based decision support systems (DSS) or tools. Computer based DSS range in their complexity from simple tactical models to assist with straightforward, agronomic or economic decision making through to detailed and complex models that assist in immediate (tactical) and long term (strategic) decisions (see also Chap. 12).

Development of DSS began in earnest in the 1970s as the scientific community sought to supply a mechanism for providing research information directly to farmers and enabling the research outcomes to be adopted beyond the direct personal influence of the team conducting the research. DSS were also developed in response to a decline in extension services which were being offered by the State Departments of Agriculture.

The development of DSS has also been a response to the fact that "in Australia, a land subject to high annual variation in grain yields, farmers find it challenging to adjust crop production inputs to yield prospects" (Hochman 2009). Yet the scientists' enthusiasm for developing these tools has not been reciprocated by farm managers or their advisers, who mostly continue to avoid their use (see Case Study below).

Much has been published regarding the poor uptake of DSS by farmers. In a survey of recognised DSS developers across Australia, Nguyen (2007) stated: "the uptake of DSS by farmers has been slow and various issues said to be contributing to this include fear of using computers, time constraints, poor marketing, complexity, lack of local relevance, lack of end-user involvement and mismatched objectives between developers and users."

However, many of those interviewed believed that if new DSS embraced the suggested criteria, farmer adoption would improve. Nguyen went on to report that to be successful, the DSS needs to address common problems: they need to be applicable to specific locations and gain strong support from local users. They also need to be simple to use, relevant, effective, low cost, and user friendly, and it is most likely that farmers would have been involved in their development (Nguyen 2007).

Maybery et al. (2005) characterised farmer personalities as those with economic, conservation, or lifestyle values. These values were also mentioned as influencing the use of DSS along with attitude towards risk management and decision making. Other factors such as financial position, stage of life and family succession plans are all factors which may influence decision making processes.

The range and sophistication of DSS tools are increasing rapidly (see Chap. 7) and there is no doubt that they have value. However, these tools are used by people, with all their biases and cognitive limitations, and they assume a model of human behaviour focussed on economic drivers, which is a significant oversimplification of how people really behave.

Despite the range of DSS available, DSS adoption rates have been extremely poor (Hochman et al. 2009b). Many farmers are aware of their existence but very few have obtained these tools to assist them in decision making processes. It has become apparent in recent years that successful adoption is more likely if DSS tools are targeted at consultants rather than directly at the farmers. The consultant is more likely to use the DSS than the farmer, as most consultants are more familiar with computers and use them regularly. This usually contrasts with the farmers they work with. In addition, the data collection required to feed information into the model is commonly done by the consultant.

37.5 A Case Study—Ag Consulting Co (ACC), The Yorke Peninsula Alkaline Soils Group (YPASG), Birchip Cropping Group (BCG) and the Development of Yield Prophet®

The following case study illustrates the interaction of farm consultants, farming system groups and researchers in providing information to farmers and assisting them in decision making. It outlines the development of two farming systems groups and one farm consultancy business and their role in the development of the DSS, Yield Prophet®. It also discusses the value of Yield Prophet® as an example of a DSS which has been thoroughly evaluated for use by farmers in Rainfed Farming Systems. One of the groups, The Birchip Cropping Group (BCG) was the key driver in the evolution of Yield Prophet®. The Yorke Peninsula Alkaline Soils Group (YPASG) followed the work done by consultant Haarm Van Rees of BCG in encouraging activities around improved understanding of soil water and the use of crop phenology models to assist in input decision making. Using Ag Consulting Co agronomist and managing director, Bill Long, as a 'champion' of Yield Prophet® at a local (Yorke Peninsula) and national level, the groups and the DSS evolved concurrently in a period of rapid change to farming systems in southern Australia.

Prior to the use of Yield Prophet® it could be argued that adviser and farmer understanding of the relationship between soil water holding capacity, soil water measurement and soil water relationships to crop yields relative to specific crop growth stages was extremely limited. Yield Prophet® offered a relatively simple-to-use mechanism to improve that understanding.

37.5.1 Ag Consulting Co (ACC)

ACC began in 1996 and offered agronomy services to farmers in the Yorke Peninsula and Mid- and Lower-North farming districts of SA (Fig. 37.1). At that stage there were few other agronomy consulting businesses servicing the area, and two of those had only been operating for a short time. Demand for services was overwhelming; growers were eager to obtain the services of an adviser with research and production input understanding, skills and experience.

Advice was production-focussed and significant yield gains were easily made by (1) increasing rates of nitrogen fertiliser, (2) improving cereal and pulse disease management with the use of appropriate fungicide treatments and (3) managing weeds, particularly annual ryegrass, with a range of herbicides. At the same time, no-till technology was creating significant interest, with growers seeking advice and guidance on its adoption. The change to no-till practice led to a review of herbicide and fertiliser application techniques which needed to be re-examined in a controlled manner to establish the most effective and safe methods of use.

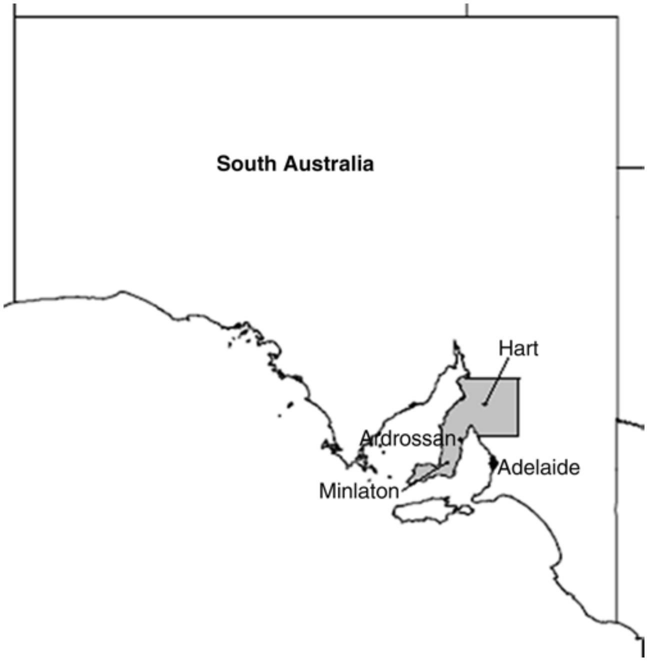

Fig. 37.1 Area serviced by Ag Consulting Co. The mean annual rainfall ranges from 250 to over 600 mm. The business is based on a farm near Ardrossan. YPASG is based at Minlaton

The availability of advisers was limited and demand for consultants to assist farmers exceeded the supply. Advisory businesses like ACC began to employ and train advisers with only a few years experience in such roles, or those who had no advisory experience but had some small plot research skills.

There was reluctance on the part of levy-based funding organisations to fund 'private' research or advisory groups such as ACC, as it was believed by some that the only beneficiaries from the research would be the farmer clients of the company. This was despite repeated release of privately funded research results to the farming public.

It became evident that ACC needed a mechanism to find answers to the questions being posed by the farmer clients. Conducting local field trials and demonstrations became necessary to find solutions to problems arising from the rapid changes occurring in farming systems.

Initially, trials were conducted with little or no support from levy based organisations such as the (Australian) Grains Research and Development Corporation (GRDC) or the South Australian Grains Industry Trust (SAGIT). ACC asked growers to pay a levy of $300/client to support trial activities.

Farmers who could not be clients of ACC because of the lack of consultant capacity to provide services to them were encouraged to become part of the trial program, if willing to contribute financially to the activities.

This activity continued and coincided with a growing interest in increasing field research within the region. In 1999 a group of farmers and consultants met at Yorketown on southern Yorke Peninsula to discuss the formation of a farming systems group to address the agronomic issues faced by farmers in the region. These were mainly related to the region's alkaline soils (pH greater than 8), often with a highly calcareous root zone. As a result of that meeting, the Yorke Peninsula Alkaline Soils Group was formed.

37.5.2 Yorke Peninsula Alkaline Soils Group (YPASG)

YPASG is a grower-driven group with over 280 members and more than 20 project activities addressing sustainable production issues and its formation allowed access to research funding related to the needs of the area. The management committee is composed of growers, advisers and industry representatives. YPASG is a non profit, incorporated association which is regularly in touch with members and the agricultural industry through its group activities, newsletters, Annual Results Book, emails, website[2] and text messages. During its first 10 years of operation, the YPASG has conducted over 60 specific issue research and demonstration programs, with financial support from a number of organisations including the Department of Agriculture, Fisheries and Forestry through the National Landcare Programs, the GRDC, and by means of private and public company sponsorship and membership fees.

Research programs are conducted through a number of organisations including Ag Consulting Co, and the South Australian Research and Development Institute (SARDI, part of the South Australian Department of Agriculture, Forestry and Fisheries).

YPASG has been involved in a wide range of research projects since 1999. Included in the 66 projects undertaken in this time are investigations into Crop variety, Time of Planting and Management, Integrated Snail Management, Controlled Traffic, Planting Systems and Weed Control, Spray Technologies, Timing of Nitrogen Application, Crop Canopy Management, Growth Regulants, Wheat Root Diseases and Bio-control agents, Production in Harsh and Saline Soils, Managing Herbicide Resistant Ryegrass and Plastic and Mulch Trials. This research has enabled many problems facing the group to be successfully resolved (see website). The success of the group is indicated by the fact that a decade after its formation it continues to gain funds for research from government and grower bodies and membership continues to grow.

[2] www.alkalinesoils.com.au

Research funding from GRDC between 2005and 2008 also provided opportunity to begin characterisation of soils in the area—in particular plant available water capacity (PAWC). The reason for gaining improved knowledge in PAWC was to improve the functionality of Yield Prophet®.

Interest in the use of Yield Prophet® began when the lead author became aware of the development of the model by BCG (see Sect. 37.5.3) and could see the potential of the model to improve productivity and profitability in the region.

The YPASG-led project has contributed to a much greater awareness of the PAWC of soils throughout the Yorke Peninsula region as well as beyond this district. Group activities between 2005and 2009 have utilised this improved knowledge on soil water holding capacity gained throughout the project by coupling it with the use of Yield Prophet®. Reports generated for discussion at field days and produced in group newsletters, have significantly increased farmer and adviser understanding of the relationship between stored soil water, in season rainfall, planting dates, plant nutrition and crop production.

37.5.3 Birchip Cropping Group (BCG)

In 1992 a group of farmers at Birchip (Wimmera–Mallee region, Victoria, Australia, see Fig. 37.2) was inspired by a trip to the Hart field day site[3] in SA (Fig. 37.1) and

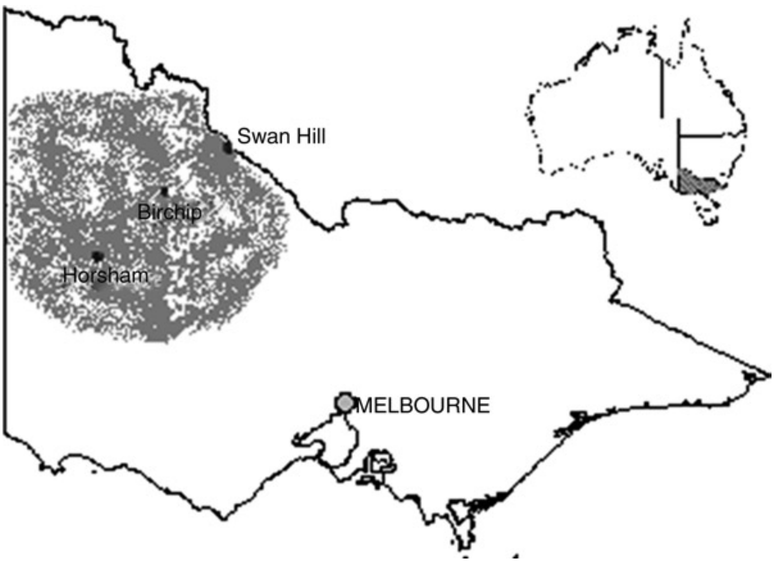

Fig. 37.2 Birchip Cropping Group region in Wimmera and Mallee areas of Victoria

[3] The Hart Field Day Site is about 20 km NW of Clare in South Australia (see map). For more details see http://www.hartfieldsite.org.au/.

decided to run a series of variety and herbicide demonstrations in their own area. Local farmer, Trevor Grogan, donated 40 acres on which to conduct research trials for the next 10 years. A committee was formed in 1993 and the Birchip Cropping Demonstration Sites were initiated.

The organisation grew rapidly and was successful in obtaining grants from various sources for research on a wide range of topics. BCG strives to improve the prosperity of rural and farming communities, to strengthen broader community vitality and provide practical solutions to farm production and business problems. BCG conducts rural and agricultural research and extension activities in the Wimmera and Mallee regions and disseminates results across Australia. They have provided information, advice and decision support tools which have enabled farmers to make informed decisions and rapidly adopt new technologies and farming practices. This has earned BCG the respect of farmers, researchers and industry representatives as a highly credible and independent organisation.

The annual BCG field day attracts over 600 interested farmers. It employs over 20 full time staff, draws on the services of four consultant groups[4] and has an annual operating budget of Australian $2.43 million.

In 2003 it was successful in winning a tender from the Agricultural Production Systems Research Unit[5] (APSRU) to commercially deliver the Agricultural Production Systems Simulator (APSIM) to grain producers across Australia (Hochman et al. 2009b). Yield Prophet® was conceptualised by Victorian farm consultant, Haarm Van Rees, as the mechanism by which APSIM could be delivered to growers to improve knowledge in crop production.

37.5.4 *Yield Prophet®—An Example of a Developing DSS*

Yield Prophet® is a web-based crop modelling service provided by BCG. It is based on the APSIM model and was developed over 15 years by APSRU[6] as a simplified, easy to use decision support tool that would assist farmers and consultants to improve cropping decision making. It simulates crop growth from information on paddock-specific inputs of soil type, Plant Available Water Capacity (PAWC), pre-sowing soil water and available nitrogen, rainfall and other climate data, irrigation (if any), and nitrogen fertiliser applications. It was first used for wheat at BCG trial sites in 2002, and its early predictions of the failure of the crop in that season generated sufficient interest and credibility in the DSS to encourage the release of a commercial version of the software to BCG members in 2003, as a monthly fax-out service. This was developed into an 'on-line' web based version

[4] For further information on the Birchip Cropping Group see http://www.bcg.org.au/

[5] http://www.apsru.gov.au/apsim/Apsru/

[6] See Glossary.

in 2004 which provides subscriber farmers and their advisers access to up to date information reports during the season and the capability to do 'what if' scenarios for fields they have set up with the required input data of soil type, information from the nearest meteorological station, farm rainfall records, and initial soil water and soil nitrogen. 'What if' scenarios relate to such issues as choice of crop variety, planting time and N fertiliser application.

Yield Prophet® appeals to growers and advisers not only for its soil water information but also for the crop physiology components and its probability based yield predictions. The model also integrates seasonal weather forecasting tools such as the Southern Oscillation Index[7] (SOI) into reports to assist decision making. Using individual paddock information and actual and expected rainfall,[8] Yield Prophet® simulates soil moisture and crop growth through the growing season and is used to: (1) optimise planting time, (2) aid variety selection, (3) manage inputs such as nitrogen, (4) estimate grain yield and protein content and (5) assist in managing risk (Long and Hunt 2007).

In order for reports to be useful, accuracy is required in the collection of specific, field soil physical and chemical properties (particularly PAWC, and soil N status) and inputs. Once the soil type is adequately characterised, the only additional measurements required are initial soil moisture and nitrogen before the cropping season begins each year.

Plant available water capacity (PAWC) is established for specific soil types, preferably in specific fields. It is defined as the difference in volumetric water content between the drained upper limit (DUL) and the crop lower limit (CLL). Estimating PAWC involves wetting the soil profile to establish DUL levels; and using crop rainout shelters to establish CLL. Soil bulk density is also measured, to soil horizon changes, to establish water holding capacity of specific soil types. This establishes the soil water 'bucket'. Soil samples are analysed to identify chemical barriers to root growth. These and the 'bucket' are combined with estimated crop water demand and soil evaporation calculations to determine the yield potential at any crop growth stage, (Long and Hunt 2007). Further information on procedures and the type of information obtained from Yield Prophet® are available from the website.[9]

37.5.4.1 Use of Yield Prophet® to Assist in Decision Making

There are several critical decision points throughout the life-cycle of a crop. Knowing how much soil moisture is available at these critical decision points will influence management decisions and their outcomes at that point. For example: Prior to or at planting: (1) a decision is made whether to retain, bale, slash or burn stubble.[10]

[7] See Glossary and Chap. 3.

[8] From probabilities based on historical, long term rainfall data.

[9] www.alkalinesoils.com.au/YieldProphet.html

[10] Stubble is occasionally burnt to remove pests—particularly snails.

Stubble retention may keep sufficient moisture in the soil to allow germination of some crop types, even in a dry period; (2) the amount of rainfall required to reach CLL must be allowed for; this amount may be significant following a spring drought and no summer rainfall; (3) a decision may be made whether to dry plant a crop.

During the growing season decisions may be made on: (1) How much nitrogen should be applied, given the knowledge of the water available to the crop and the amount of available N in the soil; (2) what fungicide, if any should be applied; (3) whether there is likely to be sufficient moisture (in the soil and as expected rain) to allow grain fill to occur, or whether the crop might best be cut for hay (4) what grain marketing opportunities there are, given the likely yield and the current market situation. Likely yield is an important consideration when considering forward selling or using futures to lock in favourable prices for crops.

Other decisions may also be assisted by information on available soil moisture, as follows: (1) Interpretation of variation across paddocks in crop yield maps. This has been attributed to variation in levels of plant nutrients, disease and weed infestation. More recently, such variation has also been attributed to changes in available soil moisture. With a better understanding of PAWC across paddocks, inputs can be adjusted to better match yield potential of soils within those paddocks. (2) Information on the PAWC of soils on properties, coupled with local rainfall and other environmental conditions will assist in assessing the yield potential of a property, which will be of value to both the owner and a potential purchaser of the property. Excerpts from a Yield Prophet® report are shown in an Appendix to this chapter.

37.5.4.2 Assessment of Yield Prophet® Accuracy and Use by Farmers

The accuracy of yield simulation achieved by Yield Prophet® was assessed by Hochman et al. (2009a) in a wide range of environments over several years. Because subscribers to Yield Prophet® have used simulated yields as a benchmark to estimate he potential yields (see Chap. 1) of their wheat crops, Hochman et al. also used simulated yields to help clarify the reasons for differences between actual and potential water use efficiency (WUE). They collected data from 334 wheat crops, mainly in southern Australia, firstly to determine which measure of water use (evapotranspiration, ET) was most closely related to crop grain yield. They found that, when ET was calculated as: (in crop rainfall + soil water at sowing − simulated soil water remaining at crop maturity) it accounted for 69% of observed yield variation. On the other hand, 'short-cut' methods commonly used to estimate ET, such as growing-season (April–October) rainfall accounted for only 50% of yield variation. They found that Yield Prophet® simulated commercial wheat yields with RMSDs of 0.80 t/ha ($r^2 = 0.71$) (Fig. 37.3).

Simulated crops achieved a higher WUE than the observed crops, probably because APSIM does not account for effects of factors such as weeds, pests and diseases and impacts of severe (extreme) weather events. Carberry et al. (2009) propose that most farmers they have investigated now eliminate problems of weeds,

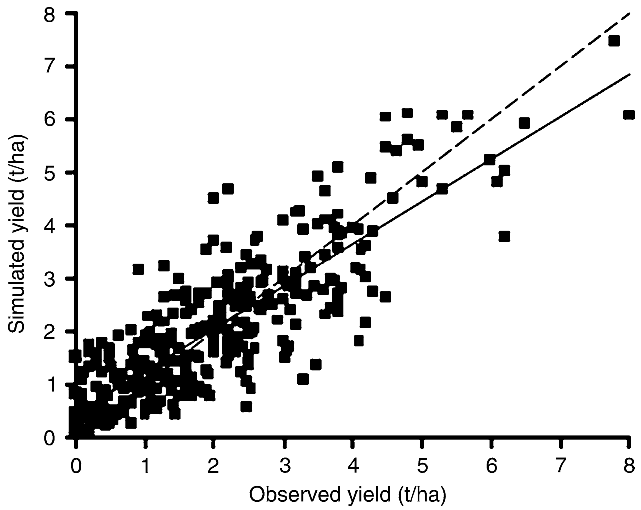

Fig. 37.3 The relationship between observed and simulated wheat grain yields across the environments and seasons represented in the Yield Prophet® data set. The *dashed line* represents the ideal 1:1 relationship. The *solid line* represents the best fit linear regression equation: observed yield = 0.801 (s.e. = 0.028) simulated yield + 0.447 (s.e. = 0.070) (r^2 = 0.71, *n* = 334, RMSD = 0.80) (Hochman et al. 2009a)

diseases and pests in their crops, so that Yield Prophet is able to closely simulate yields from farmers' fields (within about 0.5 t/ha of measured yields). This is so, provided that accurate, paddock-specific data on soil water (particularly PAWC), initial soil N, rainfall and N inputs are supplied. "Simulation accuracy is therefore largely dependent on the quality of the data describing the soil resources". Given these provisions, it is very worthwhile that Yield Prophet is conducted and assessed in farmer's fields, in spite of some human error at the farm level. It is realised by the above authors that Yield Prophet still has some shortcomings but at its present stage of development, it has the potential to greatly assist farmer decision making.

When Hochman et al. (2009a) simulated a 'what if', yield maximising strategy that included an optimal plant density, early sowing date, and non-limiting N inputs, it resulted in a yield (potential yield) of 21.4 kg grain/ha/mm water transpired, with an *x*-intercept (soil evaporation estimate) of 80 mm. These figures are close to the previously reported (French–Schultz) potential yield and intercept values (refer to Chap. 1).and those reported by Sadras and Angus (2006) The investigators also indicated that Yield Prophet® farmers have demonstrated significant improvement in on-farm productivity and WUE compared with previous studies. (for example Sadras and Angus 2006). They submit that this improvement is because farmers who use Yield Prophet have access to a tool that allows assessment of their crop yield potential throughout the growing season. This then enables them to better match farm inputs (including in-season topdressing of N) to the seasonal yield potential of their fields.

Hochman et al. (2009a, b) noted a number of potential barriers to adoption of Yield Prophet®:

1. Farmers and consultants will not use the tool until they trust its ability to simulate crop yields accurately in their own area. Feedback from some Yield Prophet subscribers has indicated that farmer confidence in this DSS is reduced when the difference between observed and predicted yields exceeds 0.5 t/ha. This was achieved by only about half of the 334 wheat crops examined. However, Carberry et al. (2009) state that Yield Prophet® can predict performance of commercial crops at a level of accuracy close to that reported for experimental yields.
2. The predictions are only satisfactory if input data are reliable (see above). Measuring these data can be expensive, slow, and labour intensive. Farmer groups and consultants need to have access to funding grants for measuring soil characteristics and building a relevant soils data base.
3. Farmers and consultants need appropriate training to understand the Yield Prophet® reports, particularly the information presented as probabilities. Consultants with appropriate knowledge can help farmers in this regard.

Hochman et al. (2009b) conclude:

> After four years of development and implementation, Yield Prophet® is a technically robust and comprehensive system that provides users with a credible science-based tool for virtual monitoring of soils and crops and for supporting tactical crop management in a risky, climatically variable, environment.

They achieved this through: (1) providing a tool that can be flexibly specified to a particular management situation, (2) situating Yield Prophet® in a supported network of farmers, consultants and scientists, (3) providing users with flexibility in problem description, and (4) providing a tool that can be used for post-decisional monitoring (Hochman et al. 2009b).

37.5.4.3 Do Growers Continue to Use DSS as a Tool to Aid on-Farm Decision Making?

Despite the considerable investment in the development of Yield Prophet® as a tool that can assist in providing a considerable amount of information to users to assist in better farm decision making, an examination of the use of Yield Prophet® shows considerable variability (Table 37.1). During the period from 2002, when use of Yield Prophet® began, to 2006, there was strong growth in the number of subscribers that used the model. During this time, there was a considerable amount of promotion and publicity surrounding the use of the model. Yield Prophet ® was promoted at farmer field days, reports were published in farming system group and consultant newsletters. Much work was done to define soil water holding capacity (PAWC) better, on a regional and state basis, to further enhance the functionality of the Yield Prophet® model. As mentioned by Carberry et al. (2009), the model had the advantages of being flexible, comprehensive and able to gain credibility in the context of specific circumstances.

Table 37.1 Yield Prophet subscribers from 2004 to 2009 (T. McClelland, Yield Prophet® coordinator, BCG, personal communication)

Year	Subscribers	Returned subscribers		No longer subscribe		New subscribers
2004	44					
2005	187	25	(58%)[a]	19	(43%)[a]	162
2006	377	108	(58%)	79	(42%)	269
2007	224	131	(35%)	246	(65%)	93
2008	183	97	(43%)	127	(57%)	86
2009	191	80	(44%)	103	(56%)	111

[a] Percentage of previous year's subscribers

Since that time, the overall number of subscribers has declined. This is despite considerable improvements and additions to the number and quality of reports available through the subscription, together with continued promotion and awareness raising of the features and functions of the model. An adjustment to the subscription 'incentive' schemes in 2009 resulted in an adjustment in the total number of paddocks subscribed but was not considered a significant factor in the change in user numbers.

Reasons for the high turnover of users of Yield Prophet are unclear. While accuracy of results has generally been shown to be at an acceptable level, the turnover of users might suggest that there are other factors that influence the use patterns of DSS. Reasons for the high turnover are the subject of research by the lead author of this chapter.

Examination of user use by State suggests that the greatest decline in user numbers is occurring in the state of Victoria, where the use of Yield Prophet® began. Initial suggestions from farmer users in SA who began using Yield prophet in 2005 are that the model has provided an opportunity to learn about the relationship between soil water and plant growth stages and that after a season or two of experience, they have a much better idea of this relationship and are able to use simple rules of thumb (heuristics) to obtain the same information. Thus, the seemingly complex issue regarding interactions between soil water, sowing date, variety and nutrition are made simple again through some experience with modelling to investigate how these factors interact. Once that learning process has occurred, it might be that users think they no longer require the use of a model and prefer to revert to preferred 'intuitive' decision making processes.

McCown (personal communication) refers to intuition as 'automatic knowing' and suggests most farmers prefer to make intuitive decisions rather than analytical decisions. He also suggests that while intuitive thinking is preferred by many in the farming community, exposure to analytical thinking helps improve the intuitive decisions by increasing the knowledge levels that contribute to the intuitive decision making process. As mentioned by Carberry et al. (2009), outputs by a DSS provide a very useful basis of discussion among farmers, consultants and researchers, on the value of simulations, as well as on the reasons for discrepancies between simulated and actual crop production outcomes.

37.6 Conclusions

The decisions that farmers must make are becoming increasingly complex. The availability of an increasing range of information is growing exponentially and many farmers are having difficulty in processing this information effectively. Moreover technology is also changing rapidly.

In Australia, since the 1980s, assistance for farmers with information and with technology change has moved from being ‘free’ from government agencies to ‘fee for service’ from government bodies and private consultants.

Consultants can be a useful resource for farm decision makers if they understand the science of the new technology as well as the social situation and specific needs of their clients. Consultants have a wide range of roles in mentoring and informing individuals and coordinating and facilitating farmer groups. The Ag Consulting Co is an example of how a consultant organisation can not only provide advice to individual farmers but also facilitate farmer groups (e.g. the Alkaline Soils Group) in gaining grants and conducting research relevant to their local farming problems. Consultants also provide a needed link between scientists and farmers.

Another role they can play is in assisting clients to understand and use Decision Support tools. DSS have had a slow uptake both in Australia and overseas and support by consultants is seen as critical to their successful use (Jørgensen et al. 2007; Hochman et al. 2009b).

There has been some success in Australia with the use of a DSS (Yield Prophet®). This occurred when the Yield Prophet® developers, farmer groups and consultants all cooperated to make it a useful and sufficiently accurate tool for assisting decisions in crop production. Developing confidence in the ability of the model to provide accurate information is crucial to its adoption and usefulness.

A study in Australia (Hochman 2009) indicated that there is a role for a DSS or suite of DSS products that would help farmers manage their crops to reduce risk and increase the chance of realising opportunities that arise from high climate variability. DSS provide an analytical approach to decision making process. However, many farmers prefer to use intuitive decision making processes to make complex farming decisions. Decision support tools assist in providing a means of learning to inform and educate users and provide input to farmer intuition. Farmers prefer to use heuristics and develop simple ‘rules of thumb’ for decision making. Many scientists and advisers prefer analytical approaches to decision making. Consultants are capable and well placed to use DSS to improve farmer understanding of complex issues. The information generated will contribute to decisions made on-farm through both analytical and intuitive processes.

37.7 Appendix

37.8 Yield Prophet® Explanation and Report Excerpts[11]

Farmers or consultants subscribe to the service in late summer and autumn and provide the Yield Prophet® team with their field names and locations. During autumn, the soil is sampled at different depths to the maximum rooting depth of their crop (e.g. 0–10, 10–40, 40–70, 70–100 cm). These samples are analysed for water content, nitrate concentration, organic carbon content, electrical conductivity, chloride concentration and pH. These data are entered by growers into the Yield Prophet® web interface, and are also used by the grower and Yield Prophet® team to select a suitable soil characterisation (an essential input to simulate crop growth, yield and protein accurately).

During the season, subscribers enter paddock management details (sowing date, crop type, variety, nitrogen fertiliser and irrigation) and rainfall. When growers wish to find out how much water and nitrogen is currently available to a crop, the likely yield of their crop, or what the likely impact of management events will be, they generate a report. Some of the types of information provided by reports are shown below.

Yield Prophet® simulates daily crop growth from planting up to the report date using the paddock specific rainfall and management data entered by the subscriber, and climate data (maximum and minimum temperature, radiation, evaporation and vapour pressure) from the nominated weather station. At every daily time step Yield Prophet® calculates the amount of water and nitrogen available to the crop, and the water and nitrogen demand of the crop. This is used to determine if the crop is suffering stress from lack of either of these resources, and any subsequent reduction in growth and yield potential. This information is then presented to subscribers in reports returned to the subscribers' account (Fig. 37.4).

In order to make predictions about crop yield, Yield Prophet® uses the last one hundred years of climate data taken from the nearest Bureau of Meteorology weather station to continue the simulation from the date of report generation to the end of the season. The model simulates one hundred different crop yields and protein contents, based on the current season up until the day the report is generated, and then on the season finishes of the past one hundred years. These yields are then plotted as a probability curve, showing the probability of yields being equal to or greater than shown by the curve (Fig. 37.5 solid line).

This is the main output of Yield Prophet®, and its value is increased by incorporating seasonal forecasts, such as the Southern Oscillation Index (SOI) phase system. That is, instead of using season finishes for the last 100 years, Yield Prophet® selects the years in which the SOI phase was the same as in the current year, and runs the future part of the simulation using only the finishes from those years. This creates another probability curve which growers can use if the SOI phase is strongly indicating wet or dry conditions (Fig. 37.5 broken line).

[11] This appendix is extracted from a page created by the lead author on the YPASG website.

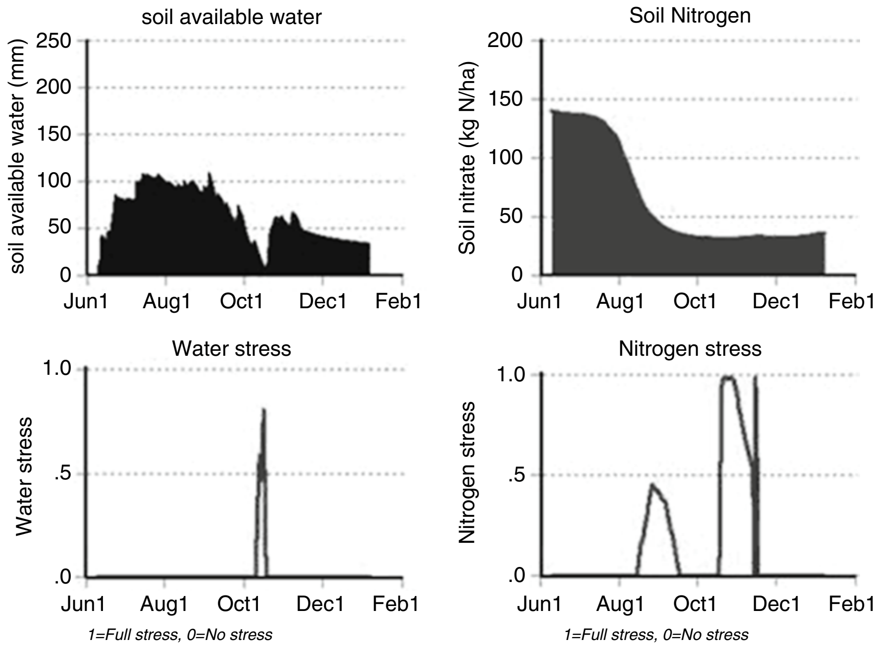

Fig. 37.4 Output from Yield Prophet® indicating the amounts of water and nitrogen available to the crop during the season. The stress graphs indicate loss of potential growth and carbon fixation, i.e. on a day when the graph is at 0.5, the crop is growing and photosynthesising at half its potential rate, 1.0 indicates severe stress with limited growth

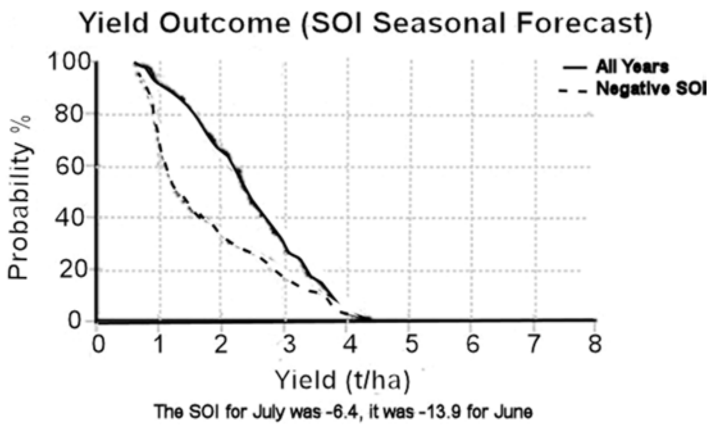

Fig. 37.5 Yield probability curve generated using season finishes for the last 100 years of climate data (*solid line*), and only those years in which the SOI phase was the same as the current phase at the time the report was generated. In the above example (*dotted line*), this is the years with negative SOI phase in June–July; the report was generated in early August 2004

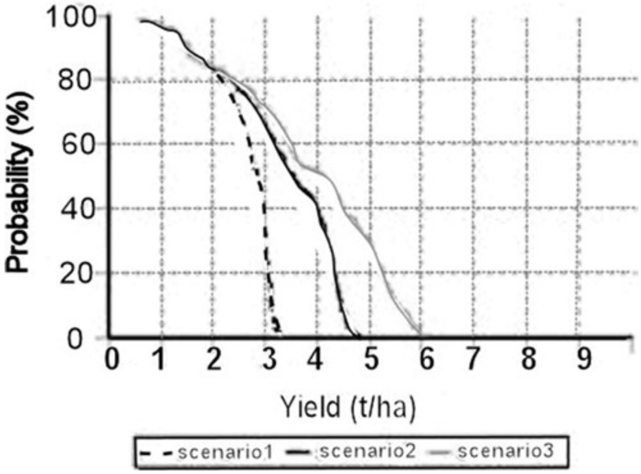

Fig. 37.6 Yield probability curves for three different nitrogen top-dressing scenarios generated for a rainfed wheat crop on 1 August 2005. Scenario 1 (*broken line*) is the yield probability if no further N added, Scenario 2 (*black line*) is the yield probability with 35 kg/ha N top-dressed on 15 August, Scenario 3 (*grey line*) is the yield probability with 70 kg/ha N top-dressed on 15 August 2005. There is an 80% chance of achieving a minor yield response with topdressing, and about a 40% chance of achieving a 1 t/ha yield response from 35 kg/ha N. There is a 20% chance of achieving a 2 t/ha yield response to 70 kg/ha N

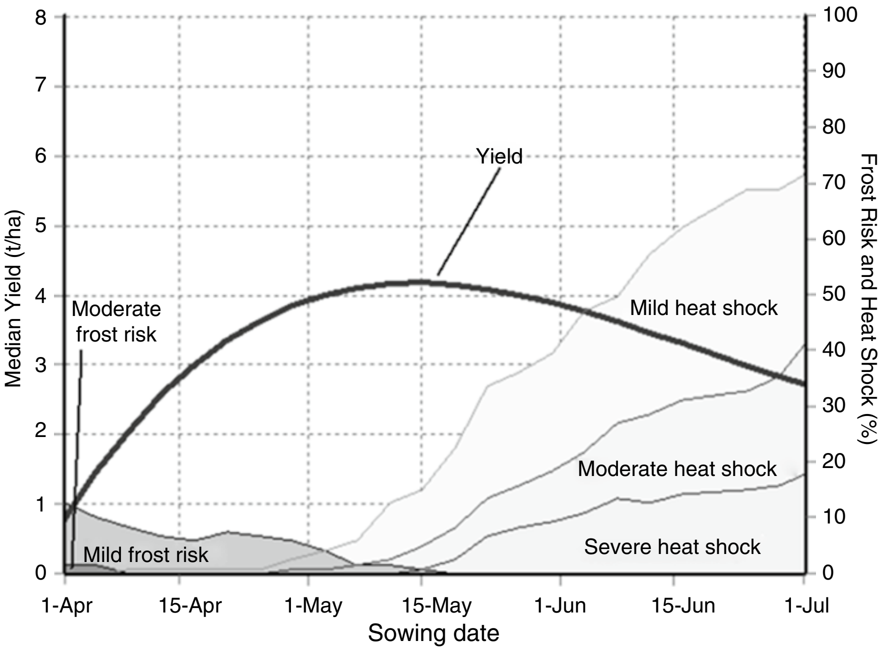

Fig. 37.7 Yield Prophet® Sowing opportunity report. Likely median yield is highest from sowing in mid May when frost risk is low and there is less than 20% risk of heat shock

Yield Prophet® also allows scenario predictions. The likely impact of different sowing dates, varieties, nitrogen applications and irrigation can then be determined by simulating different 'scenarios'. Yield Prophet® calculates a probability curve for each scenario, and subscribers use this to determine the probability of achieving or exceeding a yield response from the addition of nitrogen (Fig. 37.6) (or water).

Yield Prophet® also can indicate likely yield from different sowing dates (Fig. 37.7) based on climate records, including the probabilities of damage from frost and heat stress, for any time of planting from 1 April to 1 July. The best planting time (sowing date) for maximum grain yield is then seen to be about mid May.

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Chapter 38
When Culture and Science Meet, the Tension Can Mount

A Reflection on Agricultural Education and Extension in Tanzanian Rainfed Farming

Brian Polkinghorne

Abstract Rainfed agriculture technology and land care are changing rapidly in most Western countries, but in the majority of African countries they are either in neutral or reverse. In this chapter it is argued that powerful cultural forces can have an extremely limiting effect on any attempt in Tanzania to implement the much needed changes. Unless the deep-seated cultural forces are acknowledged and accounted for, both the local and expatriate extensionists have little chance of achieving positive outcomes of any food security goals.

Keywords Cultural clash • Third World development • Barriers to technology transfer • Limited good • Appropriate technology

38.1 Introduction

When I was a young lad in Australia, with an old Model L Case tractor, we could cultivate 50 acres (20 ha) in an extra long day on our rainfed farm (after my brother rigged up a 12 V battery and a spotlight). Now I have friends who direct drill 50 acres in an hour!

When I first came to Tanzania, East Africa, in 1970, it was estimated that 70% of the land was tilled by hand hoe, 20% by oxen and 10% by tractors. Now in 2009, as I prepare to leave, guess what? Still 70% of the land is cultivated by hand hoe! Agricultural systems in Australia started in front and have leapt ahead in rainfed farming technology and productivity. Tanzania started way behind and hasn't moved. This difference is the issue I want to address here.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_38,

My brother first visited me in Tanzania in 1995 and commented, “Wouldn’t I love to get a wideline[1] seeder going out here.” He soon realised, however, that this would put thousands upon thousands of people out of work and drive them deeper into inescapable poverty. I have lost count of the times I also have been tempted to import and introduce a few pieces of Australian equipment into Tanzania over the years, only to be rescued from the temptation by asking myself what its socio-economic consequences would be. This has then led me to abandon the ‘crazy’ Western ideas, and to start working again on tiny incremental changes to improve what is already here, in the context of economic possibilities, and socio-cultural permissibility.

As a result, day by day there have been cultural clashes in my head—the tension between the possibilities of the application of science on one hand, and the limitations of poverty, poor education and culture on the other. Many years ago, a good friend working in Third World development said to me, “Expatriate Third World development work necessarily involves a constant clash of cultures. The best one can do is to make a compromise which brings the greatest benefit to the poor”. His insight has proven to be stunningly correct, and his remedy I have used as an effective guiding principle over many years. In rainfed farming in Tanzania, and in fact in almost every department of life—‘When Science and Culture meet, the tension can mount.’

I make these reflections as a trained theologian and agriculturalist, having worked with three very different tribal groups in Tanzania for 25 of the last 39 years. I came to Tanzania all fired up with technical ‘know-how’ straight out of a good agricultural training system in Australia, and met head-on the limitations and overwhelming power of culture. Of course, I knew that our science-based approach to agriculture was superior to the miserably poor systems, almost non-systems, that were being applied here, and that it was my God-given duty to teach the students and farmers the truth! After an ashamedly long period of time, I began to awaken and understand that agriculture always functions within cultural bounds and society’s expectations. That happens in Australia, but we do not acknowledge it because our agricultural approach is an outworking of our cultural value systems. The culture of a country like Tanzania is almost diametrically opposed to Australia’s, so the cultures clash and one has to find ways and means of not only surviving the clash, but making the best out of it. For example, science says that in a rain-deficit area, you should sow the seed as soon as possible after rain to take every advantage of available moisture. Culture here deems that the first day after the opening rain is a day of rest and, if the second day is windy, that is also a rest day! In another area in which I worked, a death in the village means that nobody works on the day after the death, and if the death occurs in your hamlet, nobody works for 3 days after the death. Culture and science are on a potential conflict course.

To set this reflection in perspective it is helpful to acknowledge that, according to the World Bank Country Report of 2008—‘Tanzania is one of the poorest

[1] See glossary for unfamiliar terms.

countries in the world. Per capita annual income in 2006 was about US$350. Life expectancy at birth is 51 years.' The area in Tanzania, in which I presently work, has an annual per capita income of approximately US$220, or US¢ 60 per person per day, which is well under the internationally-declared poverty level. Agricultural GDP is said to be growing at about 3.5% per year, but a growth rate of 6–7% is needed to just halve the incidence of abject poverty by 2010. Eighty percent of Tanzania's labour force is involved in agriculture. Health and education services are very poor, and an average of 550 mm/year of summer-dominant rainfall in the Central Zone where I work now makes rainfed farming very risky in the tropical heat with high evaporation rates. It is acknowledged that here in the Central Zone there is a serious food deficit about 1 year in every 4. Farm sizes are between 0.9 and 3 ha per family. Among the quarter of a million or so people in our catchment area, over 80% of whom are smallholder self-reliant farmers, I have only seen one working tractor, with a 3-disc plough.

Let me list some of the ways that our cultures and agricultural systems have clashed, the reasons for this, and techniques I have found that have worked effectively to bring 'the greatest benefit to the poor'.

38.2 Factors in the Clash Between Science and Culture

38.2.1 Scribbles on a Piece of Paper

Let's get one thing clear. I am not going to present technical data about rainfed farming here because that does not appear on the radar screen of the vast majority of farmers in Tanzania.

Australia and other western countries have a science-based agriculture. We churn out research results and reports, confettied with graphs and charts, predictions and forecasts, to a well-educated, scientifically-oriented audience of advisors and farmers. Via the principles of information saturation and 'keeping up with the Jones', augmented by television, radio and agricultural magazines, change—often holistically positive change—takes place. Change, improved efficiency and more recently environmental sustainability, are now all taken for granted as normal in the Australian agricultural landscape.

Here in Tanzania, in an orally-based, very poorly educated society, tenderly produced research results are viewed by the vast majority of farmers as scribbles on an otherwise good piece of paper. Seeing something with your eyes and pouring it through the sieve of societal values may have an influence, but a graph in a society which does not comprehend how to read one, is like "a sounding gong and a clanging symbol".

Change and improvement are not the issues—survival is. It has been that way for centuries. "Why change?" the farmers ask themselves, "because we *are* surviving" Data produced on a piece of paper, written in either English or Kiswahili, have no chance of influencing a farmer when compared to what the neighbours say and think and, in many situations, what the ancestors and keepers of societal values may say and think.

Where survival is the unspoken default position of a society, and change is regarded as an intrusive alien, agricultural educators or extension workers really have their work cut out. For example, the Germans tried to introduce cotton into northern Tanzania pre-World War I. I tried to introduce reforestation into that community in the 1990s, and when we decided to pull out of one village because of their very poor performance, I was told we could not do that, because we had only been there 1 year and the Germans took 6 years with stock whips (literally) to get them to grow cotton. (Interestingly, the locals secretly boiled the seeds in oil before planting, and then showed the Germans that the seeds would not germinate—but the whips kept on cracking on bare backs!) The British, and later the Tanzanian Government, tried to introduce the idea of using oxen for cultivation. The people argued that oxen were not designed by God for that purpose and it took over 10 years of intensive work to get the idea to start to catch on. Similar stories can be told for rice, and the highly sensitive issue of building and using toilets. In a society where the default position is survival, the agricultural and extension workers are in for a tough time to get change, and especially the concept of improved efficiency, to take root in the psyche.

38.2.2 The I/We Factor

Although we do not officially acknowledge it or remind ourselves of it publicly, we Europeans basically operate on the 'I' (or what I call the Descartes) principle. The principle states that—*'because I think, I am'*. In total contradiction to that is the 'We' principle which operates in mainstream African psychology and which says or assumes—*because you (plural) are, I exist.*

In agriculture, the western farmer is relatively free within his or her parameters of physical constraints, to experiment, try new crops or animal management systems without obvious cultural limitations impinging too deeply. In many African societies, to experiment, innovate or improvise is a dangerous 'no-no'. To attempt to do so is to place yourself above others as a superior individual and therefore to break the bonds of relationships. Such actions potentially denigrate the honour and respect of elders and community, and question the wisdom of the traditions which have enabled the people to survive for century after century. Such radical, threatening actions as individual trials, experiments and new techniques must be nipped in the bud in many African societies, so that the 'We' factor is respected.

An example of what we did here in Tanzania to overcome this problem in one situation was to make a compromise in agriculture and reforestation which benefited all, but acknowledged the importance of both the 'I' and the 'We' factors.

The Australian and Tanzanian governments had agreed to establish a large reforestation program in northern Tanzania, and I was asked to be the Director. The plan was to acknowledge the importance of the inclusive 'we' mentality by having each village establish a community plantation on a communally-owned area. I was deeply concerned that because the trees would belong to everyone in the village, they would effectively belong to nobody in particular and therefore management and care would be a nightmare. I already knew enough of Tanzanian pastoralist mentality to know that it would be a free-for-all stampede to see who could get the greatest number of illegal cattle in the tree plantations for grazing, resulting in inevitable tree decimation. What we eventually achieved was to make a compromise which acknowledged the positive points of both African and Western cultures for the benefit of the greatest number of people. We emphasised that the villagers were to plant trees in the communally-owned area and that *every* family in the village was to plant trees—the 'we' factor, but that every family would possess their own private row of trees to care for, harvest and use privately—the 'I' factor. On top of this, we added another dimension which contributed enormously to the efficiency of labour input. Village by-laws were passed which said that every family was to plant two rows of either food or cash crops between their row and the neighbour's row of trees for the first 2 years of the plantation's establishment. Another village by-law stipulated that the trees must be weeded twice during the growing season and once more at the end of the rains. This worked like a dream. Although I have yet to learn an effective word in the Swahili language for 'efficiency', this is basically what was achieved. When the people weeded their crops, they also weeded their trees. They managed to combine short- and long-term benefits in the one operation—immediate food or cash from the crops and long-term benefits from the trees, which became their standing bank accounts. (Previously about 25% of the people had 'walking' bank accounts in the form of cattle, but now they all had a new form of security—a standing bank account in the form of trees which they could sell in times of emergency.)

The 'I'/'We' factor also came strongly into play when we looked at agricultural education and extension work.

In my experience of western agriculture, visions are broadened and the breeding ground operates for innovation, experimentation and 'improvement' (whatever that means in the long term), when a farmer is exposed to radio, newspapers and magazines, farmers organisations, advisors and 'over-the-fence' conversations about both local and international situations. In a country like Tanzania, not only are most of these awareness-raising exposures not available, but they are sometimes positively discouraged.

After the expenditure of a significant amount of sweat and frustration, I had produced my first little booklet on tree planting and care. People received the booklets willingly enough, but I soon discovered that they were not being read. Why not? Bad Swahili? Poor explanations and illustrations? Maybe I had touched some taboo, but this was not likely as I had passed the draft around to several people who were not too scared of me to adjust and edit the material. Eventually I found why I was not being read. It was because the 'We' culture in the village basically puts a ban, or a taboo, on reading. The reason for the ban goes like this. If those neighbours over there are reading, they are most likely to be absorbing new ideas which could mean two things: firstly, they will become different from us and may then be capable of exploiting us, and secondly, by being different, they are excluding themselves from us and potentially destroying our unity and relationships.

Thus that technique of education and extension by reading was unavailable to us but, after some time, we did manage to implement an effective extension program through making and screening widely a series of films. I proposed a theme for the first film but, through the strong team-spirit I had formed, the local managers told me that the only way to motivate and change people's attitudes to trees was through *shame*! They explained that in a tightly knit, conservative, gossiping village, one's status and respect are major factors in one's well-being. If a person is shamed, that is a huge burden and people will go to great lengths to avoid it. So a film theme was designed to have one of the characters shamed time and time again because he had refused to plant and care for trees. This technique worked wonders and was a major contributing factor to the planting and rather exceptional care of an extra several hundred thousand trees.

In the next agricultural program I directed, I took these lessons seriously and we devised a system of community study. An organisation here in Tanzania had produced a correspondence course with a series of booklets in Kiswahili on agriculture and livestock for group study—for those who could read and write. We went further than that and expected that all people in our target villages would be involved in the groups. We created the village expectation that *all* people would study in small groups, (the 'We' factor) and a total of over 1,300 people did the course. We had previously trained two people per hamlet (one woman and one man of course) in our ethical agriculture techniques, equipped them with a bicycle each and assigned them to gather the people of their hamlets together in groups of between eight and ten people for group 'study'. These trainees suggested that there would be desperately poor families who needed the education but who could not afford the Australian $0.75 for a course of ten booklets, so we subsidised the price and the correspondence course took off. It was a huge investment for us in time and organisation, with our own extension workers visiting the groups from time to time and our trainees meeting together with us monthly to share problems and joys. With such a high percentage of the people studying together, those who wanted to innovate were basically given 'permission' to do so by the community involvement in the process. We eventually made an impact—because it included the 'We' dimension, a very strange concept for the western or Australian farmer.

38.2.3 Limited Versus Unlimited Good

In the West, we are constantly striving for improved quality and quantity per hectare. We implicitly believe that the sky is the limit. Through breeding, soil nutrient balance, plant spacing, and timing, we believe we can produce more, and be more efficient in what we do. In other words, we believe in *Unlimited Good*.

In many African societies, the *Limited Good* mentality is alive and well. For instance, many societies believe that there is a certain amount of goodness (such as fertility, rain or grain) available in each village. If one farmer adopts an idea that the advisors or teachers have taught him or her, and yields increase, then there is less available for everybody else because there is limited 'good' available in the village! Thus, change and improvement are effectively capped. If one farmer decides to buck the system and 'go for it' by implementing a change for greater agricultural output, then the keepers of society values will be forced into taking a series of protective measures. First up, the farmer will be told that what he is doing is not good, and advised to desist from that action. If that warning is not heeded, plants will be uprooted at night, or animals will disappear, or other appropriate corrective, warning measures will be adopted. If that does not convince the disruptive innovator to cease his threatening action, the witch doctor will be consulted and his advice followed—which can lead to the inexplicable sudden death from food poisoning of the destroyer of community solidarity.

I am not saying that this is the reality in all of Africa but, of the hundred plus tribal groups in Tanzania, my experience is that there are many more groups at the *Limited Good* end of the scale than at the *Unlimited Good* end. This is a huge disincentive to rainfed farming innovation, change and improvement in efficient utilization of the natural resources so generously gifted by God.

38.2.4 The Critical Mass Factor

In Central America, Ronald Bunch (1985) discovered that, in conservative agricultural societies, you need to have at least 65% of the people in your catchment area participating in any new system of production or technology, in order for the system to be sustainable when the aid money and personnel disappear. He called this the *Critical Mass Factor*. We employed this extension technique in the community tree planting and agricultural correspondence course referred to above. To ignore this factor in conservative agriculture-based societies is to flirt with frustration and defeat. Take the example of two switched-on Catholic priests in Shinyanga region in the 1990s.

The priests had decided to use the '*Early Adopter, individually successful farmers'* approach to initiate change. Four 'innovative' farmers were selected as Early Adopters and they were all taught the best techniques of how to obtain good maize yields. They were given inputs such as seeds of high-yielding varieties, fertilisers and insecticides. With close supervision and constant encouragement from the priests, the farmers put the techniques into operation. The crops were a staggering success story. No one had ever seen maize crops like this before. The priests were very happy, sat back on their laurels and waited for the agricultural revolution to begin the next year.

In the meantime, the priests stocked up with good seeds and all the required inputs and used the success stories to illustrate certain teachings in their Sunday homilies.

Just before the rains began, they announced the prices of the inputs, where they could be obtained, and a schedule for purchasing at a highly subsidised price. The rains came, but the people didn't! In spite of more encouragement on Sundays and during home visits, still no one responded. Eventually the priests called together the successful farmers from the previous year as not one of them had taken up the offer of more inputs. With great difficulty, they managed to get these four farmers to admit that, yes, it was a good idea, but no, they would not be doing it again. Why? Well, the farmers reluctantly revealed that despite the fact that they had harvested more maize than ever before, it had turned out to be the most difficult year they had ever experienced! Why? Well, after the harvest, they had had a constant stream of people coming to them wanting loans for school fees, to pay for a sick relative, to help with a funeral or wedding, to go on a long safari to see family friends, etc. Of course, they had to oblige by giving the 'loans', but no one was paying them back. Good crops, but never again, thank you very much! What do we learn from this? It becomes obvious that in many conservative African societies, despite the best of intentions and good individual results, without acknowledging the importance of the Critical Mass Factor, no replicable or sustainable change is possible. This story also helps to illustrate from another perspective the importance of the 'We' mentality mentioned before and how science and culture can encounter each other negatively.

Finally, this example and so many more like it, also illustrate that for many farmers in Africa, relationships are more important than possessions. To us Westerners, this is a very strange concept, but I tell you, it is still very true in many African societies.

38.3 Questions About the Clash

38.3.1 Is Change Organisable or Organic?

During the hey-days of Ujamaa[2] in Tanzania, my friend Joshua was an agricultural advisor to an Ujamaa village. He was requested to take on 50 farmers and train them to be living examples of good agricultural practice. When he started they planted just 'any-old-how' and yields were typically two to three bags per acre (0.5 t/ha) of sorghum. He taught them scientifically-correct spacing, timely application of small amounts of fertiliser, thinning and weeding. Production immediately shot up to between 12 and 27 bags per acre (2–4.5 t/ha) with an average of 15 bags (2.5 t/ha). Great! He kept on working with them for 3 years, and they maintained that level of production. Now when he goes back to that village, their production is back

[2] An African form of socialism that was the basis of Julius Nyerere's social and economic development policies just after independence. It included one party rule, nationalisation of the economy's key sectors, and villagisation of production which essentially collectivised all forms of local productive capacity.

to three to four bags per acre (0.5–0.7 t/ha). When I asked him why they did not keep up with the good work, his only answer was ‘uzembe’—laziness. I do not particularly like that simplified answer and so recently put that story to a group of 35 women I was teaching. Their response was that this dramatic failure was caused by poor education, poor understanding and laziness. During the discussion it also surfaced that if one takes a longer-than normal time to plant an area (as happens when you plant in rows) you are made a laughing stock of the community and they critically joke with you and ask—“When on earth are you going to finish planting that area?” After lots of discussion that day, the sad summary was that it is more important to be ‘quick and potentially hungry’ than ‘slow and satisfied’. Survival is definitely more important than ‘success’. Distressing. And recently I discovered a new saying in Swahili—“Don’t get upset or angry at problems” The implications are—accept failure and poor results as the way life is, and this is the antipathy of our Western approach which is that problems are there to be solved. We use scientific approaches to solve our problems in the West, but here in much of Africa there is a debilitating cultural stance which accepts poor results as the way it is.

In my attempts to dig deeper into what is happening, I ask myself if change in agriculture is organisable, as my friend did it, or organic—coming from the ‘gut’ of the people. I ask myself what deep cultural limitations are hindering change, and, year by year, I come up with another clue here and another there, but the breakthroughs are few and far between.

Take as another example my friend Elias in Dodoma Region who has a remarkable model farm (Fig. 38.1). The farm is well laid out with Neem trees planted all around the boundary; each crop type is planted in 1 ha^2 and his production is 10–20

Fig. 38.1 Elias and his children—I am teaching him about nodulation on his own legumes

times that of his neighbours. His farm stands out for half a kilometre or so on every side because his neighbours all have small, scattered cropping areas, but Elias' gun-barrel straight tree lines dominate the scenery. So I have asked my friend why I do not see any of his neighbours copying his example. He has told me that some of them have enquired why he is doing things so differently and how he gets such amazing results. He has told them that he studied a small correspondence course on agriculture, became inspired, and decided to implement these rainfed techniques. Then he asked them if they would also like to study, and some agreed. He arranged to get the booklets, set them up in small study groups and they did the course. The results? Well, four of them decided to put these principles into practice but, after 3 or 4 years, they all gave up and went back to their old ways. When I asked Elias why they did that, he just shrugged his shoulders and said he did not understand, but maybe it's too embarrassing for him to think about that one. An organised approach to agriculture, or life itself, does not come easily to the vast majority of African farmers. Their response is organic; it comes from 'the gut', highly conditioned by cultural traditions and expectations.

At the time of the great Ethiopian food crisis of 1983, the late Ryoicho Sasakawa, the Chairman of The Nippon Foundation, was deeply moved by the tragedy and soon joined forces with the Carter Foundation to address the rainfed farming issues of Africa. This was a highly organised operation. They called in the Nobel Prize-winning Dr. Borlaug of Green Revolution fame, to be Technical Leader of Sasakawa Africa Association. Every tool in the agricultural research, extension and demonstration toolbox was used. Between 1989 and 1998, in some of the more productive areas of Tanzania, around 40,000 small-scale farmers and over 1,000 extension staff were engaged in the program. Yields on those farms were lifted to three times the national average of 1.3 t/ha, but this was highly dependent on fertiliser use. When the fertiliser subsidies were removed, the farmers had to face the realities of high fertiliser costs and low maize prices, and production dropped significantly. In the second phase of the program in Tanzania, in close collaboration with the Ministry of Agriculture and Livestock, over US$90 million were poured into the Soil Fertility Recapitalization and Agricultural Intensification Project in just 4 years, but the program ended in 2004 with little appreciable change to show for all the effort!

Training can be given, locally or nationally organised, and change and improved production together with care of the natural resources can also be organised. However, unless the cards of politics, appropriate input and product prices and cultural acceptability all line up, significant, rapid and sustainable change remains an illusive dream if it is not organic in origin.

38.3.2 Can Even Taste Affect Change?

We were washing carrots in the irrigation channel. A visitor from the neighbouring tribal group in the Pare Mountains came and greeted us and asked what these orange-looking things were. Carrots, we explained. My Tanzanian employee asked him if he wanted to taste one. No, he didn't. Other workers joined the teasing and joking and daring. Eventually Iligi washed a carrot thoroughly, snapped it in half, started eating one half, showing exaggerated enjoyment and handed the other half to our visitor. After lots of ragging and daring, our visitor took a gingerly taste, ran over to the irrigation channel and vigorously spat everything out, several times, to make sure that none of this obnoxious stuff was still in his mouth. Of course, everyone roared laughing, but in reality it was serious business. It showed me that even the introduction of new foods and tastes, no matter how nutritious and economically beneficial they may be, also had to be sieved through the cultural boundaries and barriers.

On the other hand, in the Mwanza Region many years later, I noticed cucumbers being hawked around the streets, then little cucumber stalls being set up, then cucumber salads appearing on the menus of some of the better-class restaurants. A little investigation revealed that these cucumbers were very similar to a wild cucumber that grew in the region during the rains, but these new ones were tastier and bigger, so they were not only acceptable, but sought after. Science and culture must invariably go hand in hand in order for a new crop to be accepted. Without being able to accommodate or leap over the cultural barrier, the agricultural extensionist faces a huge uphill battle.

38.3.3 So the Plough Never Lies?

One of the frustrating aspects of rainfed farming here is that low standards are totally acceptable. There is a saying here—'The plough never lies.' The meaning is that if you go out and plough the land and plant a crop, you will get *something*. You may have ploughed 4 or 5 acres and got only half a bag of maize, but the plough had not lied—you have got something. Trying to impart the concept of efficiency of time, money or natural resources is about as foreign as the idea of flying to the moon—and sometimes I think that the latter may be easier to achieve.

I recently took over a new managerial position. On the office computer screen was a picture of the previous manager, a wonderful, retired Tanzanian. He was standing in a very sparsely populated field of maize and he was looking at and holding one pigeon pea plant. No other pigeon pea plants were visible in the field, but this was photographed as a demonstration of intercropping! I would never have taken the picture and, secondly, I would never have made it available for the donors to see; but the retired manager did not see the incongruity of the situation. 'Something is always better than nothing' is the mentality, which irritates and irks westerners close to the point of despair. This acceptance of such low performance not only leads to a cultural clash, but is fuel for donor fatigue, and the temptation to give in to very second-best results. So what is the answer? I think that to be forewarned is to be forearmed, so expatriates need to be aware of the potential obstacles that they will meet. Secondly, to have the persistence of a blue-heeler cattle dog—never give up aiming for the stars as the Chinese say. Thirdly, be prepared for the long haul.

38.3.4 How Big Is an Office Magnet?

We always invited the District Forestry Officer with us when holding the first meeting with a new village government in the large reforestation project described earlier. On the first few occasions, he came with us but I could see that the poor man was uncomfortable. During question time, the village leaders usually asked him questions about government policy and implementation, and sometimes, slightly technical questions about trees. He was so poorly equipped for his position that it was often embarrassing to observe his responses. After a few visits, he started to find excuses for not going to the villages with us. Some vitally important forms had to be filled in, his boss might be calling a meeting, he might have to take his child to the hospital, and so on. It soon became obvious that there was something like a strong magnet in the office holding him there. It is the same with agricultural officers. Shuffling pieces of paper around the office, where it is relatively comfortable, where tea and snacks are readily available and there are lots of friends to talk with, is always more attractive than visiting the farmers who desperately needed the advice; but the ‘office magnet’ is a huge deterrent to effective extension. It is uncomfortable out there in the villages, from which many people have worked so hard to escape for the ‘better life’, so why would they want to go back? And historically, the people with the good life were the colonial officers with great power derived from a pen and paper, sitting at a desk. There was an unwritten law—if you want to get status and power in life, get behind a desk. The office magnet holds many extension people in the towns, away from the villages where they are needed, and effective extension is thwarted.

38.4 So What Is Happening?

38.4.1 The Injustice of Nutrient Transfer

There is an unrecognised, widespread and destructive dilemma in Africa—the unregulatable conflict between the pastoralist and the crop farmer. It all stems from the dichotomy between the ownership of land and its accessibility to others.

Let’s say, for example, that I am a very poor farmer with no cattle or goats. While I have a crop on my land, I am protected by the village by-laws. If a herdsman accidentally allows his animals to enter and eat or trample some of my crops, I can go to the village government authorities and seek, and often get, some form of compensation. But once I have harvested the crops, it is first-come-best-dressed. That is, my wealthier neighbours with livestock graze them on the stubble and weed residue left in my cropped area, decimating all the latent nutrients in the stubble by consuming the whole lot, then literally taking most of that off to his night cattle yard, where the cattle deposit a good portion of my nutrients as manure. Thus, at the end of the dry season, my richer neighbour has my nutrients in the form of manure readily available for spreading on his farm, and this puts him in a position of physically and financially benefiting from my poverty. If I want some of my nutrients back in the form of cattle manure, I might have to go a great distance to his compound, beg for permission to use some of the manure, most probably pay for it, and then have the burden of somehow dragging it back to my plot as I do not have any draught animals to pull a cart. On top of this dilemma is the extra long-term dimension that my land is continually stripped of organic matter. This makes the soils harder, less able to store water, seriously depleted in biota and more subject to erosion, which means that I am more strongly imprisoned in my poverty.

As an attempt to address this situation, in one area that was becoming particularly badly eroded and degraded by the high stocking rates here in Tanzania, the government imposed a total destocking policy in 1973. This caused an uproar amongst the cattle owners who were, of course, the most prosperous and influential people in the society. The government kept up the pressure for about 10 years, and erosion was significantly reduced. When the government reduced its strong-arm tactics and handed management over to the villages, the cattle crept back in and the system soon collapsed. On the other hand, the Diocese of Central Tanganyika established a participatory system of changing from extensive to intensive cattle management in a cluster of villages. This has been much more successful and continues to this day. It has been concluded that by this method, “more people can survive per square kilometer and it particularly favours poorer households” (Holtland 2007).

In one way, the fortunate thing is that, in the vast majority of villages, nobody recognises that nutrient transfer is happening so there is no resultant conflict. As the old song says however, ‘The rich get rich and the poor get poorer’. Poverty becomes self-perpetuating as land degradation marches on unhindered.

38.4.2 Good Intentions, Not-So-Good Outcomes

Before the Sasakawa project, referred to in Sect. 38.3.1, there had been many attempts to improve rainfed agriculture with the best of intentions, but not such good outcomes.

As a result of food aid (often gifts of wheat) coming into Tanzania in the late 1960s and early 1970s, the people of Tanzania acquired a taste for wheat flour, as bread and other wheat products became more readily available. In an attempt to address this issue without using precious foreign currency to purchase wheat overseas, the Tanzanian and Canadian governments co-operated to institute a large, highly-mechanised Wheat Scheme in Tanzania. Land was allocated, machinery and experts poured in from Canada and a large-scale operation was established with varying degrees of success and frustration. The large Canadian equipment needed a fleet of Canadian technicians to operate and maintain it, and they came willingly with the very best of intentions. Almost before we knew what was happening, the Wheat Scheme was taken to court. The problem was that the large allocation of land cut straight across a natural migration route for a tribe of people who had been moving their cattle back and forth over the years between winter and summer grazing areas. Because of the extra distance and shortage of water to skirt around the wheat allocation, they just cut through the middle and knocked down large swathes of wheat. This irked the Canadians who asked the government to stop the pastoralists, but the situation just went from bad to worse, and finished up being battled out in the courts for years. Relationships soured and bitterness mounted year by year. Good intentions, but not the happiest outcome.

Although not a rainfed agriculture example, another aid project in the south-west of the country enabled farmers to start irrigated rice production. They were allocated large areas of good land, but their use of the water was very wasteful, and vast amounts were allowed to flow through the production area and out into the never-never. Some years later, it was claimed that the blackouts and lost production in the capital Dar es Salaam were caused by this rice scheme. The claim was that the irrigation scheme had taken so much water from the river system that the hydro-electric dams were not filling, electricity generation was seriously reduced, and the national output of the few effective Tanzanian factories was negatively affected.

38.4.3 The Rake, Match and Plough Syndrome

There is something of a frenzy of activity in the farmers' fields here a month or so before the rains arrive. People are out in the fields with a three-pronged local rake and a box of matches. They rake together in small heaps or lines every tiny piece of remaining stubble and weeds from the previous season that has not been consumed by the cattle and goats. Then, like the good pyromaniacs that we used to be in Australia, they burn the lot. Now the field is nice and 'clean' and ready for the sun to bake, and for erosion to be exacerbated. Locally, they call this 'kuberega' and it is dominant in this zone. When I ask the people why they do it, they come up with a long list of limp reasons such as that it gets rid of the scorpions, that any tree stumps remaining in the ground are visible and therefore when hand hoeing they will not accidentally hit one of these and have the hoe bounce off and bite into their bare feet, causing an injury. When I start talking about caring for God's earth, instead of aggressively destroying the soils and deepening the poverty of their children and grandchildren, together with all the advantages of no-till, illustrated with pictures and local success stories, they look at me as if I am an alien from outer space. For people who take their faith seriously however, I have a point that stabs their hearts. I ask them what sort of Christians they are to be coming to church on Sunday and saying "Praise the Lord" and then going out to their fields on Monday and destroying the Lord's creation. This then opens the door for meaningful conversation and learning.

Depending on the soil types, many people use their own, or hired, oxen and a plough to further expose these fragile soils to the sun and oxygen for the total breakdown of any organic matter that would dare to survive. Whenever I ask farmers about their crop yields over the years, they all agree that their yields are falling. When I make the connection between production of virgin soil with high organic matter and the way they have sterilised their soils through 'kuberega', they understand. Yet translating that into practical remedial action is a long, hard road involving a total cultural and mental switch. Once I start pushing Appropriate Technology Conservation Farming, we have yet another source of cultural conflict—and when science and culture meet, the tension usually mounts. Scientifically, I can show them the way forward, but culturally the brakes are on.

For changes to occur in rainfed farming systems there are mountains of problems to be overcome on top of the cultural and socio-economic ones, such as what happened to us recently. We had designed a demonstration/trial with peanuts. The trial consisted of replicates of peanuts planted in plots that had been ripped, fully tilled, or direct planted. This was done in one area with dry, tall grass from the previous year, and also in 'kuberega' areas (the rake and burn process). The best result came from 'fully ploughed in dry tall grass from the previous year', followed by 'ripped lines in grass', then the 'fully ploughed kuberega' area. I have rarely seen such a dramatically impressive trial, showing just the effects we wanted to demonstrate for soil improvement and labour efficiency. But then the word must have been passed around. The baboons came from quite some distance away and very methodically went through our best plots with the most mature peanuts, pulled up about 20% of the plants, neatly shelled the developing peanuts and then spread the husks on the ground. There goes another trial down the drain—or down the gullet actually!

38.4.4 Appropriate Technology Conservation Farming

Our Western Conservation or No-till Farming involves the use of sophisticated machinery and expensive inputs. Apart from the tiny minority of African farmers living with good soils, comfortable climates and non-binding cultures, these inputs are way beyond the reach of most African farmers, financially and experientially—unless the price of food escalates and the price of fuel stays low. But, at our church-based agricultural institute, we have demonstrated that it is possible to use the hand hoe (Fig. 38.2), the oxen rippers and direct planters in a minimum-till regime to build up both organic matter and productivity. This is technically possible, but it will take perhaps a generation or two for this to become anything like a widespread approach—and a turn-around of the extension systems to get these ideas to the farmers. I keep on thinking about what I heard from an English radio broadcaster many years ago. Although not very interested in the details of his talks at the time, I do remember his theme, spoken in the most alluringly broad West-country accent, "The answer lies in the soil". It is now clear to me that from the best farms in the west to the worst in Africa, the answer lies in the soil.

For example, I have just returned from a work assignment which involved 27 h sitting on local buses. During the tiring round trip, I saw only one area where

Fig. 38.2 Appropriate technology conservation farming

agricultural production was 'export-orientated' because the people were growing more than they needed. When I spoke with the people in that area, they told me that they could grow huge crops of bananas without any fertilisers because their soils were almost perfect. That was great, but what is needed to build up the soils in the rest of the country where production is slipping away?

Appropriate Technology Conservation Agriculture is perhaps our best hope of improving our soils—the basis of good life. Starting this process through effective and persistent education, establishing linkages between faith and culture, and providing some incentives for machinery and other purchases is difficult but very important work. The longer we delay the introduction of this approach, the more difficult the soil rehabilitation becomes.

38.4.5 The City Conversion from Consumption to Production

During the 1970s, I came to understand that the biggest city of the area, Dar es Salaam, had reasonably good soils and rainfall, but people had a very laissez-faire attitude. Production was extremely low, gross poverty rife and nobody cared. Now, people from all over the country are going to work, and then retiring, in the city. They take up land on the fringes and, because of a poor national retirement system, are turning into good farmers. However their contribution to overall food supply is small. Africans are farmers at heart—it is just that they have been terribly restricted by knowledge, cash and culture.

38.4.6 The Politics of Agriculture

The official stance of the Departments of Agriculture is starting to change. We traditionally tried to copy the *High External Input Agriculture* approach of the west, but now *Low External Input Agriculture* is being taught in the few remaining Farmers Training Centres. It is encouraging to see that the Tanzanian government has recognised the reality that the vast majority of farmers are resource-poor, and it is teaching within those limitations.

As well as that, despite the scary escalation of the Tanzanian population, and the somewhat emotional concerns about having enough land for the farmers in the future (85% of the population), the Tanzanian government has changed to encouraging private external investment in some large-scale agricultural production schemes. Before the time of the fall of the Berlin Wall, under the strict socialist system in Tanzania, with its built-in antipathy to foreign investment and private ownership, this was unimaginable. Now, with the assistance of some international donors, the investment processes have been streamlined. Access to land has been legalised with very reasonable 'rents' available and some encouraging tax breaks. The previously stringent limitations on internal and external marketing systems have been dramatically eased. There is every chance of employing and training local labour and managers, thus leading to an all-round increase in the nation's human capital and food security. All these changes have come into place in a relatively short time, and this new venture is now pregnant with hope.

One positive political decision in Tanzania is that the 8th of August has been declared as Farmers Day and is a public holiday. Local and national Agricultural Fairs are held around the country, open for the week before the 8th, and some of these are most helpful. The Department of Agriculture and the Municipal Councils arrange some good demonstrations and models. The problem is getting people to the Fairs and analysing what is happening there. In an attempt to utilise this positive activity, this year our organisation is offering cash for bus fares and lodgings to the farmers who take the initiative and get themselves to the Fair gate. We will then conduct them on a guided tour of the Fair. We will register these people and call them together the week after the Fair for follow-up and encouragement of the ideas they believe are appropriate.

38.4.7 The Right Time and Place Factor

In the 1970s, the cotton-growing area of Tanzania suffered a severe drought, transport was collapsing and so cooking oil, which is the approximate equivalent of milk, butter and cheese in our diet, was in very short supply. I wondered if there would be a way of producing our own cooking oil and decided to try sunflowers. I imported varieties from universities in France, USSR and the United States.

The USSR varieties thrived. I grew about a third of a hectare from the saved seed, bulked that up, planted a few hectares for ourselves and gave the rest to farming neighbours. I managed to buy a small Chinese electrically-operated oil-press, set it up in the nearby town, and we were in business. Farmers started knocking on the door for seed. I left Tanzania and returned to Australia. Six years later, I came back to the Kilimanjaro region and was amazed. Sunflowers were everywhere all the way from the airport to the town of Moshi and beyond. In the town, there were two commercially-operated oil extraction factories. The idea had taken off and was booming. I had 'planted a seed' and a large industry had grown and continues to thrive. The people of this area are undoubtedly some of the most progressive farmers, so being innovative in the right place at the right time can have an enormous positive impact.

Catholic Relief Services had been operating a variety of agricultural programs for both relief and development in the Lake Zone of Tanzania when, around the year 2000, they turned their attention to adding marketing to the recipe of factors they had been working with. They noticed that in the broad valley floors where chickpeas were typically grown on the residual moisture left after a maize crop, there was a huge potential for improvement in both variety and marketing. CRS devoted considerable financial, managerial and technical resources to enabling the farmers to make significant steps towards escaping the poverty spiral.

The outcomes of this well-planned and directed work are significant. For example, the area under chickpeas increased from 12,000 to 70,000 ha in just 7 years. Farmer returns on investment increased by 30–50% due to collective marketing. Although a savings and internal lending scheme was introduced to the farmers only late in the 7-year cycle, the results far exceeded all expectations and the local internal savings effectively surpassed the annual donor investment. This exercise came at quite a heavy price financially to the donor, but is judged to have been well worth the effort because the increased savings and borrowing in areas beyond the reach of the banks will have on-going benefits to the small-scale farmers well into the future. But the interesting cultural factor which arose from this exercise was that, although it has been quite clearly demonstrated that yield, price, and resistance to diseases and pests are significantly increased by two new varieties of chickpeas that CRS introduced, the adoption of those varieties has been almost negligible. The science has proved its point that the new varieties have a panoply of advantages, but the old variety is still the clear favorite.

So an individual or organisation being in the right place at the right time can make a significant difference to food production and human dignity where there are no cultural barriers. Yet if the new ideas or approaches do not take into account the particular cultural sensitivities, then we can expect verbal agreement but practical apathy.

38.5 So Is Africa Destined to Remain a 'Basket Case[3]?

Africa generates some rather stark and disturbing labels: 'Basket case', 'Aids Dissemination Centre', 'Corruption Epicentre', 'Perpetual Poverty Zone', but for rainfed agriculture, maybe it ought to be labelled something like 'Sympathetic Survivors'. Apart from the local and sometimes devastating impact of soil erosion, the vast majority of Africa farmers are globally sympathetic because they consume such infinitesimally small amounts of non-renewable resources.

If you look at the latest Worldmapper[4] project images of greenhouse gas emissions for example, Africa is a midget. While the vast majority of its agriculture is rudimentary, it also consumes incredibly small amounts of resources such as phosphorus fertiliser, and destroys and pollutes far less than its size would suggest. Africa may be totally left behind in the production and efficiency races but, with such small inputs, it might be argued that it is efficient in its own way—that is, not by the tonnes of food per hectare, but by the very small amounts of non-renewable natural resources needed per tonne of food. Use that last parameter and I imagine that Africa is up with the world leaders. The first President of Tanzania, Mwalimu Julius K Nyerere, said in the 1960s "Let us run while they walk". He believed that Tanzania had the capacity to catch up with the West in factory production, education, health, agriculture and so on if they put in extra effort and commitment. The reality is that the West has forged ahead, and Tanzania lost its impetus in a few years. It now lags behind, but maybe that could be reckoned as good for the health of the planet?

Here is a radical thought. If all people on earth lived like Australians, I am told the human population would need about 3.5 planets of resources to keep the human adventure on the road. That means that Africa must remain poor so that the rest of us can keep on living our exorbitantly expensive lifestyles. If Africans consumed like us, the human species would rapidly become extinct!

What then are the implications for agriculture? When all the pious platitudes are stripped away, maybe our task as mission workers, humanitarians, educators and development aid workers is to strive towards enabling Africa to live with dignity in its poverty. That's another radical and disturbing thought, but the escape routes are narrow and perplexing. Not only are there many cultural barriers to improving African agriculture, but politics, corruption, poor education, malnutrition and ill health are all stumbling blocks to change. So is Africa a basket case? Are there no lights at the end of the tunnel?

Yes, I believe that there is hope, but aid, research and development philosophies may need to adopt some radical new parameters. But here are some encouraging signs.

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[3] Slang for a nation or organisation with serious financial or other problems.

[4] www.worldmapper.org

38.6 The Human Factor

If you travel around Tanzania, you will come to areas where you think that all I have been saying about our poor agricultural system, bound by culture and the tension with science, is completely wrong. There are regions where I have seen positive changes in agriculture over the years that I have been here; but these are the minority of situations and farmers. Yet whether or not there are fertile soils, comfortable climates and motivated people, there is one factor for positive change that applies everywhere, and that is that there is no substitute for honesty, faithfulness in work and commitment to more than just increased production. These are sure to offer the hope for the ongoing constructive change that is needed.

Two of the ‘successes’ that I have had in Tanzania have been directly linked to the human factor. In the mid-1970s, I was managing a small-scale, home-made kerosene incubator, chicken hatching business. The President heard about us and visited. We felt greatly honoured, but he handed out an enormous challenge. After looking at our hatchery, he told me that the country was losing precious foreign currency by having to buy about a million day-old chicks a year from overseas. He then looked me in the eye and asked if I would use our church farm to hatch a million chickens a year! Fortunately, I had thought about expansion and realised that with kerosene incubators, I was very limited as we could only operate incubators with one layer of eggs, depending on radiant heat for the process. I responded that we could set up a large hatchery, but that we would need electricity. He told me that the government would bring electricity to us free of charge, if I would make all other arrangements. The process went ahead, and I must say I am pleased and proud when I return there from time to time to find that now, 34 years later, the whole process continues very effectively. The primary school leaver and the religious brother I trained for the job are still churning out the chickens. That is the result of the human factor—honesty, dedication and commitment to a higher cause—rare and precious items.

Likewise in the 1990s, I was directing a large reforestation project in Northern Tanzania funded by the Australian government through a consortium of churches.

We had employed four local foresters as Cluster Managers, and I could only get to see each one of them once a week. I set about building a team, which became very strong and effective, and we shared all the successes and problems equally. I strongly encouraged openness, honesty and commitment by helping them to understand that they could cheat me, cheat the local people and the two governments, but they could not cheat God. The whole operation worked so well that when the project concluded, although Australian aid funding to Tanzania was all but zero at the time, the Australian government was sufficiently impressed with this cohesive and effective team to fund them for an extra 3 years on another reforestation project in a nearby district. It was the human factors of honesty, faithfulness and, in their case, commitment to a higher cause that were key elements in their resounding success in working with farmers for environmental and financially positive change.

We have gone astray for many African people by divorcing agriculture from the all-pervasive spiritual aspects of life here. One day, I gave a lift home to some women who had been attending one of my seminars. They were talking excitedly in the back of the vehicle in the Gogo language. When they dropped down I asked my friend who was traveling with me what they were talking about in such an animated way? “Well,” he said, “one of those women was going on about the fact that she had attended three previous agricultural training seminars and went home and promptly forgot all about them. But, she says, she is compelled to change now, because she has finally understood that she cannot go on claiming that she is a Christian if she doesn’t put into practice what that old European said, because unwittingly she has been destroying God’s creation and the future of her family by happily destroying God’s property, the soil”. The science and technology are available in abundant supply, but linking that with the best virtues of the human spirit and applying the knowledge to the spiritual realities of Africa is the exciting challenge we face now. As is famously said these days—“It can be done” and we must do it together, but it will only work for the benefit of Africa and the human race if the deep cultural forces are fully acknowledged and the indigenous spiritual perspectives are addressed with serious determination.

38.7 Conclusion

There is hope that farmers in the deep pit of poverty and ignorance can climb out of it, but the rungs on the ladder provided must be thoroughly impregnated with cultural awareness and sensitivity. Technology is great—I love it—but it must be moderated by economic realities, environmental impact, education, and experiential awareness in order to play a constructive role in increasing food security. Agricultural research is fascinating, but the fine details are totally lost on a resource-poor, hungry farmer. Research results need to be effectively translated through good educators in order to assist the recipients to respond. Global trade is such a powerful incentive in food production, and farmers here can respond, if ‘the price is right’ and the weather is kind. But at the foundation of our Western and African type societies there will always be a conflict as the West is a ‘doing’ society and Africa a ‘being’ society. So finally, in the broad sweep of all phenomena here, it is human nature and its concomitant culture which hold the key for the change needed in escaping poverty and increasing food security through rainfed agriculture.

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Chapter 39
Advances in No-Till Farming Technologies and Soil Compaction Management in Rainfed Farming Systems

Rohan Rainbow and Rolf Derpsch

Abstract With non-selective herbicides providing effective weed control, the system of no-till farming has gained significant global momentum. The initial focus in the development of no-till technology was to improve crop establishment, and this was followed by improving soil opener operation in heavy crop residues and in difficult soils. The benefits of conservation agriculture are further increased by development of controlled traffic, crop scanning and weed eradication technologies, precision agriculture systems such as autosteer guidance, total surface cover with crop residues and cover crops to reduce germination of weed seed.

Keywords No-tillage • Direct drilling • Controlled traffic • Precision agriculture • Herbicide resistance • Soil openers

39.1 Introduction

The development of conservation farming practices such as no-tillage (no-till) farming has been part of the evolution of broadacre grain growing technology in the quest to increase production efficiency.

The key driver for the change to no-till sowing technologies was the introduction of the non-selective herbicides, firstly paraquat and diquat, then glyphosate and the subsequent release of many selective herbicides.

No-till farming has now been adopted on more than 105 million hectares world-wide (Derpsch and Friedrich 2009); of this, approximately 47% are in South America (mainly in Brazil, Argentina, Paraguay, Bolivia and Uruguay),

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_39,

38% in the United States and Canada, 11% in Australia and about 3.7% in the rest of the world, including Europe, Africa and Asia. Adoption is increasing fastest in South America.

This profound change in farmer attitude to no-till farming has been helped by conservation agriculture and no-till organisations which have addressed issues of awareness, motivation for change and positive change experience with clear and simple messages. The requirements for successful no-till farming practice (Rainbow and Slee 2004) include:

- optimum soil physical condition for sowing and plant establishment
- accurate sowing depth
- adequate stubble handling
- balanced nutrition
- effective weed and disease management (given the absence of tillage and presence of plant residues).

Each of these must be planned for before the first implementation; then, with experience, farmers have continued to find more robust ways to manage each of them.

The no-till farming system continues to evolve. Seed drill designs have been substantially changed to allow functions such as deeper soil loosening, fertiliser banding, and accurate placement of the seed while moving through heavy surface residues. As no-till continues to be adopted, farmers are becoming more conscious of the impact of traffic in the field on surface and sub-surface soil compaction.

While there have been considerable advances in no-till seed drill design which have resulted in improved crop establishment, growth and grain yield, successful no-till farming also requires the integration with a range of technologies such as controlled traffic, guidance and autosteer. This chapter describes advances in no-till and the benefits from such integration. One benefit of these technologies is to minimise impact on the soil of the increasing weight of agricultural equipment in this low soil disturbance farming system.

39.2 Soil Openers for No-Till Sowing

This section deals with the key requirements of sowing depth, soil condition and stubble handling. Soil openers for no-till should give good penetration with minimal soil disturbance (Schaaf et al. 1980) and be able to operate in heavy crop residues.

Soil openers and covering devices should protect the seed from direct radiation while maintaining high soil moisture within the groove micro-environment, especially where sub-surface soil moisture is limiting (Choudhary and Baker 1981). Openers should minimise surface soil disturbance to maximise the cover of surface mulch and yet physically loosen and shatter the sub-surface soil to assist in rapid root development.

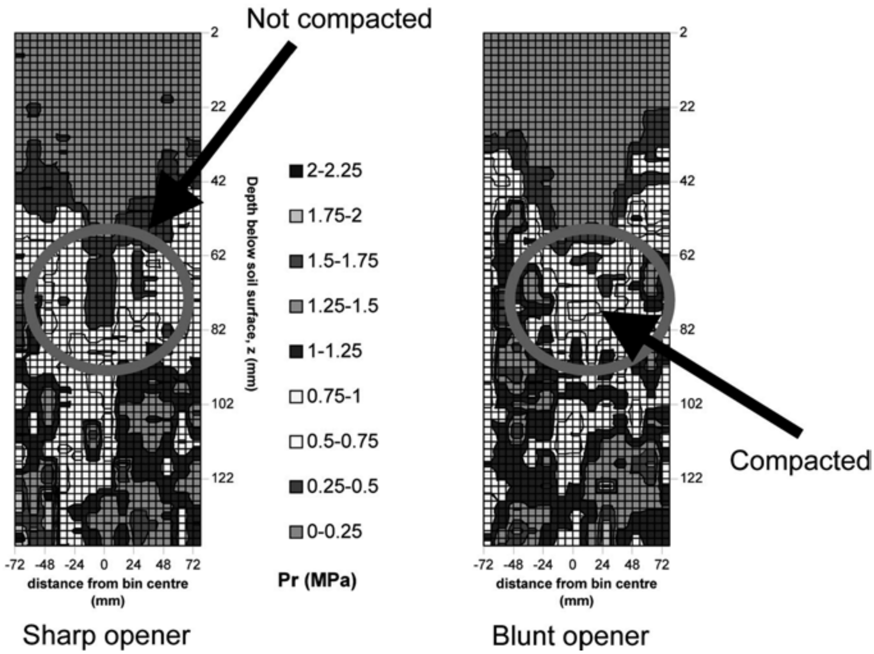

Fig. 39.1 Effects of a sharp and blunt soil opener on soil compaction at the base of the seed-bed (Rainbow 2000)

Plough pans or hard pans created by traffic can affect plant root growth; even the soil openers on seed planters can cause some shallow compaction or smearing (Fig. 39.1).

The spear-type seed drill soil opener with a press wheel covering device (Deibert and French 1989, 1990, 1991) currently provides the best wheat crop establishment for a range of soil conditions and crop residues. The main features of the spear-type soil opener include superior seed placement in a distinct V-shaped seed groove and a sharp leading edge which reduces the potential for soil smear in the seed groove. This type of opener has been manufactured by John Deere™ for a number of years.

The width and sharpness of the leading edge of a spear-type opener will affect crop establishment and growth (Rainbow 2000); wide and sharp type spear openers give 8–20% higher grain yields than narrow and blunt spear openers. Soil opener shape factors such as a flat underside and a blunt leading edge can increase penetration resistance and the energy requirement by increasing soil bulk density; this can lead to reduced plant emergence and hence grain yield. However, soil opener manufacturers appear to prefer blunt openers in an attempt to improve wear life of tungsten carbide inserts.

In North America, a range of openers, including the spear type, have given satisfactory performance under a range of soil moisture contents and degrees of compaction in sandy soils and in dry clay soils (Schaaf et al. 1979), but not in wet clays. In Queensland, Australia, the most practical set-up for heavy clay soils combines the spear opener with a smooth coulter[1] and single-rib press wheel (Ward and Norris 1982).

Large and small rake-angle shoe openers, with their sliding action through the soil, create minimal soil disturbance, whereas a triple disc soil opener can result in excessive smearing in the seed-bed when the soil is compacted and wet (Anon 1975).

Poor seed placement resulting from 'hair-pinning[2]' (when surface stubble is pressed into the seed-slot) will reduce establishment. 'Hair-pinning' can be a problem with disc seeders in wet conditions, but not with hoe openers which also provide more effective seed placement when soil conditions are dry at or soon after sowing (Lindwall et al. 1995).

Disc openers can smear the soil (Baker and Mai 1982a, b; Baker et al. 1996) as do hoe openers with a large flat base, but these smears are important only if the furrow remains uncovered after drilling and the smears are allowed to dry to form crusts. Inverted-T openers[3] smear the base of the furrow as much as most hoe openers but cause minimal compaction and leave a closed furrow. Consistent seedling establishment has been obtained with an inverted-T winged soil opener in a range of optimal and sub-optimal wet and dry soil conditions and in the presence or absence of surface residues. Several soil openers can place seed accurately at speeds of up to 10 kph (Slattery and Rainbow 1995). The inverted-T type soil openers gave similar or better seedling establishment and grain yield in direct-sown wheat compared to wider 200 mm soil openers on loamy sand soils (Bligh 1990). Derivations of the inverted-T opener have become popular in Australia, especially those manufactured from cast metal alloys with tungsten carbide pieces attached to the wearing edges (Baker et al. 1996).

The commercially-named Cross-slot™ opener,[4] described by Choudhary et al. (1985), can operate at speeds above 12 kph but requires draft power of more than 10 kW per opener. Its vertical down force of 9,800 N needs a static machine mass of 1,000 kg per opener for effective penetration of the soil (W.R. Ritchie 1995, Personal communication, Massey University, New Zealand). This means a draft requirement of two to three times that of most hoe openers currently used by Australian farmers, and this greater weight of tractor and seeder may increase soil compaction. The costs of manufacture and operational problems have discouraged the commercial use of this opener in Australian rainfed farming systems.

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[1]See glossary.

[2]See glossary.

[3]The inverted T opener consists of a knife type opener with flat (low lift) wings extending to 5 cm each side in a T configuration.

[4]Scalloped disk opener with wings for seed and fertiliser placement.

Optimal soil opener design is often a compromise between cost of manufacture and operation, suitability for operating in a range of field texture, compaction and residue conditions within an optimal speed range, and most importantly, achieving a seed-bed environment for optimal crop establishment. Tine-mounted openers often provide the most cost effective solutions to no-till farming, but are compromised by a large quantity of surface residue and are less able to accurately place seed at high sowing speeds. Disc openers while often more expensive to manufacture and operate, are a very effective no-till sowing system for farmers but can suffer some soil blockage and opener adhesion in clay-textured, wet soils (Desbiolles 2004).

39.3 Optimising Soil Physical Conditions for Plant Establishment

Soil openers must achieve a seedbed environment that has sufficient seed–soil contact for optimal seed germination, and with friable soil to enable optimal plant emergence for a range of crop species. Hard-setting and compacted soils can make the determination of a suitable opener for planting a difficult compromise. Soil openers can loosen the soil, manipulate soil moisture levels, and achieve accurate seed placement into a firmed seedbed environment.

Cultivating deeper than the seed row with a knife-type opener can lift moist soil and mix it with a drier surface soil at sowing depth; this can improve seedling emergence as long as the soil is then firmed to increase seed soil contact and reduce moisture loss (Tessier et al. 1991a).

Using a modified drill that cultivates 10 cm deeper directly under the seed row can result in improved root growth and higher yields than with either conventional direct drilling or sowing after deep ripping in a sandy soil (Schmidt and Belford 1993). Increasing the depth of soil disturbance (below seed placement) can improve grain yield by 32 kg/ha with each 1 cm increase in cultivation depth on a deep sandy soil (Schmidt and Belford 1994). The grain yields on deep sandy soils are improved because of increased root density and water use efficiency when the deep soil is loosened (Schmidt et al. 1994).

Deeper seed row tillage also offers some benefits for control of fungal root disease such as *Rhizoctonia* spp.; however, it can also have adverse effects. For example modified soil openers such as hoe or disc types which are used to band fertiliser below the seed can significantly loosen soil in the seed zone and break down soil aggregates, and also increase rapid drying of the soil furrow post seeding (Tessier et al. 1991a, b).

The spear-type soil opener minimises these problems. Optimal spear-type opener designs incorporate both deeper seed row-aligned tillage and optimal seed placement, sowing depth being controlled by a press wheel on a parallelogram mechanism (Fig. 39.2).

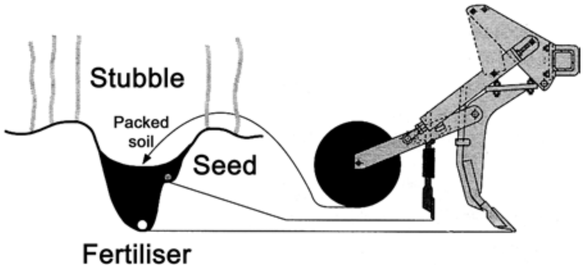

Fig. 39.2 Conserva Pak™ sowing mechanism for optimal soil tilth and seed placement now manufactured by John Deere™ (J. Halford 2000, Personal communication, Conserva-Pak)

39.4 Interaction of Seed Drill Soil Openers with Covering Devices

Both press wheels and trailing finger-tine harrows can be used to cover seed, although harrows have limited capacity with crop residues. Press wheels give better seedling establishment than harrows on both loam and clay soils even if hard-setting (Finlay and Tisdall 1990; Rainbow et al. 1994; Slattery and Rainbow 1995). They can therefore improve grain yield, particularly in dry soil (Foster 1991; Rainbow et al. 1992, 1994; Slattery and Rainbow 1995; Tessier et al. 1991b)—as long as soil moisture does not become limiting later in the growing season (Riethmuller 1995).

The spear-type soil opener in combination with a press wheel provides the best establishment for most crops. The relatively simple design and low manufacturing cost of the spear-type soil opener contribute to its universal popularity in Australia and North America.

Press wheels can be used in combination with harrow-type covering devices. Seedling emergence can be improved if press wheels push seeds into the base of soil grooves before bar-harrowing the surface (Choudhary and Baker 1980). However, the shape of the opener and that of the press wheel, combined with the weight of packing, are important for crop emergence. Although double disc openers produce a narrow furrow, a narrow press wheel may then pack the soil above the seed rather than around it, and impede emergence. Soil bulk density is increased as the size of voids is reduced. Smaller voids in contact with a seed are more likely to hold water and transmit it to the seed than larger voids, which tend to drain and become filled with air. Research by Johnston et al. (2003) found that opener-packer/press wheel combinations in Canada resulted in variation in grain yields of less than 10%, and a press wheel pressure of 333 N per wheel resulted in adequate emergence and grain yield across varied environmental conditions. Deep loosening by soil openers can significantly reduce soil bulk density in the seedbed. However, increasing the bulk density of the soil below the seed (using furrow firming openers, seed row firming devices or press wheels) to optimal levels of 1.0–1.38 t/m^3 (Adem et al. 1990) creates a firmer contact for the roots of the seedlings (Hultgreen et al. 1990).

39.5 Residue Management and Crop Establishment in No-Till

The benefits from combining stubble retention with no-till practice are well documented (Radford et al. 1993); however, tine seeders can have problems with heavy and long stubble. Levels of wheat stubble cover heavier than 3–4 t/ha can create handling problems with narrow plant row spacing (Slattery 1995); but reducing stubble length and density by slashing, harrowing or partial removal (grazing/baling) can minimise machinery blockages at sowing.

Reliable establishment of crops such as canola in heavy stubble is still a major issue for most no-till farmers (Desbiolles 2005), and problems at sowing are often best managed by planning as early as the previous harvest time. Surface standing stubble height should be kept below 60–65% of the effective tine vertical clearance. Fallen stubble length should be less than half the lowest value of inter-tine spacing i.e. the narrowest clearance between components of any two tines or between tine and wheel, in any direction (Fig. 39.3).

Wetting stubble increases friction and adhesion, which reduce the ease of flow across a tine. It also increases resistance to cutting and lowers resistance to bending, which promote hair-pinning with disc coulters and with narrow edge-on shanks in long stubble. As heavy stubble on the harvester trail[5] remains wetter for longer, sowing should be delayed until it has dried.

Stubble that has been rolled or trampled is often wetter, decomposes more quickly with less mass and shear strength, but can be more difficult to handle than standing stubble. Residue is easiest to cut with disc openers when wet and when the soil is hard.

Poor crop establishment when using tine systems in stubble and incorporating herbicides at sowing can be linked to issues such as soil throw, seed placement and soil disturbance. Soil throw can be minimised by operating at a lower speed or by using wider row spacing as for break crops such as oilseeds and pulses (Desbiolles and Kleeman 2002).

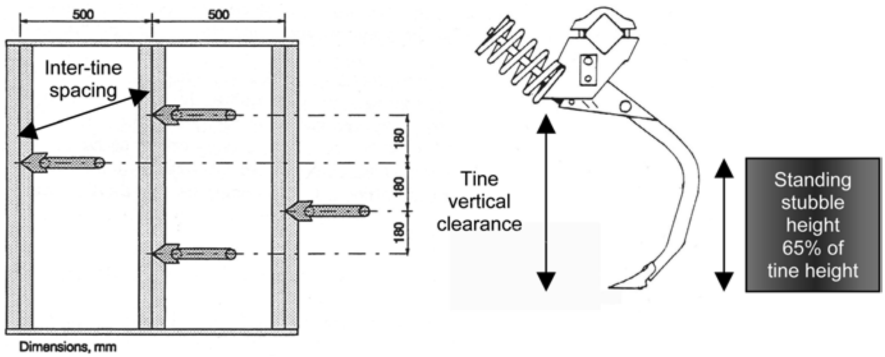

Fig. 39.3 Tine layout and inter-tine clearance for optimal stubble flow

[5]The trail of straw and chaff left behind a combine harvester.

Options for changing existing tine configuration are generally limited (Slattery 1995; Desbiolles 2005), but farmers can consider optimising the tine shape to improve stubble shedding and so minimise the size of stubble clumps. A circular tine shank of 40–50 mm cross-section is less susceptible to ‘hair pinning’ in longer, damp stubble than narrow ‘edge-on’ shanks. Vertical or slightly reclining straight shanks encourage imbalances in stubble clumps leading to quicker shedding. Commercial flat-on C shanks, free from bracket obstructions, can perform best in tall, standing stubble.

Layout should maximise the actual inter-tine spacing by increasing planter inter-seed-row spacing, tool rank spacing and the number of ranks on the machine. An inter-tine spacing of 550–600 mm generally will not induce blockages in 350–450 mm high wheat standing stubble (3.5–4.5 t/ha density). But for longer stubble, the minimum inter-tine spacing threshold should be increased to 650–700 (rolled stubble) and 800 mm (standing), and increased further towards the rear of the machine where stubble clumps get bigger (Slattery 1995).

To increase the stubble-handling ability of existing tine machines, residue-cutting disc coulters can be fitted at the front of the seeder bar in line with each seed row. These rely on two complementary principles (Desbiolles 2005)—effective slicing of the stubble and an efficient parting/wedging action. These conditions are obtained when there is enough soil reaction to sustain compression and wedging effects by a sharp blade at the soil surface (e.g. sufficient soil strength) and when there is adequate differential speed at the cutting edge to achieve efficient slicing (e.g. greater rotational to forward speed ratio, promoted by thicker discs and smaller wedge angles).

Yetter® fingered wheels (manufactured in USA) set at 15–18° sweep and the less aggressive Gessner® version (manufactured in Australia) can be used as rotary rakes to shift stubble out of the path of the disc (Desbiolles 2005), while the spring ‘tickle’ tine is a cheaper alternative used in Southern USA and is suitable for short (slashed) stubble. A tug wheel running alongside each tine, developed in the US (Siemens et al. 2003), is designed to continuously pin residue down beside the tine shank and it assists the shedding process.

As tine seeders (Figs. 39.4 and 39.5) can handle only a limited amount of crop residue, they will have to give way to appropriately designed disc seeders. Double discs the same size and a little offset give satisfactory performance for sowing and closing the furrow under common levels of residues; but they may not be able to cut through higher levels of residues produced under higher levels of soil fertility or as left by green manure cover crops such as Saia oats.

Disc sowing systems have been successfully developed and widely used by growers in South and North America, but in Australia disc sowing systems, while used, have been less successful. In Brazil, a commonly used disc system (Fig. 39.6) has one bigger leading disc (generally 40 cm in diameter) with a smaller (generally 35 cm in diameter, sometimes offset) following disc.

As the discs rotate at different speeds, they have a better self-cleaning action and cut more efficiently through high amounts of crop residues. They can also penetrate hard clay soils better than equal-sized double discs but are less satisfactory in closing the furrow; they therefore need devices to close the furrow and firm the soil behind the discs.

Fig. 39.4 Tine sowing systems are limited by the amount of crop residue they can handle

Fig. 39.5 Too little soil cover and too much bare soil in between rows as a result of sowing with tines

Although successful no-till sowing with discs has developed mainly in higher-rainfall cropping areas, disc sowing technology should be tested for the drier areas. The higher residue cover (Fig. 39.7) should improve moisture storage and retention

Fig. 39.6 Brazilian disc seeder designs can seed into high residue conditions (7 t/ha of plant residues)

Fig. 39.7 These high residue levels are the likely upper limit for tine seeders

and thus rainfall use efficiency; similarly, better soil carbon will also increase water use efficiency by increasing the water-holding capacity of the soil.

Disc seeders have been used successfully by a number of growers in the southern regions of Western Australia, on the lighter, sandy soils of South Australia and on the heavy clay soils of Northern New South Wales and Queensland. However, crop establishment has been a problem in sticky clay soils in wet sowing conditions in South Australia (Desbiolles 2004; McCallum et al. 2005)

Disc sowing systems offer many advantages for no-till farming, in particular through creating very low levels of soil disturbance and the ability to sow through significant amounts of surface stubble residue without blockage. While there are some problems with disc openers such as soil adhesion and blockage and soil smearing in the seedbed on clay textured soils, disc openers are increasing in popularity in many countries including Australia, and both North and South America.

39.6 Taking No-Till to the Next Level

39.6.1 Economics

No-till farming provides a range of priced and un-priced benefits contributing to whole-farm economic benefit. Many of the longer-term benefits from no-till farming are difficult to quantify and the net-present value of the benefit is often low as it takes many years to achieve a return on investment. Most financial benefits from no-till are a direct result of saving in inputs and labour, with additional productivity increases. The effects of direct drill (full-cut one pass) and no-till (low-disturbance one pass) systems on farm profitability have been assessed in South Australia (Krause 2006; Chap. 41). Direct drill sometimes performed better than no-till, but both systems generally performed better financially than conventional tillage (cultivation prior to sowing). Although there are savings in fuel, direct drill and no-till incur extra costs in herbicides and fertiliser. Profits have generally been higher but, as the higher costs are committed before sowing, they increase risk. In the USA, adopting no-till increased profitability in western Kansas due mainly to higher yields; but there was no difference in yields or costs in central and eastern Kansas (Dhuyvetter and Kastens 2005). The negative impact of erosion and soil degradation from conventional tillage and benefits of soil health improvement from no-till have to be considered—although difficult to quantify in financial terms.

39.6.2 Stubble Retention and Cover Crops

To progress no-till a step further, farmers need to practice full stubble retention and to keep the soil surface permanently covered with high amounts of crop residues. The organic matter content of the soil is probably one of the most important characteristics in relation to soil quality, due to its influence on soil physical, chemical and biological properties (see Chap. 14).

Moving no-till to a more sustainable farming system means developing an economically-viable approach using: (1) more diverse crop rotations, (2) green manure cover crops that are maintained on the surface, and (3) full stubble retention zero-tillage systems with disc seeders; this can reduce water evaporation, runoff, and erosion, increase water use efficiency and reduce weed infestation intensity (Derpsch 2005).

Higher yields of cash crops after appropriately chosen green manure cover crops can be attributed to one or several factors including allelopathy, reduction of crop diseases, pests and weeds, higher water infiltration rates and thus a higher rainfall use efficiency. Sorrenson and Montoya (1984) studied the economics of cover crop utilisation in the high-rainfall no-till system in Paraná State, Brazil (where the rainfall is sufficient for two crops per year). The study found that the combination of Saia oats (*Avena strigosa*) as a cover crop followed by soybeans (one cash crop a year) gave higher economic returns than soybean after wheat (two cash crops a year). This is because soybeans produced 770 kg/ha higher yield after Saia oats than after wheat (Derpsch et al. 1991). Also crop sequences that included other cover crops resulted in higher economic returns than rotations without cover crops. Cover crops may be used to improve soil in low-rainfall environments such as in southern Australia. However, there are trade-offs in farm profitability due, on one hand, to the loss of a cash crop in the cover crop year while, on the other hand, there are productivity benefits from weed, disease and pest control for the following crop. See also Chap. 25 for northern Australia.

A more sustainable no-till system is achieved using full stubble retention. However, full soil cover may not be achieved in the semi-arid Mediterranean environment of Western Australia where there is rarely enough crop residue left on the soil surface in the no-till system to improve soil organic matter—often because the residue is baled, burned or grazed. In the examples quoted below, almost all the benefit of the no-till system comes from the permanent cover of the soil, and maximising biomass production, but little from not tilling the soil.

Without plant residues on the soil surface, no-till will result in poorer crop development and yields than under conventional tillage. For example, in a low-rainfall area of Bolivia, Wall (1998) concluded "in all seasons the highest yields were obtained from the plots with no-till and crop residue retention, and the lowest yields from the plots with no-till and no residues". Wall found there were appreciable increases in soil moisture in the top 30 cm, especially with 4 t/ha of residue cover. There was little available moisture in the plots without ground cover. Also water infiltration rate was greater with straw cover: 2 t/ha gave an 80% increase in initial infiltration rate compared to plots without ground cover, and 4 t/ha of residues gave an increase of 280% in water infiltration rate. With more than 30 mm rainfall, moisture penetrated to twice the depth in the 4 t/ha residue plots than it did in plots without residues.

At both a low-rainfall (350 mm mean annual rainfall), loamy sand soil site and a higher rainfall (450 mm), loam soil site in South Australia, wheat gross margins were significantly higher in a long-term no-till environment (>10 years of no-tillage) than under short-term no-till (first 2 years of no-tillage) (Rainbow and Bennet 2006;

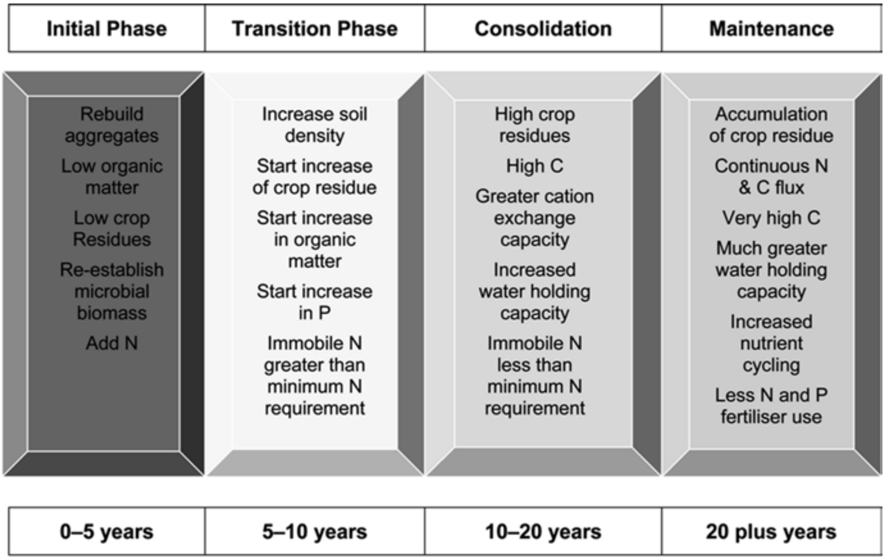

Fig. 39.8 Suggested soil health evolutionary scale of the no-tillage system (J.C. de Moraes Sá 2004, Personal communication, University of Ponta Grossa, Brazil) (OM = organic matter, CEC = cation exchange capacity, N = total nitrogen, P = available phosphorus, C = carbon). Time (years of continuous no-till with full stubble retention). In the initial phase (0–5 years), the soil starts rebuilding aggregates but measurable changes in the carbon content of the soil are not expected. Crop residues are low and nitrogen needs to be added to crops. In the transition phase (5–10 years), soil density increases in all soil textures and the amounts of crop residues, soil C, and P content start to increase. In the consolidation phase (10–20 years), crop residues are heavier and C content; CEC and water holding capacity are higher with better nutrient cycling. In the maintenance phase (>20 years), the maximum benefits for the soil are achieved (higher water holding capacity, higher nutrient cycling and continuous N and C flux. Less fertiliser is needed

Krause 2006). The optimum economic nitrogen (N) application at the higher rainfall site was more than 43 kg N/ha for the short-term treatment whereas it was between 30 and 43 kg N/ha for the long-term treatment. These results are relevant to understanding how to take no-tillage to a sustainable level as suggested by de Moraes Sá (J.C. de Moraes Sá 2004, Personal communication, University of Ponta Grossa, Brazil) in the evolutionary scale of a no-tillage system in Fig. 39.8.

On degraded soils in the Cochabamba region of Bolivia, "grain yields at all sites and in all years have been directly related to the amount of ground cover applied after the previous harvest. Consistently the lowest yields were obtained in no-till with no residues" (Wall 1998).

Some farmers till the soil occasionally to bury ryegrass weed seeds, or loosen the soil or to eliminate compaction, but interrupting a no-till system with occasional tillage can prevent the full benefits of the system ever being attained (see also Chap. 33).

Using no-till disc seeders, full stubble retention and adequate crop rotations will allow farmers to maintain soil organic matter, and this may be reached earlier by using occasional green manure cover crops. But any further tillage performed means a return to the initial state. Farmers practicing a no-till system without full stubble retention—that is baling or burning the residues, or letting livestock graze the paddocks, (even limited grazing compounds problems with increased weed seed burial)—will probably never leave the initial phase. Those using a tine-sowing system, even when practicing no-till with full stubble retention, will only reach the transition phase.

39.7 Managing Soil Compaction in No-Till Systems

Over the last 25 years, the axle loads of tractors and other agricultural equipment have steadily increased. Many current large, dual-wheeled 4WD tractors weighing over 15 t (>300 kW = 400 hp) have loads of up to 7,500 kg per axle. Tracked tractors with a total mass of 16 t but with up to six multiple axles fitted to the track assembly have a load of more than 2,500 kg per axle; but as they confine the compaction to a smaller width of wheel track than dual-wheeled tractors, compaction is potentially deeper.

Heavier tractors, larger seed and fertiliser hoppers on seed drills and greater volume spray tanks all contribute to soil compaction. Harvesters can add to soil compaction, particularly if soils are wet during harvest, as modern machines weighing more than 12 t with a grain tank capacity of over 5 t produce a load of more than 8.5 t per axle. This increase in agricultural vehicle mass over the last 25 years combined with continued conventional tillage practices has contributed significantly to soil compaction in cropping soils. Figures 39.9 and 39.10 show a typical soil compaction effect as a result of wheel traffic.

Compaction can be a serious problem in the soils of many countries including the USA, Canada, Australia and New Zealand. Serious soil compaction reduces water infiltration and root growth of crops, resulting in reduced crop water availability. Although many farmers in the USA, Canada and Europe believe that the freezing and thawing of soils to 1–2 m depth will break down compacted layers, especially with typical high soil water content, it may take several years to ameliorate heavy compaction. Similarly, severe compaction in cracking and swelling (self-mulching) vertosol[6] clays in Australia may take up to 5 years to recover.

As up to 85% of soil compaction effects occur in the first wheeling (McHugh et al. 2004), a soil may be re-compacted in the first growing season after amelioration.

Soils with high sand content do not ameliorate themselves and require mechanical treatment such as deep ripping. Sands and loamy sand soils have some of the worst soil compaction in Australia, and deep ripping followed by conventional wheel traffic appears to be effective for 2 years at most. The continual process of deep ripping and continued compaction leads to deeper compaction following each amelioration event. Biological amelioration using plants with a deep taproot

[6] Australian Soil Classification http://www.clw.csiro.au/aclep/asc_re_on_line/soilhome.htm

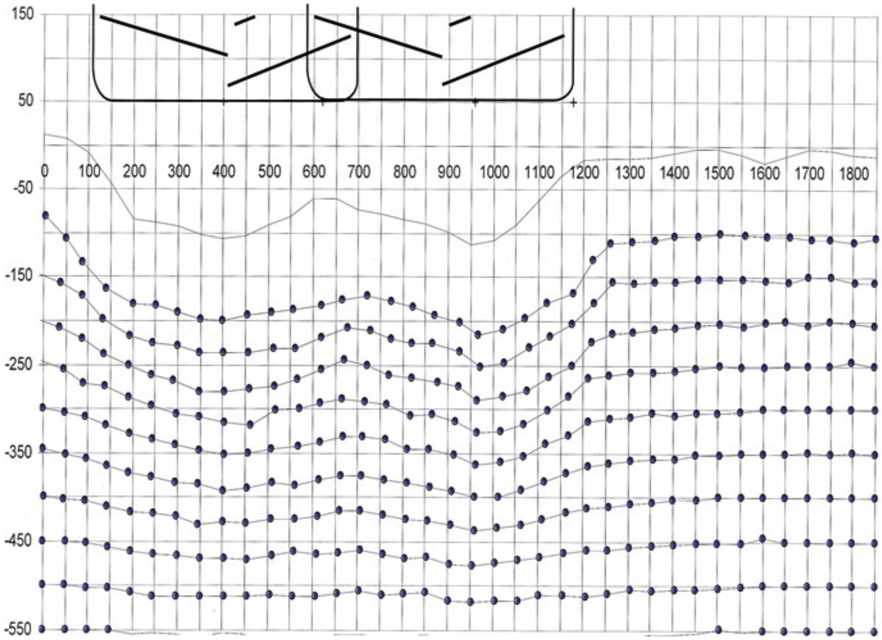

Fig. 39.9 Effects of two passes of a harvester wheel on soil displacement and compaction (width (x axis) and soil deformation (y axis) in mm) (Walsh 1994)

Fig. 39.10 Effects of two passes of a harvester wheel on soil displacement and compaction (Walsh 1994)

has had some success, but less in severely compacted sands and loamy sand soils. Soil compaction will continue to be a problem where conventional deep tillage continues to be practiced. In the short-term, the need for amelioration of soil compaction is being reduced by the global trend towards reduced tillage and no-till sowing systems.

39.8 Improving the Seedbed Environment with No-Till and Controlled Traffic Farming

The recent interest in controlled traffic farming (CTF) systems is a good example of farmer innovation leading the way to improvements in efficiency and performance of no-till farming systems. In Australia, more than 1 million hectares were under controlled traffic farming in 2002 (Chapman et al. 2003), and this figure more than doubled in the following 5 years (Tullberg 2007).

Equipment wheels may cover more than 85% of the field area in a given season in a conventional tillage grain-growing operation, and around 50% in a no-till system. Under controlled traffic, wheels are confined to permanent lanes taking up about 15% of the field area (Fig. 39.11).

CTF systems have led to yield improvements of 10–15% on a range of soil types across Australia (Blackwell et al. 2004; Ellis et al. 1992; Tullberg 2001), much of it as a result of increases in water infiltration and available soil water at the end of the growing season (Tullberg 2001). The resulting annual value to the farm business has been around AUS$7.50/ha in input savings from reduced overlap and AUS$30/ha in increased yield (Blackwell et al. 2004; Gaffney and Wilson 2003).

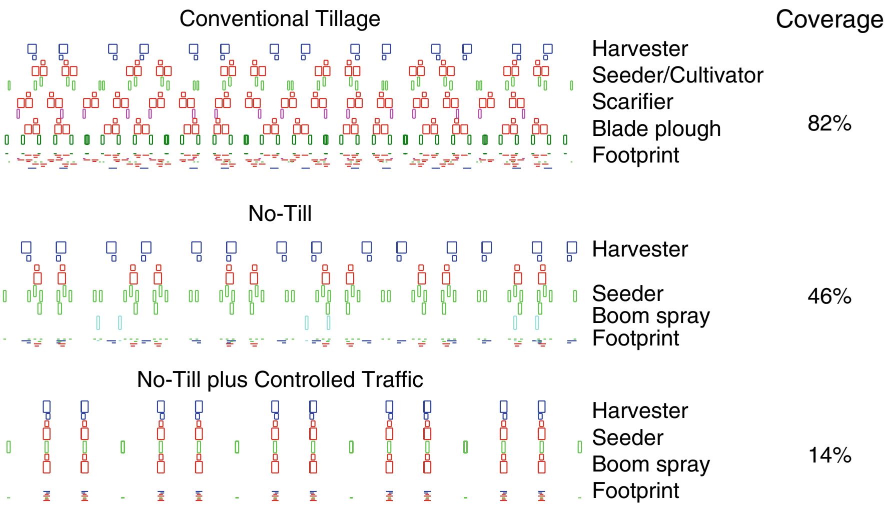

Fig. 39.11 Wheel track coverage of conventional tillage, no-till and controlled traffic (Walsh 1998)

39.9 Benefits of a Controlled Traffic Farming System

Adopting traffic management with no-till could avoid the need for future deep ripping to ameliorate compaction effects. Controlled traffic farming (CTF) can offer some significant advantages even under conventional tillage systems. These (Rainbow and Long 2001, Chap. 34) include:

- *Reduced costs.* Reduced overlapping can save fuel and reduce fertiliser, seed and spray inputs by 4%. Savings in input costs can amount to 10% (Blackwell et al. 2004). With wide-row spaced crops (beans and summer crops), inter-row spraying can additionally reduce chemical applications by 66%.
- *Reduced draft requirements.* Smaller tractors are being used, as less power is required to pull the same machine at sowing. In heavy clays, power requirements can be reduced by as much as 50% with normal sowing moisture (Tullberg 2001), resulting in significant reductions in fuel use. A 250 hp tractor could need 50 hp less in a controlled traffic system than in a conventional system.
- *More timely operations*. Herbicide and fertiliser applications can occur at more appropriate times due to increased trafficability in wet conditions. Crucial operations such as fungicide application can take place sooner after rainfall events, reducing disease levels. Post-sowing fertiliser applications can occur while the soil is still wet, increasing their efficiency of use.
- *Improved spraying window and night spraying accuracy.* Defined, permanent wheel tracks with global positioning guidance increase the accuracy of night spraying operations. This provides a wider window of opportunity for spraying if poor weather conditions occur regularly.
- *Reduced fertiliser and herbicide application costs.* The greater time available for operations allows fertiliser and herbicide to be applied more accurately with the farmer's own equipment rather than if relying on contract operators. This results in less crop damage and fewer weed escapes. Better weed and disease control is likely as higher water rates are used with ground application units.
- *Better placement of seed and fertiliser.* This produces more uniform plant emergence and growth.
- *More accurate sowing allows for more accurate herbicide and fertiliser placement.* Between-row weed control is already practised in wide-row spacing crops. A combination of between-row shrouded spray units with highly accurate differential global position system (DGPS), real time kinematic (RTK)[7] ±2 cm autosteer tractors and guidance equipment allows the use of non-selective herbicides for weed control. This may delay the development of resistance to selective herbicides. Inter-row or side dressings of fertiliser are also possible to increase fertiliser use efficiency.
- *Opportunity for inter-row sowing.* With highly accurate RTK ±2 cm autosteer tractors, it is possible to sow between the previous year's crop row, and, by

[7] See glossary.

adjusting the tynes, improve stubble residue handling. In Australia, this may result in a 6% increase in barley grain yield because of less soil-borne root disease inoculum in the current crop row (McCallum 2005a, b).

- *Improved soil drainage with raised beds.* This advantage is important in higher rainfall regions with flat land and poor surface drainage.

39.10 Implementing Controlled Traffic Farming Using Precision Agriculture

Matching agricultural machine track widths creates the greatest degree of difficulty for farmers. The idea is to align all tractor, implements and the combine harvester wheels on wheel tracks of the same track width, but no farmer is likely to sell an entire farm plant at one time to match tractor wheels. For most farmers, the options are generally 2 m track widths (distance between the centre-line of each wheel) as this requires the least amount of modification and adjustment to tractors, air-seeder carts and spraying equipment.

Sowing equipment is ideally matched with the same maximum width as the combine harvester pick-up front to minimise soil compaction at harvest. Spray booms have to be in multiples of either two or three times the seeder width; a spray boom width three times the seeder width is preferable as it facilitates overlap management of the first and last run. Many now have 12-m wide sowing equipment with 24- or 36-m boom sprays that can operate along every second or third sowing run. Combine harvester pick-up fronts that are centred and have a belt or draper delivery system are now available with widths of up to 14 m. Grain tank discharge auger extensions may need to be used to allow for the wider pick-up fronts. If chaser bins are to be kept to the same wheel tracks, an offset loading chute to the chaser bin tank is needed to move product to the centre of the grain bin.

To align harvester wheel tracks with tractor and other equipment, axle lengths have to be spread to 3 m centres. This is relatively easy on many tractors with adjustable track-width stub axles, and many front-wheel-assist tractors can have axle spacers inserted to increase the front axle spacings. Some farmers have inserted cotton reel inserts in the front axle to widen spacings on early-model front wheel assist tractors, but this increases the risk of premature bearing failure in the hub assemblies.

Controlled traffic farming (CTF) is generally carried out with parallel runs or ‘up and back’. This is popular in the establishment phase when marking out the tramline marks at sowing. Tramline runs would ideally be up to 3–4 km long as this reduces turning on headlands to a minimum. Most farmers lay out the direction of the tramline to allow the longest run, and base it to minimise interference from existing fence lines, creeks and trees. CTF has been successfully implemented on fields with significant slope. The benefits of controlled traffic on slopes are even greater as water infiltration is increased and hence run-off and erosion are reduced, particularly when implemented in conjunction with no-till and stubble residue retention. Sowing straight up and down the slopes is preferable to sowing across the slope as it is easier to hold a straight track position, particularly with a trailing air-seed and fertiliser delivery cart. Contour banks to control water erosion can be engineered if there is sufficient topsoil, that so the planter can seed straight over the top as it moves up and down the slope.

The issue of permanent tramline wheel tracks versus sown or fuzzy[8] tramlines has attracted some debate. Several options of controlled traffic tramline systems have been used in Australia. The simplest and most popular has been permanent wheel tracks as these can be constructed and defined with simple disc end-marker arms at planting with sowing rows being removed in the wheel tracks. This can result in some problems with weeds in the wheel tracks—in Australia with the weed annual ryegrass. For this reason, many farmers are now using fuzzy tramlines where crop seed is scattered or sown shallow in the wheel tracks without fertiliser to save cost but to compete with weeds. This is preferred to machine sowing tramlines where trafficability benefits in wet conditions are lost. Shallow cultivation in the wheel tracks to control weeds needs critical timing for effective control; it also reduces the benefits in wet soil conditions and can contribute to wind and water soil erosion in the wheel track.

More recently autosteer technologies have been used to successfully implement chemical (shrouded sprayers) and non-chemical (tillage) weed control (Rainbow 2006) and inter-row mowing (Butler 2007).

The advent of DGPS autosteer has enabled farmers to establish and maintain permanent wheel track positions more accurately. With RTK base station technology, autosteer systems are now accurate to ±2 cm. But, as mechanical and electrical problems sometimes prevent these systems from working effectively, permanent wheel tracks are an advantage as a fall-back system.

39.11 Conclusions and Challenges for the Future

Broadacre crop production has seen more change to farming systems in the last 10–15 years than in the last 40 years. There is no doubt that this period of rapid change will continue with further successful adoption of new technology. No-till sowing and controlled traffic systems detailed in this chapter offer wide ranging and significant benefits by overcoming compaction limitations, improving trafficability, soil condition, nutrient status, soil water use and drainage, and the efficient use of fuel, fertiliser and herbicides.

To optimise the no-till system for sustainable production, it is necessary to

- diversify crop rotations to maintain effective weed and disease control
- use green manure cover crops
- maintain full surface cover with stubble retention
- minimise soil disturbance using disc seeders.

[8] See glossary.

Using the no-till technologies described in this chapter will ultimately reduce runoff and soil water evaporation, and so increase water use efficiency—the key driver of production. Adoption of specialised new equipment will however require significant financial outlay. While some farmers consider this a barrier to adopting no-tillage farming, others find they need only a few modifications to existing equipment.

Effective weed management is essential for successful implementation of no-till practice. In Australia and Canada, dinitroanaline herbicides (such as trifluralin) have become popular selective herbicides for early residual in-crop weed control, but their widespread intensive use has resulted in reports of resistance in annual ryegrass in Australia (Boutsalis 2006) and green foxtail in Canada (Morrison et al. 1989). The increased incidence of resistance to trifluralin, which has been a mainstay for weed management in no-till farming for over 10 years in Australia and Canada, has increased concerns of many farmers. The incorporated-by-sowing (IBS) weed management system (i.e. spray then sow) has significant benefits to crop safety by removing chemical-treated soil over the crop row. The widespread use of trifluralin by this method using knife points and press wheels (registered in Australia in 2003 by Nufarm®) has also encouraged farmers to experiment and broaden the range of herbicide groups, and many of these have been used at higher rates than in conventional farming practice.

Because the use of trifluralin in every crop, every year has accelerated the onset of herbicide resistance to this product, chemicals with different modes of action, including metolachlor and tri-allate, are now being used to broaden the weed control spectrum. Many no-till farmers are concerned that the current no-till system depends on chemical weed control. The development of weed resistance to a number of herbicides has had a marked influence on the global adoption of the Roundup-ready® crops and increased dependence on glyphosate herbicide use. Use of competitive crops, increased soil cover with residues, and even occasional tillage have not been effective on their own in reducing the weed seed bank; weed seed collection systems on harvesters and the use of hay enterprises have shown moderate success.

Farmers need to use all available chemical and cultural control methods to stop weeds setting seed. Ideally, herbicides would be secondary to other non-chemical or cultural weed control methods. In South America, cover-cropping, with the allelopathic benefits (Rainbow 2006) of Saia oats, and knife rolling are practised widely (Derpsch 2005) and have resulted in a more sustainable farming system and less herbicide resistance in weeds. However, this may result in reduced cropping intensity in lower rainfall areas.

The interest in disc seeders globally is increasing with an increasing range of designs becoming available (Ashworth 2007). Disc seeders have been more successful on lower-rainfall sandy soils than on loam and clay soils. This is particularly the case on high clay content soils in higher rainfall regions where tined seeders give more reliable crop establishment in these sticky soil conditions.

Integration of Conservation Agriculture, Precision Agriculture and Controlled traffic (Fig. 39.12) is important, to gain maximum efficiency of operations and input use.

Fig. 39.12 Integration of no-tillage, controlled traffic and precision agriculture has significantly improved production and efficiency in Australian grain farming

These technologies have been effectively integrated on farms in Australia (see Chap. 34).While this requires considerable capital expenditure, it can be cost effective. In six case studies of grain growers across Australia (Robertson et al. 2007), the capital investment in precision agriculture above the cost of no-till and controlled traffic varied from AUS$55,000 to AUS$189,000. This represents capital investment per hectare ranging from AUS$14 to AUS$44. As the estimated net annual benefits from PA ranged from AUS$14 to AUS$30/ha, these capital costs were recovered within 2–5 years and in more than half of the cases within 2–3 years.

The recovery of costs of implementing DGPS guidance and autosteer begins as soon as the system is implemented. There are additional yield benefits in wheat of 5–6% from improved crop establishment in stubble and reduced impacts of soil-borne root disease (Simpfendorfer 2006; McCallum 2005a, b).

Many farmers are only beginning to consider no-till farming. However once the key decision is made to adopt the technology, the learning process will continue and further technologies such as improved disc seeder designs, controlled traffic and precision agriculture will be a natural progression. The main challenge is to continue research that will broaden weed control options resulting in a more holistic approach for the management of weeds by farmers. There will continue to be many ideas and concepts contributed by farmers that will enhance the development of future technologies. It is important that these ideas and knowledge are captured by the grains industry.

The integration of no-till systems, controlled traffic and precision agriculture technologies have been successfully achieved in Australia and North America. It is in South America, however, where the use of crop rotation and the successful, widespread use of cover crops have reduced dependence on the use of fertiliser and herbicide inputs in no-till farming. Farmers must use all these technologies and successfully integrate the practices to achieve efficient, productive and sustainable no-till crop production.

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Chapter 40
No-Tillage Agriculture in West Asia and North Africa

Rachid Mrabet

Abstract Agriculture in West Asia and North Africa (WANA) is losing momentum. Serious problems of land degradation, desertification, declining soil quality, reduced soil fertility and low agricultural production levels may be irreversible if appropriate measures are not taken soon. Past research in agriculture focused on testing cropping systems under conventional soil management which may no longer be relevant to the WANA region. Most of WANA's soils need skilled management practices such as no-tillage and stubble retention to ensure sustainable agricultural production. This chapter reviews research on no-till (NT) and conservation agriculture (CA) and their application in rainfed regions of WANA. In WANA countries where water scarcity is becoming endemic, NT could rehabilitate productivity of soils and farmers' returns, although it can result in lower yields where weeds are not controlled. Institutions need to disseminate the principles and practices of no-till in order to improve productivity and profitability and benefit both the environment and society.

Keywords No-tillage systems • Conservation agriculture • Carbon sequestration • Sustainability • Economical development • WANA

40.1 Introduction

There are great challenges to agriculture and the natural resources of West Asia and North Africa (WANA) because agricultural development is needed to satisfy future food consumption requirements, to encourage job creation and to reduce poverty. Agriculture in the region is dominated by rainfed cereal cultivation in conjunction with livestock production. It employs nearly 50% of the population in, for example, Turkey and Morocco.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_40,

Over the past centuries, the increasing population has led to intensification of agriculture, over-tillage and over-stocking, and accelerated human-induced soil degradation (Lal 2002). Despite the priority given to rainfed cereal research by national and international institutions, only limited advances have been made in productivity; crop yields are generally low at 0.6–1.5 t/ha (Heng et al. 2007).

The WANA region encompasses a wide variety of cropping rotation systems where water is a major limitation to productivity. Even though several of the crops grown originated in the region, it is chronically food-deficient. Recently, more effort by international organisations and development institutions is encouraging adoption of no-tillage (no-till) practices in particular and conservation agriculture in general. This chapter reviews information on no-till (NT) systems in WANA region, mostly from Iran, Morocco, Syria, Sudan, Tunisia and Turkey.

The main concerns of this chapter are the reversal of degradation in soils along with increased productivity and economic returns, and removal of current constraints on use of no-till systems within the farmers' communities.

40.2 Agriculture in WANA Region

The region has a land area of 1.7 billion hectares with a population of 600 million—about 14% of the total area of the world and 10% of the world's population. Desert or semi-desert covers 70% of the total area, with 22% as grazing lands. It is characterised by high population growth, low and erratic rainfall, limited arable land, and severely limited water resources.

Most of the region is semi-arid, with pronounced rainfall variability. The total agricultural land area is 147 million hectares, about 76% of which is rainfed. There are few possibilities for expansion of irrigated agriculture (Ryan et al. 2006), which occurs mainly in the Nile valley in Egypt and Sudan and the Tigris–Euphrates in Iraq and Syria.

Arable land represents about 8% of the total land resources, and is very limited in relation to the population, with an average of 0.25 ha of arable land per capita. Over time, all countries, except Sudan and Turkey, will face high population pressure on their arable lands. Permanent pastures and rangelands, which cover around 30% of the total area and provide around one-third of the diet of livestock, have been severely degraded by unrestricted grazing and desertification. The region is characterised by low-productivity ecosystems with soils of low physical, chemical and biological quality.

The average annual rainfall can be higher than 500 mm, but most of the cropping areas receive 200–500 mm and this varies widely from year to year and within seasons. Climate change is predicted to reduce rainfall by 20–25% by 2050, while temperatures rise by 2–2.75°C (Ragab and Prudhomme 2002). This may exacerbate existing water scarcity.

The production systems are dominated by cereals, primarily wheat[1] in the wetter areas and barley in the drier areas, in rotation mainly with food legumes such as chickpea and lentil, as well as some corn, sunflower and forage legumes. The most common systems are continuous, annual mono-cropping of cereals (a consequence of population pressure) and wheat–fallow (either clean or weedy) for water conservation. In fact, where annual precipitation is less than 450 mm, farmers using conventional tillage have regarded fallowing as necessary to produce sustainable wheat grain yields. However, weeds must be controlled during the fallow to store adequate soil moisture (Bouzza 1990; Pala et al. 2008).

40.3 No-Till Systems

No-till methods are a part of conservation tillage and conservation agriculture (CA).[2] Conservation tillage is any tillage or planting system in which at least 30% of the soil surface is covered by plant residue after planting. This reduces erosion by water or wind. CA embraces crop production systems where there is minimal soil disturbance and retention of residues on the soil surface, in contrast to conventional tillage (CT) operations that invert the soil and bury residues. This reverses the traditional system that emphasises the need for a clean seedbed without crop residues on the surface.

Conservation agriculture was introduced by the Food and Agriculture Organization of the United Nations (FAO) as a concept combining resource-efficient crop production based on integrated management of soil, water and biological resources, with external inputs.

The no-till (NT) system consists of a one-pass planting and fertiliser operation in which the soil and the surface residues are minimally disturbed. Weed control is generally achieved with herbicides or, in some cases, with crop rotation. NT systems have been adopted in countries world-wide, on more than 100 million hectares (see Chap. 39). They are based on four principles: (1) buffering of the soil surface, with mulch/crop residues, against direct impacts of atmospheric elements (rain, wind, solar radiation) and of traffic; (2) minimum disturbance of soil structure, while achieving high soil quality and optimum placement of seed and fertiliser; (3) varied crop sequences for productive and healthy crops; and (4) environmentally-benign weed control based on herbicide use and crop rotations. However, in practice farmers may not adopt all components because of limited access to inputs such as herbicides or use of crop residues for other purposes (Mrabet 2001a).

So far, few of the WANA countries have invested significantly in CA research and development. Evidence from overseas no-till research (mainly from USA) helped establish nodes of research and development in Morocco in the early 1980s (Mrabet 2008), Syria in mid-1980s (Ryan et al. 2008) and more recently in Tunisia (M'hedhbi et al. 2003). At present, no-till is applied to approximately 10,000 ha in

[1] See glossary for botanical names of crops.

[2] See glossary.

Sudan (Rasheed et al. 2006), 9,000 ha in Tunisia (M. Ben Hammouda 2008) and more than 2,000 ha in Morocco.

No-till research and development are still fragmentary and embryonic, but the results from studies so far generate optimism and the desire to promote the no-till systems through international cooperation and national efforts (Mrabet 2008).

Large on-farm participatory projects in the region operate as follows:

- The Arab Authority for Agricultural Investment and Development (AAAID), with the support of governments in several Arab countries (Morocco, Yemen, Tunisia, Jordan, Syria and Sudan), has been active in the demonstration and extension of no-till and reduced tillage practices since 2000 (AAAID 2007).
- The French Agency for Development (AFD), with scientific support from CIRAD (Centre International de la Recherche Agronomique pour le Développement), started experimenting and promoting direct sowing, mulch-based cropping systems in Tunisia in 1999 (AFD 2006). Similar projects are underway in Algeria and Morocco.

40.4 Effect of No-Till Methods on Crop Production and Cropping Systems

40.4.1 Grain Yields of Cereal Crops

Most available results comparing cereal yields over a number of years under NT and conventional tillage systems in WANA are summarised in Table 40.1 and Fig. 40.1. No-till systems permit early seeding which has a major influence on growth, development and water use efficiency (Oweis et al. 2000) during the Mediterranean growing season, particularly in semi-arid environments (Mrabet 1997). Under NT, planting is no longer determined by the adequacy of rainfall for tillage and seedbed preparation or by excess rainfall restricting access to the field, although it is still dependent on adequate weed control.

Short-term (equal to or less than 4 years) and medium-term (5–8 years) effects of NT systems on wheat yield have been variable but short-term benefits are important because they determine the attractiveness of NT to farmers and decision makers. The variability in short-term crop responses to NT is principally the result of the interacting effects of crop nutrient requirements, seed drill performances, weed control, soil characteristics and climate. Where moisture is limiting, crop yields under NT may improve in the short term—Vadon et al. (2006) in Tunisia; Mrabet (2002) in Morocco and Hemmat and Eskandari (2004a, b, 2006) in Iran—but may be depressed by weed infestation in wet conditions if herbicides are not applied appropriately—Yalcin (1998) in Turkey.

Mrabet (2008) concluded that:

- No-till is a sustainable alternative to traditional and conventional tillage systems.
- Chemical fallow which leaves crop residues (straw) on the soil surface could substitute for clean tilled and weedy fallows.

Table 40.1 Wheat yields (t/ha) under no-till and conventional tillage in the WANA region

Country	Species	Rotation	No-till	Convent. tillage[a]	Years[b]	References
Iran	Bread wheat	Wheat–fallow	1.70	1.40	3	Hemmat and Eskandari (2004a)
		Continuous wheat	1.43	1.01	3	Hemmat and Eskandari (2006)
		Wheat–chickpea	1.60	1.24	3	Hemmat and Eskandari (2004b)
Morocco	Bread wheat	Continuous wheat	2.47	2.36	4	Mrabet (2000a)
		Wheat–fallow	3.70	2.60	10	Bouzza (1990)
		Continuous wheat	1.90	1.40	10	Mrabet (2000b)
		Wheat–fallow	3.10	2.40	19	Mrabet (2008)
		Continuous wheat	1.60	1.60	19	
Tunisia	Durum wheat	Continuous wheat	3.90	3.30	2	Vadon et al. (2006)
			2.18	1.94	5	M'hedhbi et al. (2003)
Turkey	Bread wheat	Wheat–corn	2.40	3.35	–	Yalcin (1998)
Turkey (Central Anatolia)		Wheat–fallow	2.16	2.70	3	Avci (2005), Avci et al. (2007)
		Wheat–chick pea	2.13	2.60	3	
		Continuous wheat	2.00	2.23	3	
Syria	Bread wheat	Wheat–chickpea–watermelon	2.53	2.96	12	Pala et al. (2000)
	Durum wheat	Wheat–lentil–watermelon	2.08	2.41	12	Pala et al. (2000)
	Durum wheat	Wheat–lentil	3.33	3.85	5	Thomas et al. (2007)
	Barley	Barley–vetch	1.55	1.39	7	Jones (2000)
		Continuous barley	1.09	1.01	7	Jones (2000)

[a] Disk plough-based tillage system
[b] Duration of the experiment

As a conclusion, generally, no-till methods have enabled higher cereal yields to be achieved in the long- and medium-term experiments, but for WANA farmers to be convinced to attempt and achieve this, they need appropriate seed drills and weed control practices.

40.4.2 Yields of Row Crops

These crops include lentils, chickpeas, vetch, corn, sunflower, sesame, cotton and sorghum (Table 40.2). Grain yields of row crops have been consistently higher

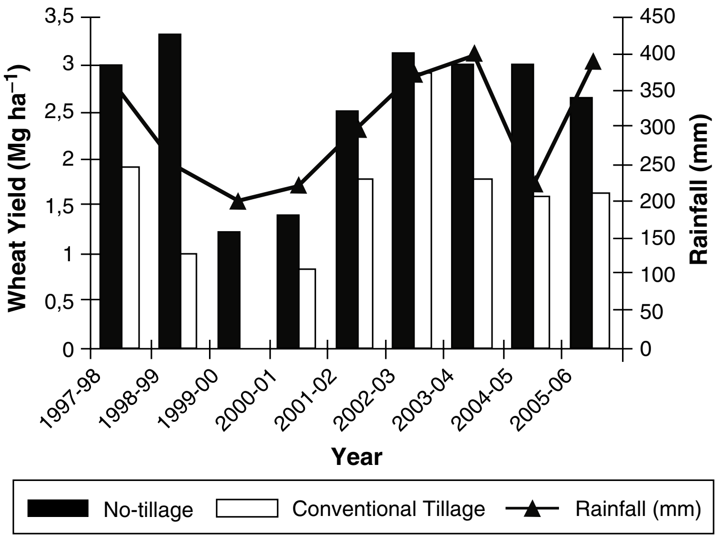

Fig. 40.1 The effect of tillage system on wheat grain yield in a semi-arid Moroccan farm (Mrabet 2008) (Wheat under CT did not yield grain in 1999–2000 because of low growing-season rainfall)

Table 40.2 Row crop grain yield (t/ha) under no-till and conventional tillage in WANA region

Country	Species	No-till	Conventional tillage	Years	References
North-western Iran	Chickpea	0.81	0.51	3	Hemmat and Eskandari (2004b)
Morocco	Corn	1.61	1.50	4[a]	Mrabet (1997)
	Sunflower	2.71	3.02	2	Aboudrare et al. (2006)
Sudan	Sesame	0.77	0.18	2	Rasheed and Hamid (2003)
	Sunflower	1.21	0.40	2	Rasheed et al. (2006)
	Corn	2.63	0.59	3	
	Cotton	1.12	0.53	2	
	Sorghum	2.57	1.24	2	
Syria	Lentil	0.90	0.80	12	Pala et al. (2000)
	Lentil	1.10	1.10	12	Pala et al. (2000)
	Chickpea	0.80	0.77	12	Pala et al. (2000)
	Lentil	1.12	1.14	5	Thomas et al. (2007)
	Vetch	0.67	0.77	7	Jones (2000)
Western Turkey	Corn	6.40	6.70	2	Bayhan et al. (2006)

[a] Water regimes dry to wet depending on amount of water added as supplementary irrigation

under no-till than either mouldboard or chisel ploughing in Sudan and in north-western Iran. However, in Syria, Morocco and Western Turkey, crop yields under NT and CT were similar.

What emerges from the results shown in Tables 40.1 and 40.2 is that no-tillage systems can produce yields that are usually as high as or higher than those from crops produced by conventional tillage; but they can also create other long-term challenges, such as weed and pest infestations. Row-crop yields in semi-arid WANA regions can be profitably increased, in the short- and long-term, with a combination of an adequate no-till seed drill and careful weed management (Mrabet 2008).

40.4.3 Water Use Efficiency by Crops and Crop Diversification

Drought and intermittent water deficit have been major constraints to crop productivity in the semi-arid regions of WANA; extended dry periods are common, especially in the critical grain-filling stage in late spring (Yacoubi et al. 1998). Crop rotation is a key component of a sustainable agriculture, but the rainfall (300–500 mm) and soils of dry lands often limit the options for varying cash crops. Thus efficient use of rainfall is critical for maximising the range of crops grown.

WUE can be defined as the ratio of crop grain yield to precipitation used during the growing season, and is a basic agronomic indicator of the effectiveness of agricultural practices (see Chap.1 for more information). Elimination of soil tillage for seedbed preparation, together with residue retention enhance WUE by reducing losses due to runoff and evaporation and decreasing soil surface temperature (Lal 2008; Mrabet 2008). Thus water use efficiency and crop yield in arid zones with an annual precipitation of less than 300 mm can be increased by implementing a no-till (residue retention) wheat–fallow rotation (Bonfil et al. 1999; Bouzza 1990).

A no-till system with residue retention helped to increase wheat WUE in three rotations in Iran (Table 40.3), but water is wasted if fields are left fallow in years with above-normal precipitation (Hemmat and Eskandari 2004a, b, 2006).

According to Bouzza (1990), in Morocco no-till and reduced tillage systems increased WUE in both continuous and wheat-fallow rotations. These results are confirmed by Mrabet (2000b) for continuous wheat (Table 40.4).

Table 40.3 Wheat rainfall use efficiency as affected by tillage systems and rotation in Iran (average of 3 years)

Wheat rotation	No-till	MD	CD	Reference
	kg/mm/ha			
Continuous wheat	4.4	3.0	3.8	Hemmat and Eskandari (2006)
Wheat–fallow	5.4	4.4	6.0	Hemmat and Eskandari (2004b)
Wheat–chickpea	4.9	3.8	4.3	Hemmat and Eskandari (2004a)

MD mouldboard ploughing followed by disking, *CD* chisel ploughing followed by disking. Rainfall use efficiency is calculated by dividing dry grain yield by growing season precipitation (October–June)

Table 40.4 Wheat water use efficiency as affected by tillage systems and rotation in Morocco (average of 4 years)

Wheat rotation	No-till	MD	CD	Reference
	kg/mm/ha			
Continuous wheat	7.1	6.6	7.1	Mrabet (2000b)
Continuous wheat	9.6	7.5	8.5	Bouzza (1990)
Wheat–fallow	9.9	9.2	8.8	Bouzza (1990)

MD mouldboard ploughing followed by disking, *CD* chisel ploughing followed by disking. Rainfall use efficiency is calculated by dividing dry grain yield by growing season precipitation (October–June)

Table 40.5 Wheat water use efficiency as affected by tillage systems and rotation in Syria (average of 12 years)

Wheat rotation	No-till	DP	CD	Reference
	kg/mm/ha			
Wheat–lentil–melon	6.4	7.3	7.2	Pala et al. (2008)
Wheat–chickpea–melon	7.7	8.9	8.9	Pala et al. (2008)

DP disk ploughing followed by harrowing, *CD* chisel ploughing followed by disking

Water use efficiency is calculated by dividing dry grain yield by growing season (October–June) precipitation, corrected for pre- and post-season water in the soil profile

In Syria (Tel Hadya) over 12 years (Table 40.5), average WUE declined under no-till, compared to disk ploughing and chisel ploughing. This was due to a gradual increase in grassy weeds and inappropriate weed control in early seeding of bread and durum wheat (Pala et al. 2008). However, lentil and chickpea WUE were not affected by tillage systems, where seasonal rainfall ranged from 234 to 504 mm.

Changes in cropping patterns from continuous cropping of wheat to more diversified rotations are good indicators of the success of the transition from conventional tillage systems to conservation agriculture. No-till and straw mulch management improve soil water storage efficiency and increase the potential in dry climates to plant more intensively and with greater diversity of crops than with the traditional crop–fallow system. In semi-arid Morocco, the 3-year rotations (fallow–wheat–barley, fallow–wheat–vetch, and fallow–barley–lentil) are now recommended in place of common continuous wheat and wheat-fallow (Mrabet 2008) in areas receiving between 300 and 500 mm annual rainfall.

40.4.4 Weed and Disease Management

Weeds are a major problem in rainfed WANA agriculture, especially in North Africa where weedy fallows used for grazing ensure a continued supply of weed seed. The frequency of control of the weeds varies with tillage systems, rotations and herbicide strategies (Tanji 1995a, b). Consequently, changing tillage systems will change the distribution and density of weed seeds in agricultural soils. Understanding how the different tillage systems affect evolution of weed populations could help organise more effective weed management programmes (see also Chap. 8).

Under NT, weed control is often laborious and costly in the first years. Farmers will need good knowledge of herbicides, weeds and application technology to manage no-till crops successfully (Derpsch 1998). An integrated weed management programme—combining crop management, allelopathy and herbicides—has been proposed for successful implementation of no-till systems in farmers' fields (Mrabet 2008).

During the past few decades, the development of effective herbicides and application methods has made it possible for farmers to control weeds in rainfed no-till systems (El-Brahli et al. 1997; El-Brahli and Mrabet 2000). In these systems, crop and herbicide rotation have been cited extensively as an effective method of weed management.

Reduced tillage increases the risk of foliar disease epidemics because increased levels of primary inoculum are present on crop residues at the soil surface; so plant disease control has been critical to the acceptance of no-till systems (Sturz et al. 1997). So far, grain and straw have not promoted any important disease outbreaks in NT crops in Morocco (Mrabet 2008).

40.4.5 Integrating Livestock and Crop Residue Management

In the low-rainfall areas of much of Africa and Asia, sheep and goat husbandry and cereal cropping are the two most important agricultural activities (Belaid and Morris 1991), with livestock considered as the key to security for smallholder farmers. Crops and livestock are ethnically, functionally and operationally linked enterprises (Schiere et al. 2002). However, these low-rainfall areas are characterised by a rapidly growing livestock population with inadequate sources of feed (Mrabet et al. 2007; Ben Salem and Smith 2008).

Crop residues are important for livestock feed in semi-arid WANA, so mulching with crop residues for CA profoundly alters the flow of resources on the farm. Wheat straw, mostly for feeding animals, represents an important commodity; its average sale price per unit weight being not less than 40% of that of grain (Annicchiarico and Pecetti 2003; Table 40.6). In recent years, however, an increase

Table 40.6 Ratio of prices of durum wheat straw to grain (on a dry weight basis) in three Mediterranean regions (Annicchiarico and Pecetti 2003)

Country	Ratio
Palestine	0.55
Syria	0.43
Morocco	0.41

in stubble burning has been observed in several countries, particularly in Syria (Tutwiler et al. 1990), and this is a contentious crop management issue.

No-till agriculture requires a critical level of crop residues (a minimum of 30% cover) to maintain or enhance soil quality and prevent land degradation. No-till crops and livestock compete for the same resources and require proper integrated management to meet objectives of sustainable production of both animal products and grains.

Means to strengthen the co-evolution of agriculture and livestock under no-till may depend on the local conditions of farmers (Mrabet et al. 2007). Strategies for resolving the problems of the integration of crops and livestock while developing no-till systems include:

- Introduction of annual forage legumes (i.e. vetch and Sulla (*Hedysarum coronarium*)) in the cropping systems. These are an important source of high-quality feed for animals (Abd El Moneim and Ryan 2004), for nitrogen inputs and as a weed and disease break from cereal monoculture
- Introduction of cash crops for generating higher returns to guarantee feed purchase, especially if supplementary irrigation is possible
- Allocation of adequate crop residues for soil protection and enrichment, as well as for livestock feed. It has been estimated that some 30% of the residues can be used for livestock feed without reducing wheat grain yields in semi-arid Morocco (Mrabet 2002)
- Flexible, seasonal, controlled grazing on stubble with appropriate stocking rates to avoid overgrazing
- Establishment of forages for direct grazing and for cut-and-carry (use of fodder trees, shrubs and cactus)
- Conservation through ensiling and the use of supplemental feed blocks to give more efficient use of a wide range of agro-industrial by-products
- Temporary transfer of animals to pasture to allow degraded soil to recover
- Strategic application of inorganic fertilisers and manure to enhance crop biomass yields and soil quality
- Production of better-quality straw through genetic improvements.

40.5 Effect of No-Till on Soil Quality

Soil quality and productivity are interlinked (Cassman 1999) and both must be maintained as population pressure increases. The environmental benefits of adopting no-till with residue retention are wide-ranging both on- and off-farm. No-till can deliver a range of benefits that are increasingly desirable in a world facing population growth, environmental degradation, rising energy costs and climate change, among other daunting challenges (Uri et al. 1998). However, the immediate problems of poverty, food insecurity and poor agricultural productivity relegate soil degradation prevention to a lower level of the farmer's list of priorities.

40.5.1 Soils of WANA

The soils of the region are diverse, reflecting the influence of geology, topography, vegetation and climate. The major soil orders are: Lithosol, Inceptisol, Entisols, Aridosols and Vertisols[3] (Kassam 1981). The soils have high levels of free calcium carbonate and low contents of organic matter and major nutrients (N and P).

Conventional tillage has adverse impacts on the soil physical properties important for crop growth, whereas conservation agriculture has been shown to increase soil physical, chemical and biological fertility under a wide range of conditions. No-till systems with retention of surface residue create a biologically-intensive and ecologically-protective interface between the soil profile and the atmosphere. The impact of any soil and crop management practice on soil quality attributes in any ecosystem can only be assessed objectively under long-term agronomic trials (Kapur et al. 2007). However, there are few such trials that include effects of tillage systems.

40.5.2 Water Conservation and Control of Evaporation

Control of soil evaporation by reducing or eliminating tillage and retaining surface residues conserves water in the root zone and improves biomass productivity (Mrabet 1997). Increased water conservation results from increased infiltration and reduced evaporation from the soil surface. Figure 40.2 shows that, after watering,

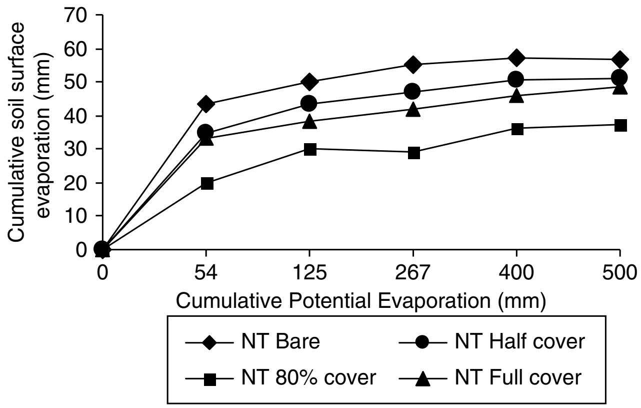

Fig. 40.2 Cumulative soil surface (0–100 mm) evaporation under no-till with various levels of residue cover (Mrabet 1997) (data taken over 57 days following irrigation of plots during summer)

[3] This chapter uses the FAO system of soil classification.

evaporation decreased as the amount of residue was increased, and the surface soil remained moist for longer. Most evaporation occurred from a bare, no-till surface.

No-till with residue cover tended to be better than all other tillage systems (Fig. 40.3) until the end of the 57 day measurement period. No-till crops become more tolerant to drought because of the better storage of water, either in the fallow or during the growing season.

Compared with a clean, cultivated fallow, water storage efficiencies in fallow improve with stubble mulching (but not stubble incorporation) and improve further with deletion of cultivation in a no-till (chemical) fallow (Table 40.7). NT with sufficient residue cover can increase water storage efficiency by 40% by reducing evaporation early in the fallow (Peterson et al. 1996), and this can be

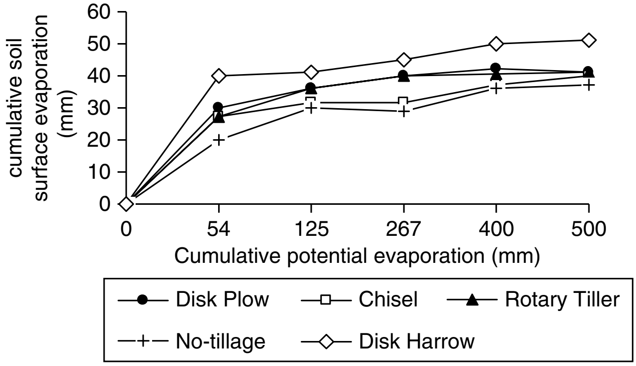

Fig. 40.3 Cumulative soil surface evaporation (0–100 mm) under various tillage systems (Mrabet 1997) (over 57 days following irrigation of plots during summer). No-till with 80% residue cover, chisel with 45% residue cover, disk harrow with 12% residue cover, rotary tiller and disk plough were bare (no residue cover)

Table 40.7 Storage efficiency and amount of stored water for different types of fallow in semi-arid Morocco (Bouzza 1990)

Type of fallow	Fallow storage efficiency (%)[a]	Amount of stored water (mm)[b]
Chemical	28	84
Clean	18	54
Stubble mulch	21	63
Weedy	10	30

[a] Calculated as the ratio of stored water and the rainfall received during fallow period

[b] Amount of water stored in 1.2 m profile

used either to increase crop yields, or if sufficient water is available, to increase cropping frequency (Bouzza 1990; Avci 2005).

40.5.3 Soil Erosion Management Using No-Till

Erosion and other related soil degradation effects are the most important threats to food production and security in the Mediterranean Basin (Bou Keir et al. 2001), yet many WANA farmers seem unconcerned about the problem. Soil losses due to erosion in the region (Table 40.8) are the highest in the world with annual levels reaching as high as 2,000 t/km^2 (20 t/ha/year) in Algeria (Demmak 1982) and 4,000 t/km^2 (40 t/ha/year) in Morocco (Belkheri 1988).

In the Mediterranean basin, erosion induced by tillage can cause irreversible soil degradation (Roose and Barthès 2006). Mechanical tillage may cause a form of desertification with a denuded soil, decrease of its effective rooting volume, depletion in its nutrient capital and a reduction of its water-holding capacity (Lahmar and Ruellan 2007). The traditional tillage system based upon off-set disking caused runoff and soil loss under rainfall simulation and surface sealing in response to soil pulverisation in semi-arid Morocco (Dimanche and Hoogmoed 2002).

Soil cover is the most important factor that influences water infiltration rate into the soil, thus reducing runoff and erosion. Dimanche (1997) found that a no-till treatment reduced the runoff volume by 30–50% and sediment loss by 50–70% compared with disk ploughing on a sandy clay loam soil at Ras Jerri (Meknes, Morocco). In comparison, with chisel ploughing, no-till reduced runoff volume by 24–53% and sediment loss by 43–65%.

In Tunisia, despite low residue cover, NT and direct seeding reduced average annual soil losses by 30–40% compared to conventional tillage (2–4 t/ha/year vs 3–7 t/ha/year). Water infiltration rates were 65 mm/h versus 45 mm/h for no-till and conventional tillage, respectively (Raunet et al. 2004).

Table 40.8 Extent and erosion rates in selected countries of WANA

Country	% of country's area subject to erosion	Soil loss[a]	References
Algeria	45		Chebbani et al. (1999)
Lebanon		50–70 t/ha/year	FAO (1986)
Morocco	40		FAO (1990)
Syria		50–200 t/ha/year	FAO-UNEP-UNESCO (1980)
Tunisia	45		Chevalier et al. (1995), Boussema (1996)
Iran	38		Lal (2001)
Turkey	50		Celik et al. (1996)

[a] Soil loss tolerance under Mediterranean climate varies between 2.5 and 12.5 t/ha/year. It is defined as the maximum amount of erosion at which the quality of a soil as a medium for plant growth can be maintained

40.5.4 Water Dynamics in Soils

No-till facilitates water infiltration. In Iran, the ease of early water entry in soil by capillarity was slightly higher in no-tilled loamy soil (0.425 cm/s$^{0.5}$) than in conventionally-tilled soil (0.3 cm/s$^{0.5}$) (Sepaskhah et al. 2005). Soil disturbance through tillage reduces soil organic matter (SOM) and the number and stability of soil aggregates; it consequently induces a decline in physical and hydrodynamic properties of the soil (Mrabet et al. 2001a, 2004; Lahlou and Mrabet 2001).

As recorded in Fig. 40.4, infiltration rates under well-managed NT are higher over extended periods than under conventional tillage systems—mainly because of better soil porosity. Essentially, NT takes advantage of biological processes in the soil to accomplish biological tillage; this improves networks of interconnected pores, nutrient recycling, and soil physical and biological health.

40.5.5 Carbon Sequestration Under No-Till

Conventional agriculture is said to contribute 15% of greenhouse gas emissions, most of it from soils (40%), enteric fermentation[4] (27%) and rice cultivation (10%) (Baumert et al. 2005). Soil organic matter is recognised as an indicator for soil

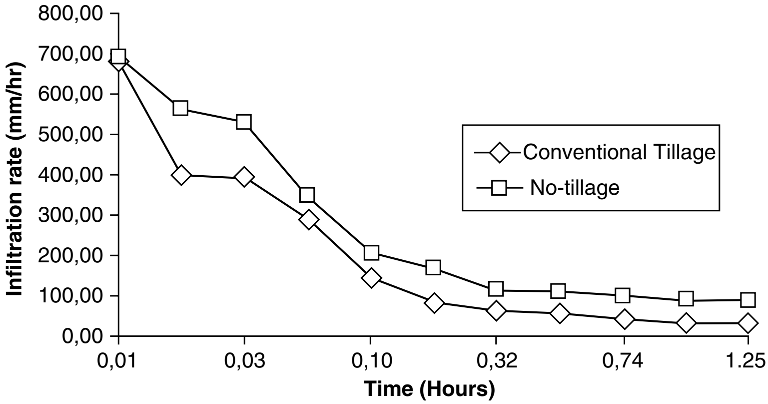

Fig. 40.4 Impact of tillage system on infiltration process in Sidi El Aydi clay soil. Conventional tillage = off-set disking (Mrabet 2008)

[4] Enteric fermentation is fermentation that takes place in the digestive systems of animals (methane production in ruminant animals).

Table 40.9 Effect of tillage systems on soil organic matter (%) in different WANA countries

Country	Soil order	Horizon (cm)	Years	NT	CT	References
				SOM (%)		
Northern Syria	Inceptisol	0–10	10	1.75a	1.10b	Ryan (1998)
Morocco	Vertic Calcixeroll	0–5	5	1.73a	1.66b	Ibno-Namr (2005)
	Vertic Calcixeroll	0–20	11	2.89a	2.35b	Saber and Mrabet (2002)
Central Iran	Calcic Cambisol	0–20	4	1.84a	1.44b	Hajabbasi and Hemmat (2000)
Norwest Iran	Calsixerollic Xerocherepts	0–15	3	0.95a	0.90a	Hajabbasi (2003)

Values followed by the same letters are not significantly different at 5% level

quality and agro-ecosystem fertility (Manlay et al. 2007). In rainfed farming, reaching and maintaining an adequate level of SOM is crucial to sustaining soil fertility, increasing soil moisture storage and mitigating drought (Rosenzweig and Hillel 2000). Under high temperatures and low precipitation, organic matter is oxidised quickly, and development of sustainable farming systems becomes difficult.

NT systems increase the maintenance of carbon inputs (e.g. residue retention) and reduce soil organic carbon decomposition (e.g. through reduced tillage) (Ibno-Namr and Mrabet 2004). Soil organic C was higher under NT than CT in a number of experiments (Table 40.9). The effectiveness of conservation tillage in carbon sequestration is enhanced when used in conjunction with appropriate crop rotations, especially with incorporation of leguminous crops in the rotation cycle (Jenkinson et al. 1999).

40.5.6 Aggregation Process

Soil aggregation involves the binding together of soil particles into secondary units. Soil aggregate stability is the main factor controlling soil permeability and erodibility at the soil surface and the transfer of energy and fluids through the profile. It is a function of chemical and biochemical properties of the soil, mainly its organic matter, and is affected by land management e.g. tillage, stubble retention and compaction.

Shifting to no-till generally increases soil aggregate stability (Table 40.10) through increased organic matter at the surface. The process is accelerated with increased crop residue input (Lahlou and Mrabet 2001).

Table 40.10 Tillage effect on soil aggregate stability in different WANA countries

Country	Soil	Horizon (cm)	Unit	NT	CT	References
Morocco	Mollisol	0–2.5	PSA[a]	65	48	Lahlou and Mrabet (2001)
			MWD[b]	3.78	3.21	Saber and Mrabet (2002)
	Vertisol	0–5	MWD	3.40	2.90	Kacemi et al. (1992)
Central Iran	Calcic Cambisol	0–15	MWD	0.62	0.41	Hajabbasi and Hemmat (2000)

[a] Percent of water aggregate stability (1–2 mm aggregates)
[b] Mean weight diameter (mm). An index of soil aggregate stability which is equal to the sum of products of the mean diameter of each size fraction and the proportion of the total sample weight occurring in the corresponding size fraction

Table 40.11 Dry bulk density (t/m^3) of soil surface (0–5 cm) as affected by tillage systems

Country	Soil type	NT	MT/RT	CT	References
Central Anatolia (Turkey)	Clay loam	0.98	0.80	0.82	Yavuzcan (2000)
	Sandy	1.34	1.28	1.34	Cakir et al. (2003)
Morocco	Clay	1.26		1.23	Mrabet (2006)
	Clay	1.08	1.01		Kacemi et al. (1992)

NT no till, *MT* minimum tillage, *RT* reduced tillage, *CT* conventional tillage

40.5.7 Effect of Tillage System on Soil Compaction and Consolidation

Soil compaction decreases porosity and increases bulk density (BD). Crop growth can be reduced by bulk density higher than a critical level (Andrews et al. 2002). Compaction in agricultural soils can be a serious problem because it restricts root growth and the uptake of nutrients and water by crops (Oussible et al. 1992). Surface soil density is generally higher in unploughed soils, and NT methods maintain this greater bulk density. However, as shown in Table 40.11, values do not exceed critical bulk density levels for optimal plant growth (1.3–1.5 t/m^3) (Dimanche 1997).

Most agriculturalists in WANA have been advising mouldboard and disk ploughing to facilitate water entry, infiltration and conservation (Karaca et al. (1988) in Turkey; Mansouri (1995) and Mansouri and Chaabouni (1996) in Tunisia and Kribaa et al. (2001) in Algeria). However in Central Iran, reduced tillage systems (chiselling) appear to be the accepted alternative management compared to conventional practice (mouldboard plough) and no-till (Hajabbasi and Hemmat 2000).

Ploughing may loosen a clay soil more than chiselling and no-till, but natural processes and tillage for seedbed preparation cause the soil after planting to be re-compacted to about the same density as before.

In Central Anatolia (Turkey), a medium-textured clay loam soil (Cambisol) exhibited greater soil strength and bulk density under no-till, regardless of depth, compared with conventional tillage systems (Yavuzcan 2000). However, all tillage systems allowed optimum root growth (Raper et al. 1993).

The high levels of soil organic matter under no-till reduce soil surface compaction in the long term, and biological activity is more intense in undisturbed than in cultivated soils.

No-till farmers should not worry about short-term increases in surface consolidation when changing to no-till systems, but may find it beneficial to break any plough pan first.

40.5.8 Soil Chemical and Biochemical Properties Under No-Till

In the WANA region, nutrient deficiencies are widespread, and fertilisers are needed for economic yields.

The introduction of no-till requires an understanding of the change in N dynamics and fertiliser use efficiency. In a no-till system, stratification of crop residues, soil organic matter and soil biota slows cycling of N and other nutrients. The consequent imbalance between crop demand and N supply from the soil may increase the requirement for N input into the system, especially in early years.

Residue retention in no-till is often associated with more stable year-to-year soil moisture, but large amounts of cereal residues with a high C:N ratio (>30:1) that are left on the soil surface temporarily result in a net immobilisation of mineral N in the soil. However, residues with a lower C:N ratio (<10:1) such as green legume material, increase soil concentrations of plant-available nutrients as soon as environmental conditions allow enough microbial activity. Release of P and S from crop residue can follow temporal patterns similar to N. Soil organic matter, nitrogen and phosphorus content of the soil surface (0–5 cm) increased linearly with increased crop residue maintained on the surface (Ibno-Namr and Mrabet 2004; Ibno-Namr 2005). Total nitrogen (Table 40.12) at the seeding zone (0–7 cm) was much higher under NT than CT (Mrabet et al. 2001b) but differences were smaller below this depth.

Crop residue releases nutrients more slowly than artificial fertiliser applied in a single dose at the start of the growing season. When converting to no-till systems, more nitrogen fertiliser is normally applied to compensate for slow release from organic matter—especially under sub-optimal physical and biological conditions. NT wheat farmers not using adequate mineral fertiliser will suffer N deficiency and yield reductions in early years of adoption. Maintenance of optimal nutrient requirements under NT will lead to higher yields, repeated additions of relatively large amounts of crop residues and consequently a greater soil C content. This may lead to greater net N mineralisation after a new equilibrium is achieved (Erenstein 2002). Thus, optimum fertilisation is more critical with NT, and soil analysis is necessary before applying fertiliser. Split N application may increase efficiency, and precise banding to separate fertiliser from residues can reduce N immobilisation.

No-till management causes surface enrichment of low mobility nutrients such as P and K (Mrabet et al. 2001b; Ibno-Namr and Mrabet 2004), from both crop residues

Table 40.12 Soil total nitrogen, extractable-P, exchangeable K and pH under no- and conventional tillage applied for 11 years (Mrabet et al. 2001b)

Depths (mm)	No-till	Conventional tillage	Difference
Total nitrogen (g/kg)			
0–25	1.84A	1.33B	0.51
25–70	1.49A	1.34B	0.15
70–200	1.20A	1.20A	0
Extractable P (mg/kg)			
0–25	29.9A	18.0B	11.9
25–70	19.3A	16.5B	2.8
70–200	8.7B	10.9A	–2.2
Exchangeable K (mg/kg)			
0–25	476.4A	284.1B	192.3
25–70	291.7A	256.9B	34.8
70–200	148.6B	177.9A	–29.3
pH(water)			
0–25	7.8B	8.0A	–0.2
25–70	8.1A	8.0A	0.1
70–200	8.2A	8.2A	0

Means followed by the same letters in the row do not differ by LSD test at p = 0.05

and P fertilisers. There is also a slight lowering of pH of the surface soil which can increase availability of other nutrients to crops (Table 40.12).

Like mineralisation of organic N, mineralisation of organic P is mediated by soil micro-organisms. Net P mineralisation is usually positively correlated with residue P concentration and negatively correlated with C/P ratio and lignin concentration or lignin/ P ratio.

The likely advantage of direct drilling is the formation of a thin surface layer rich in accumulated plant available P, which can thus meet plant P requirements at the early growth stages. However, there is a decline in P and K content with depth below the seed zone under NT, and this may require deep P and K banding to avoid any risk of deficiency in the crops (Table 40.12).

Tillage affects the soil physical and chemical environment in which soil organisms live. By affecting soil water, temperature, structure, aeration and the location of crop residue, no-till methods influence the environment and food supply to soil flora and fauna. By avoiding soil disturbance, mulch from leftover residues promotes increased microbial activity, protection of the soil surface, and accumulation of particulate organic C in the soil (Bessam and Mrabet 2001, 2003).

40.6 Economic Benefits: Putting Principles into Practice

No-till research and development programs have been implemented in more than 40 countries, but NT crop production has been adopted extensively in only a few regions. No-till has revolutionised agricultural systems because it allows individual producers to manage greater amounts of land with reduced energy, labour, and machinery inputs. In addition, NT controls erosion, and improves water and fertiliser use efficiency resulting in higher crop yields. Increases in crop yields and savings in production cost contribute to the overall profitability of no-till systems for wheat in the WANA region (Mrabet 2001a; Pala 2000).

40.6.1 Production Costs and Returns Under No-Till

To be economically attractive for WANA farmers, no-till must be perceived by them to provide a net economic benefit in terms of lower production costs, higher crop yields, higher net returns, lower business risks or some combination of these. While the elimination of tillage operations is a significant advantage of NT, the costs of agricultural inputs—herbicides, pesticides, fertilisers and certified seeds—promoted as part of the NT packages, have been deemed significant barriers to NT adoption by smallholders throughout the region (Mrabet 2001a).

WANA farmers face rising input prices, particularly for fuel, chemicals, fertilisers and machinery, and constant, or even declining, prices for the commodities they produce. Their long-term economic viability relies on long-term productivity; NT permits greater stability in yields and consequently higher ratios of outputs to inputs. In Lebanon, average cost of production was about $250/ha less in no-till than conventional tillage system (Bashour and Bachour 2008). Production costs for no-till become higher in the presence of difficult-to-control weeds as these can substantially raise herbicide costs (Mrabet 2008).

40.6.2 Energy Consumption and Efficiency

Tillage requires the highest power in the agricultural production process. The need for sustainable farming and the increasing cost of fuel in tillage operations will certainly encourage farmers to change to no-till.

Energy for primary and secondary tillage operations varies according to factors such as soil type and condition, the amount and type of residues, the plough depth employed and differences in machinery and tillage implements. Differences in terms of energy and time savings between no-tillage systems and an array of conventional tillage systems (El Gharras et al. 2004; Dale and Polasky 2007) are shown in Table 40.13. No-till is about eight times more efficient in fuel consumption than conventional tillage and eliminating tillage can be more energy efficient than eliminating herbicide use (El Gharras et al. 2004).

In the light soils of Odemis in western Turkey, conventional tillage and planting required seven times more fuel than direct-planting, while a no-till system had five

Table 40.13 Energy, time and power use by different tillage systems in Morocco (El Gharras et al. 2004)

Tillage systems	Power (hp/m)	Time (h/ha)	Fuel use (L/h)	Number of passes
Conventional tillage system	100–140	6.5–8.5	31–45	4
Deep disking	50–70	3–4	10–15	
Stubble plough	20–30	2–2.5	10–12	
Seedbed preparation	15–25	1–1.5	6–8	
Seeding	15	0.5	5	
Simplified Tillage system	50–70	3.5–5	21–25	3
Stubble plough	20–30	2–3	10–12	
Seedbed preparation	15–25	1–1.5	6–8	
Seeding	15	0.5	5	
Traditional tillage system	30–40	2–2.5	11–13	2
Off-set disking	15–25	1–1.5	5–8	
Seeding	15	0.5	5	
No-till: Seeding (no-till drill)	25–35	0.6–1	5–7	1

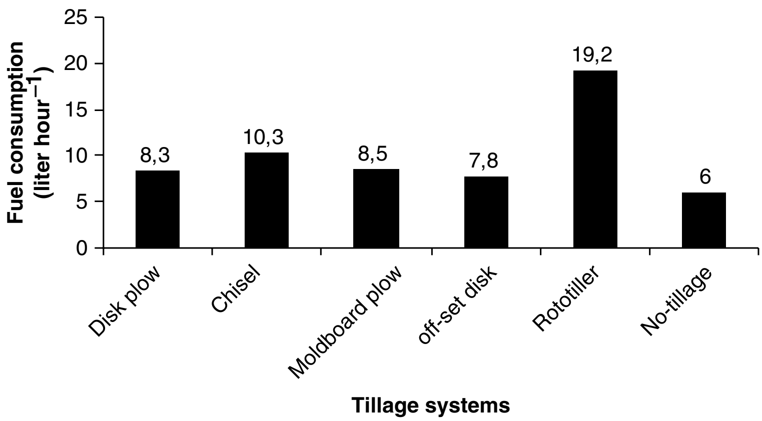

Fig. 40.5 Fuel consumption by tillage operations (Bourarach 1989). Fuel consumption refers to the quantity used for each operation for seedbed preparation and planting of wheat

times more field efficiency[5] than conventional tillage (Yalcin and Cakir 2006). Direct drilling may require more power than sowing in tilled fields. However, with time, no-till planting is done in better structured soils, with lower machinery and fuel costs (Fig. 40.5, Bourarach 1989; Chekli 1991).

[5] See glossary.

40.6.3 Machinery Development

No-till requires the integration of several components: machinery, pesticides, seeds, rotations, crop residues, knowledge and skills. Limitations can usually be overcome by modifying technology, as in no-till seed drills. Specialised drills are able to place the seed accurately, in intimate contact with an undisturbed soil, while operating on a thick crop residue layer.

Across the world, more than 100 manufacturers offer no-till machines and accessories capable of specific requirements in direct planting and nutrient management (Murray et al. 2006), but their high price, and restricted availability are a drawback for low-income farmers (Mrabet 2001b; Vadon et al. 2006).

Obstacles to NT adoption by smallholders are manifold and diverse (Mrabet 2008). However, advances in design and manufacture of seed drills by local manufacturers have allowed farmers to experiment and accept this technology, as in Morocco (Mrabet 2008) and in the Indo-Gangetic Plains (Baker et al. 2007). The no-till drill designed in Morocco to plant rainfed cereals (Bahri et al. 1993; Bourarach et al. 1998) is a hoe type that moves the dry surface soil to the side, 5–10 cm deep, to allow the seed to be placed near the P and N fertilisers. However, most imported no-till drills are disk types and are available through international companies.

40.7 No-Till Sociology: Bridging Farmer and Scientific Knowledge

Despite the wealth of research showing the benefits of the no-till system, it is not yet practiced extensively in WANA. There is often a delay in the benefits of CA as the farmer switches from exploiting his soils to improving them. In Brazil, NT was first introduced to farmers in the mid-1970s but it took almost 15 years before the NT area reached 1 million hectares (Derpsch 2005).

The no-till system is a knowledge-intensive system more than an input-intensive system. It is not only a production technology but also a social construct, being a complete departure from conventional tillage. For Hobbs (2007), probably the first challenge faced in spreading the use of no-till systems was overcoming the mindsets of farmers in retaining the traditional way of farming, where tillage is considered essential. This needs a common language between farmers, extension workers and scientists. In developing countries, including WANA, the limited adoption of conservation cropping systems is related to the failure to take into account the local experience and needs of farmers. Relevant scientific knowledge must be integrated with local knowledge.

The participation of farmers in this technology transfer can add value to decision making. It can ensure that all relevant environmental and social concerns are addressed and contribute to an honest accounting of the social, economic, and environmental costs and benefits of a decision. These participative approaches have been used in various projects related to conservation agriculture in Morocco (El-Brahli et al. 2004) and in the other countries of the Maghreb region (Vadon et al. 2006).

Institutional constraints that may prevent the adoption of NT include the lack of efficient organisations of farmers and lack of access to markets for suitable direct drills. Poor land tenure security in the rainfed, mixed-farming systems of the developing world and poor access to credit are additional disincentives for investment in no-till systems which must be addressed.

40.8 Conclusions on Implementing No-Till in WANA

The feasibility of no-till for rainfed, small-grain cereals, legumes, sunflower, and other major crops in the major arable areas of WANA has been systematically assessed since the 1980s. In spite of much research and assessment, no-till is still a new experience in agricultural development of most countries of WANA. This is not surprising since conventional tillage was, for centuries, the foundation of both traditional and modern agriculture. Hence, it is of importance to adapt extension services to promote no-till systems.

Our review of the literature illustrates the consistent value of applying no-till systems to rehabilitate degraded agricultural lands, enhance crop productivity and promote social capital in farmers' holdings of WANA. From individual research projects, it is generally accepted that the less the tillage, the higher the soil moisture in the upper soil horizons due to better infiltration, less runoff and reduced soil water evaporation. Retention and management of crop residues in no-till systems can help reduce water-loss.

Wind and water erosion are the main forms of soil degradation in WANA, and conservation agriculture systems (including no-till) represent effective methods for controlling these problems.

For a durable agriculture in WANA, the main technical components of no-till systems are permanent residue cover, minimal soil disturbance, controlled or zero grazing, diverse cropping rotations and integrated weed and disease management.

WANA farmers are skilled in surviving the severe and diverse environmental and socio-economic challenges associated with conventional agriculture, and they should be capable of adapting to no-till systems. However, their abilities need strengthening and the constraints need to be reduced. Incentive and motivation mechanisms (including subsidies, micro-finance, and access to markets) should be constructed to achieve satisfying results from NT agriculture. Analysis and adaptation of research and development results from around the world, as well as from WANA, are needed to provide the most appropriate technology for adoption. Wide adoption of No-till technology will not be based solely on its own technical or agronomic merits; it has to fit with existing local cropping and farming systems.

Decision makers in WANA will need to show dynamism and imagination to bring about this transformation, satisfy the requirements of the transition and hence succeed in establishing a no-till revolution as has occurred in Brazil, USA and Australia.

In conclusion, there is no single strategy for disseminating no-till systems in WANA. NT introduction has to be fitted to local farming conditions and farmers' experience. Hence, there is a need for partnering among all stakeholders. The start-up or transition phase is critical to the eventual success of any NT adoption process and should be skilfully organised, managed and guided.

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Part V
Farm Case Studies

While authors have inserted case studies and examples in several chapters throughout the book, Part V contains nine individual or sets of case studies that show how farmers have responded to external change over the last 30–50 years.

The farm systems in the studies differ in their environment (climate and soils) and structure. The owners and managers differ too in their goals and priorities, their operation and management, and in their response to challenges (environmental, biological, economic and family) and opportunities.

These changes over the decades start with earlier generations of farmers using traditional systems and methods of farming. These traditional farming systems had many positive attributes but became unsustainable when subjected to change. The case studies show how the operators responded to keep their farms economically and environmentally sustainable. They show the various pathways they took to achieve this, the management options they chose and their hopes and plans for the future.

Chapter 41
A Comparison of Three Farms in South Australia

A Case Study of Alternative Strategies for Different Rainfall

Mike Krause and Ian Cooper

Abstract This chapter compares the performance of three family-operated, rainfed farm systems in different rainfall areas of South Australia. Each of them has been improved over the two decades to 2006, and is economically viable. While their strategies have some common elements such as a business-like and innovative approach and the use of no-till, there are differences in the structure of the systems and the ways in which they are operated that reflect the differing soils, climate, property sizes and management goals of the owners. An Excel model is used in each case to show the economic benefit of the changed system.

Keywords No-till • South Australia • Innovation • Economic viability

41.1 Introduction

This case study is a comparison of three farms in differing rainfall areas of South Australia. The information was originally gathered in late 2006 at the behest of the South Australian No Till Farming Association (SANTFA) (Krause 2006a, b, c). The three farms are operated by farm families and have cropping enterprises reliant on rainfall. Comparing the three gives a deeper insight into how and why they have modified their systems over time, in order to make them more economically and environmentally sustainable and to cope with changing circumstances. The studies also give an insight into how rainfall, soil, property size and family aspirations can affect the farming system design.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_41,

South Australia has a Mediterranean climate with the rainfall growing season occurring in the cooler months (approximately April–October). The terms 'higher', 'medium' and 'low' rainfall are used in relation to the range of rainfall in South Australia. Most farming in the state is carried out in areas receiving between 250 and 600 mm of mean annual rainfall.

The three farms have a number of common features; for example, they are all operated by farm families, have each adopted no-till and continuous cropping systems, are open to new technologies, have difficulty recruiting labour, and need to find ways to remain viable. Differences occur between the farms in rainfall, soils, property size and the influence of livestock in the farming system.

41.2 Property 1 – Higher Rainfall (500 mm)

41.2.1 Introducing the Business

This property in the Lower North region of South Australia (Table 41.1) is now in the hands of the fourth (Murray and Ann) and fifth (Kym and Katie) generations of the I'Anson family (Krause 2006a). The fifth generation husband and wife team is well educated, with Kym holding an Honours degree in Agricultural Economics and Katie a Degree in rural Science with a Ph.D. in Animal Nutrition (Fig. 41.1). They are slowly taking over the operation of the business which is characterised by innovation and a business approach to farming. Two board meetings are held per year with all the four partners, the accountant and an independent financial advisor for strategic planning.

The partners meet regularly to plan monthly and weekly activities, and each has individual responsibilities such as maintaining the accounts, paddock recording

Fig. 41.1 Kym and Katie I'Anson

Table 41.1 Property 1 details

Area	1,258 ha
Soil	Predominantly acidic: • Red clay loam – 75% of the property • Black cracking clay – 10% of the property • Grey shale – 15% of the property
Vegetation	High-rainfall country supporting blue gum (*Eucalyptus leucoxylon*) and peppermint gum (*Eucalyptus odorata*) The land is lightly wooded and undulating
Water	The only water supply is that collected in dams. Water captured from roofs of several hay sheds on farm is used for spraying. Adopting No-till has meant that surface runoff has been significantly reduced
Topography	The country is undulating with a mean elevation of 435 m
Rainfall	Mean annual rainfall – 500 mm; growing season rainfall – 400 mm

to support the Quality Assurance program, Occupational Health and Safety, along with managing farm operations. The older generation, with their experience, has oversight of strategic planning and major business decisions.

The family has made continual management changes over the years (Table 41.2). They estimate that the last time their property was being managed 'traditionally' was in 1985. The characteristics of the system in 1985 and 2006 may be compared as follows:

1985 farming system: The cropping rotation was cereal–legume–cereal–pasture, with two cultivations before the crop was sown. The cropping program was quite complex with production of commercial cereal and pulse grain, grain for seed, and clover seed for sale. There were also significantly more self-replacing merinos than in 2006.

2006 farming system: The crop rotation was oaten[1] hay–canola–APW[2] wheat–feed barley, using no-till techniques. However, some deeper tillage was used to assist with the management of a hardpan. Fewer self-replacing sheep were kept than in 1985, as they were restricted to the less profitable cropping areas and the rangeland.

The challenges to their farming system have been clearly identified through the years and, with the help of their consultant agronomist, systematically researched and solutions identified. The family would be the first to say that they still have much more to learn, particularly to manage their farm as a system.

Farm records show that the efficiency of use of growing season rainfall in wheat has improved significantly from 48% in 1985 to 88% in 2004. The technologies that have assisted with this improvement include no-till with press wheels, targeted fertiliser application, the regular use of lime and gypsum (to correct pH and improve soil structure), more intensive cropping and use of controlled traffic. Use of these technologies has been an evolutionary process, as a great deal of learning has been required.

The family's goals are: to improve physical and financial sustainability by debt consolidation, by completion of the business quality assurance and introducing

[1] See Glossary for botanical names of crops.

[2] Australian Premium White – one of a number of Australian wheat grades (see glossary).

Table 41.2 Timeline of system development 1985–2006

Year	Development
1985	Stubble retention began on the property
1990	Increased cropping intensity
	Most of the livestock were taken out of the farming system
	120 ha (300 acres) of additional land was leased
1991	An airseeder was purchased
1992	Herbicide resistant annual ryegrass became a problem
1993	Press wheels were put onto the airseeder
1995	Advisory services were being used to overcome some agronomic challenges
	The application of urea was increased
1996	No-till was fully adopted in the cropping program
2000	An additional 230 ha of cropping land was purchased
2001	Soil mapping commenced on a on all paddocks
2002–2006	Yield mapping, quality assurance programs and controlled traffic commenced

standard operating procedures to improve efficiency. In order to be more self-reliant efforts being made to enable the farm to be more self-reliant include the use of composting animal manures for slow-release nitrogen.

For the near future they are assessing the leasing of hay storage on their property as it is well located for receiving and distributing hay. They are also considering options such as simpler rotations, to ease demands on labour – one of their most scarce resources.

41.2.2 Issues Faced and Strategies Used to Manage Them

The main issues facing the I'Ansons are: (1) soil erosion and maintaining soil structure; (2) plant nutrient management; (3) efficient use of rainfall; (4) fertiliser use efficiency in relation to seasonal conditions and crop needs; (5) risk management; (6) shortage of skilled labour; (7) smooth operation of the organisation (farm) through good communication.

41.2.2.1 Soil Erosion and Maintaining Soil Structure

Maintaining adequate ground cover has controlled wind erosion. This has been accomplished through stubble retention and significantly decreasing the number of sheep on the property.

No-till is practiced. The airseeder used is an 11 m DBS[3] bar with Horward Bagshaw box with double shoot boots[4] allowing deep banding of fertiliser.

[3]Deep Blade System.

[4]System allowing separate placement of seeds and fertiliser.

The hydraulic tines allow a high breakout to suit all conditions. Eighteen centimetre (7″) knifepoints are used to allow up to 15 cm (6″) working below the seed placement. This no-tillage system with one-pass creates less than 20% soil disturbance. The aim is to allow sideways fracture and a rip at depth, which allows better water infiltration and root movement. The fracturing of the deep ripping point is very effective in the sodic soils. This deep ripping has meant the soil is more permeable, and water erosion is no longer an issue. In 1985, stubble retention began and no-till has been in operation since 1995. Burning of stubble now only occurs on a limited basis, and is mainly used to control snails in the canola stubble.

The I'Ansons are moving to controlled traffic, since on their soil types there is a hardpan effect caused by the weight of implements. Implements such as the air seeder, boomspray and trucks use the same tracks in the paddock. The result is less soil compaction where the crop is grown. Gypsum is applied where necessary to improve soil structure.

41.2.2.2 Plant Nutrient Management

A standard 100 kg/ha DAP[5] is applied to all crops as the heavy, acid soils with high iron content readily fix phosphorus.

Nitrogen is also applied at planting with the amount based on soil test results and paddock history. Initially, high nitrogen applications were maintained but, in recent years, this has significantly decreased. Long-term stubble retention eventually provides more available nitrogen release, and nitrogen application now depends only on rainfall and available soil moisture. Nitrogen can be applied through the season depending on crop growth, with the aim of better canopy management. Hence, it is 'flexible management' when it comes to nitrogen. In some instances where N levels are adequate, no additional N is applied.

Soils are mapped to a grid of 1–4 ha using infrared mapping techniques. These grid maps assist with decisions on nitrogen, lime and gypsum applications. Yield mapping has been practiced on the property since 2002 but the benefits from this information are yet to be realised.

41.2.2.3 Efficiency of Use of Growing Season Rainfall

This is calculated according to the French and Schultz (1984)[6] formula (see also Chap. 1) and is used as a 'key performance indicator' of improved water use efficiency (WUE) that management is continually striving for. For wheat it has improved from 48% (1985) to 88% (2004) which is an indication of better management of the system.

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[5]Diammonium phosphate.

[6]See Chaps. 1 and 4 for further detail on this concept.

41.2.2.4 Responsiveness to Seasons

The major response to seasonal conditions is with the application of fertiliser, especially N. The application of N depends on soil test results, moisture availability and crop needs through the season. The improved farming methods now allow variable seasons to be better managed. However, it has taken 10 years to establish the system, as the evolution of a new concept does not happen overnight.

41.2.2.5 Risk Management

Keeping the cropping enterprises diverse spreads the seasonal and commodity price risks. Livestock, while a minor component of the system, also provide diversity. The I'Ansons undertake some forward selling of grain, and grain-swaps lock in some grain profits. However there are risks associated with forward selling such as not being able to deliver in a poor season.

Hay production and storage for sale has greatly helped cash flow management. Stored hay can be sold at times when there are no other sources of cash. The proposal to lease hay storage provides another way to diversify risk.

41.2.2.6 Labour

Shortage of labour is seen as a major restriction to the business; the following strategies are used:

- Seasonal labour is hired for planting, haymaking and grain harvest.
- Contractors are used for haymaking including windrowing, hay squeezing (conditioning), baling and transport.
- Machinery and labour are exchanged with neighbours when required.
- The managers continue to assess and reduce the labour requirement of farm activities.
- The use of no-till has significantly increased the capacity to manage a larger cropping program.
- Controlled traffic with auto guidance (10 cm accuracy) has allowed more timely and efficient operations to occur, reducing stress on operators.

41.2.2.7 Communications

Regular Board and farm management meetings are conducted, with minutes and action notes taken. This ensures that the partners and their advisors (accountant and agronomist) maintain good communication and are aware of all aspects of the farm.

41.2.3 Owners' Assessment of the Changes in System Structure and Management

41.2.3.1 Benefits of the New System

The owners believe the farm system provides the following advantages:

- An ability to consistently grow a profitable crop in a wide range of seasons.
- A cost of production that is being reduced through lower reliance on nitrogen fertilisers through retained organic matter and better nitrogen management. This helps with reducing risk.
- Reduced reliance on labour and the reduction in working time of the new no-till system have together led to a better lifestyle.
- Soil health and productivity have improved through the beneficial effects of no-till, stubble retention and controlled trafficking on soil structure, compaction and organic matter content and rainfall infiltration. Problems of soil acidity are being rectified by 3-yearly additions of lime, and of soil sodicity/salinity by 3-yearly applications of gypsum. The frequency of these additions will be reduced when the soil problems are rectified.

41.2.3.2 Challenges of the New System

Challenges brought about by the system changes include:

- The improvement in soil structure and stubble retention has caused a problem with slugs and snails.
- Nitrogen is now more plentiful in the system, requiring better management to limit early crop growth, so as to conserve moisture for production of high grain yields and high-quality export hay.
- Management has to be at a higher level to understand and manage the dynamics of the no till system and to make best use of technologies such as controlled traffic and soil and yield mapping.

41.2.4 Economic Impact of the Changes

An Excel model was used to assess the financial impact of the changes to this property. It estimated the whole-farm results for both the 1985 and 2006 farming systems, using 2006 commodity price expectations and expenses for the land farmed in 2006. To allow for risk management aspects of both systems, a decile[7] 3 rainfall

[7] See 'rainfall deciles' in glossary, for explanation.

Table 41.3 Cropping programs and grain yield expectations of the 1985 and 2006 farming systems, at three levels of seasonal rainfall

Season	% of farm area (1,258 ha)	Bad season (decile 3) t/ha	Average season (decile 5) t/ha	Good season (decile 7) t/ha
1985 Program				
APW wheat	25	1.3	2.8	3.7
Malting barley	6	1.4	2.5	3.5
Seed oats	7	1.3	2.5	3.5
Canola	3	0.3	1.2	1.8
Seed triticale	7	1.6	2.5	3.5
Peas	3	1.2	2.0	3.0
Lupins	3	1.2	1.8	2.5
Clover seed	6	0.20	0.35	0.50
Pasture	41			
2006 Program				
APW wheat	22	2.0	4.0	5.0
Durum wheat	9	2.0	4.0	5.0
Feed barley	16	3.0	4.5	5.0
Seed oats	4	2.0	3.5	4.0
Canola	19	1.0	2.0	2.3
Oaten hay	24	5.0	8.5	9.0
Pasture	6			

event was used to estimate a 'poor rainfall season', decile 5 an 'average season' and decile 7 a 'good season'.

The value of current no-till machinery is about AUS$1.1 million. It is higher than that for the equipment used in traditional farming but this is required more for labour efficiency than for the 'one-pass' requirement of no-till. It is difficult to estimate but if the same cropping program were to be put in using the conventional tillage methods, two sowing plants, more labour and significantly more fuel would be needed.

The seasonal rainfall effects on the productivity of both systems are provided in Table 41.3. This table also illustrates the crop production variation between the 1985 and 2006 systems. Note the significant increase in cereal and canola production.

Table 41.3 also indicates the significant change in the cropping program between 1985 and 2006. The cropping program of 1985 is characterised by more crops and a focus on certified seed production, legumes, pasture and clover seed. It was an intensive and high labour-demanding cropping program. The 2006 cropping program had a higher reliance on cereal, oil seed and hay production.

The potential yield performance has greatly improved since 1985. Table 41.4 illustrates the average and potential yield (French and Schultz 1984) results between the cropping systems and the efficiency (average/potential) %.

One of the keys to this improvement in water use efficiency has been the simplification of the cropping program, and the use of no till and precision farming.

Table 41.4 Actual and potential crop yields and WUEs from both I'Anson farming systems

	Average yield (t/ha)	Potential yield (t/ha)	Efficiency (average/potential) %
1985 Cropping program			
APW wheat	2.8	5.80	48
Malting barley	2.5	6.20	40
Seed oats	2.5	5.80	43
Canola	1.2	4.05	30
Seed triticale	2.5	5.80	43
Peas	2.0	4.05	49
Lupins	1.8	4.05	44
2006 Cropping program			
APW wheat	4.0	5.80	69
Durum wheat	4.0	5.80	69
Feed barley	4.5	6.20	73
Canola	2.0	4.05	49

Table 41.5 Whole-farm and individual crop gross margins (AUS$) from the 1985 and 2006 farming systems, at three levels of seasonal rainfall

	1985 System			2006 System		
	Poor (decile 3)	Average (decile 5)	Good (decile 7)	Poor (decile 3)	Average (decile 5)	Good (decile 7)
Return on capital (%)	–5.9	–2.6	0.0	–4.9	2.0	4.3
Gross margin ($/ha)						
APW wheat	–$95	$160	$313	$24	$364	$534
Durum wheat				$38	$418	$608
Malting barley	–$40	$147	$317			
Feed barley				$208	$433	$508
Seed oats	$53	$413	$713	$303	$783	$943
Canola	–$268	$65	$287	–$9	$361	$472
Oaten hay				$205	$625	$685
Seed triticale	$164	$434	$734			
Peas	–$40	$160	$410			
Lupins	–$40	$110	$285			
Clover seed	$260	$710	$1,160			
Self-replacing Merino	$196	$196	$196	$223	$223	$223

The consequent increase in the cropping area has resulted in a rise in whole farm return on capital, as indicated in Table 41.5. The 2006 system provided greater profits in all seasonal variations assessed, which shows that this system improves both profitability and the management of seasonal risk (Fig. 41.2).

These figures also illustrate that if the farming system had not changed, as described above, the farm business would no longer be viable, as losses would be experienced in average seasons and would breakeven only in 'good' seasons.

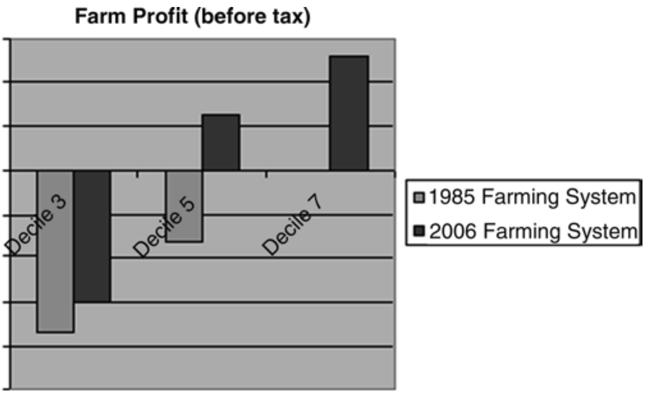

Fig. 41.2 Whole-farm relative financial results (see Table 41.5 for details)

The cropping gross margins[8] are shown in Australian dollars for comparison purposes between the systems. They have improved due to the yield improvements of the crops retained in the new system.

The interesting differences between these gross margin estimates are:

- The cereal gross margins are higher, with positive gross margins now expected in a decile 3 season.
- Canola gross margins have also greatly improved.
- Sheep gross margins remain relatively unchanged, which indicates why the area to pasture has decreased.
- The relatively low gross margins of peas and lupins have resulted in them being omitted from the 2006 farming system.
- The strong gross margin performance of oaten hay (due to good prices and efficient production) has seen this enterprise become a greater part of this farm's current operations.
- While clover seed provided good gross margins in the 1985 farming system, it is very labour intensive and clover diseases have made it difficult to maintain these gross margin levels.

It is also interesting to note that the proportions of the total gross margin coming from these enterprises have changed between 1985 and 2006. Changes include:

- The reliance on self-replacing Merinos has gone from 35% of the total gross margin to 3%.
- Reliance on cereal grain production has gone from 44% to 49% of the total gross margin.
- Hay production now represents a third of the total gross margin.

[8]Gross receipts less the variable expenses (e.g. fertiliser, fuel, seed) see also glossary.

41.2.5 Future Plans

The younger generation will be moving more into the management of the farm over the next few years as Murray and Ann move into retirement. They plan to continue the process of improving the farming system. The next challenge will be to better understand the relationships of the various soil types and to determine more precisely the water availability at seeding and throughout the growing season. This will take them to the next step into being more responsive to the seasonal conditions.

The high price of land and the limited availability of farm labour will be another challenge to the farming business as it continues to expand. Strategies are already in place to use better the business resources of the farm, such as by leasing out hay storage to the export hay industry.

41.2.6 Summary and Conclusions for Property 1

The family's story is one of continual innovation to overcome the various challenges of farming. They have used technologies such as no-till and precision agriculture together with improved management strategies (good planning communication and quality control) to overcome these challenges. The changes they have made to their farming system over the period considered have enabled them to stay economically viable while (1) improving soil structure and efficiency of use of rainfall, and (2) reducing soil erosion, water runoff and requirements for labour. This has been achieved through changing rotations and building up the soil by retaining organic matter, use of lime and gypsum and targeted fertiliser use.

There will be other challenges in the future, and their attitude of always aiming for improvements to their farming system and business performance equips them well for achieving long-term business and environmental sustainability.

41.3 Property 2 – Medium Rainfall (350–450 mm)

41.3.1 Introducing the Business

This property in the Mid-North region of South Australia (Table 41.6) is owned and managed by a husband and wife team – Craig and Lyn Humphris (Fig. 41.3) – with the involvement of Craig's brother David and parents, Julie and Ross (Krause 2006b). When the property was purchased in the 1940s it was grazing only but, since the 1980s, the business has moved into cropping with no-till. This move has been brought about by the decline in returns from sheep.

The family has been open to new farming practice techniques, and they were relatively early innovators in tillage systems. They began experimenting with reduced

Fig. 41.3 Craig and Lyn Humphris

Table 41.6 Property 2 details

Area	Cropping 2,430 ha; non-arable 404 ha
Soil	Jamestown property has red brown earth with a rock base
	Georgetown property has black self-mulching soil
	Soils are mostly neutral to slightly acid with some alkaline rises
Vegetation	Rolling hills with some trees
Water	No mains water is on the property. Water comes from bores and rainfall harvested in dams and tanks. Bore water quality varies from poor to good but all is suitable for stock. Some Lucerne flats benefit from an accessible water table
Topography	Slightly undulating to hilly
Rainfall	Annual rainfall – 350–450 mm; growing season rainfall – 300–320 mm

tillage in the early 1980s. While farming is their core business, various members of the operation have branched into rural computing and tillage component distribution. This has provided a diversity of business interests.

A third of the 2,430 ha cropping program is wheat, a third barley and the remainder canola, peas and hay. There is also a 1,000-ewe prime lamb enterprise which uses the property's feedlot in periods of the year feed availability is tight and when they need finishing.

41.3.1.1 1982 Farming System

Traditional tillage was last used in 1982 when the rotation was wheat–barley–pasture–pasture–fallow. Tandem discs provided the main tillage and numerous cultivations, especially during the fallow phase.

Wheat stubble was burnt and generally the land was then cultivated twice before the barley phase of the rotation. Barley was under-sown with clover (rose clover *Trifolium hirtum* and sub clover *Trifolium subterraneum* varieties) to provide 2 years of pasture. This allowed the property to carry 3,000–4,000 Merinos and, when wool prices were good, provided a sound return. As wool prices declined, clover seed production began to rise in profitability. Clover was harvested during the second pasture year.

41.3.1.2 2006 Farming System

The rotation has become more crop-intensive with wheat–wheat–malt barley–feed barley–canola–peas on the arable country. A 1,000-ewe prime lamb enterprise is run mainly on the 404 ha non-arable country, with a feedlot to help finish the lambs. A no-till system is used, splitting the seed and fertiliser. Knifepoints are used to give less than 20% soil disturbance. Press wheels are used to direct rainfall into the seeding furrow.

Table 41.7 illustrates the changes that have occurred in the family business since they operated in the traditional farming system in 1982.

Table 41.7 Timeline of system development 1982–2006

Year	Development
1982	Wheat–barley–pasture–pasture–fallow rotation with two full cultivations before sowing. Cropping area 800–1,000 ha
1986	Clover harvesting started, and proved to be profitable for a number of years
1993	Farm experiments indicated value in using Lucerne Points. At this stage, these were the only narrow points available. Cropping area increased to 1,130 ha
1996	Direct drilling with knife points was fully adopted, and all arable land was cropped. Pasture phase replaced with canola and peas. Nitrogen fertiliser use increased. Clover harvesting stopped as profits were low. Livestock numbers decreased to 2,000 Merino ewes. Minimal weed problems. Rotation of durum wheat–wheat–barley–barley–canola adopted
2000	485 ha (1,200 acres) of land purchased. Weeds were becoming a problem so peas and export hay were added to the rotation
2001	Rotation now wheat– wheat–barley–barley, then 2 years of break crops with canola and peas/hay. GPS guidance introduced, allowing spraying at night. Prime lamb enterprise replaced the Merino wool flock. A good season allowed hiring of four full-time farm hands. Brome grass (*Bromus* spp.) and silver grass (*Vulpia* spp.) became a problem so simazine was used for the first time
2003	A feedlot was used for the first time to finish off the lambs. Ewe numbers cut back to 1,000. Introduced double seeding rate to obtain higher yields of export hay.
2004	Introduced auto-steer with sub-metre GPS. Professional agronomists consulted for the first time
2005	Took out a 4-year lease on an additional 485 ha (1,200 acres). The cropping area was now 2,430 ha. (6,000 acres)
2006	An improved GPS with base station was installed, allowing inter-row planting. Stubble used as a trellis for lentils and peas, to assist in frost protection

Along with improved economic an environmental sustainability the main goals of the farm's managers are: (1) to improve the management of the farm by means of precision and controlled traffic farming, in order to (a) reduce the soil hardpan with the use of inter-row sowing, (b) match the machinery to enable use of tram lining[9], (c) fully use the technology of auto steer and yield mapping, (d) gain all the possible advantages of the planting technologies, (e) understand the implications varying of inter-row spacing to determine the optimum. (2) To keep investment options open for the next generation to take over the farming business, using Family Trusts and off-farm investments.

41.3.2 Issues Faced and Strategies Used to Manage Them

Issues faced by the Humphris family include: (1) maintaining soil structure and health, (2) managing soil erosion, (3) improving overall system efficiency, (4) responding to varying seasonal conditions, (5) maintaining good communication.

41.3.2.1 Soil Structure and Health

In the 1980s the soil needed to be in better health and to be more friable. The lack of soil surface cover was leading to a problem of erosion. The strategies used include changing tillage methods and moving to no-till. The planting method now involves the use of:

- 25 cm (10″) row spacing and 16 mm wide knife points.
- A sowing depth of 25 mm and working depth of 75 mm.
- Fertiliser placement below the seed at a depth of 25–75 mm.
- Press wheels in conjunction with rolling harrows (which can lift out of the way). This provides ideal seed establishment.
- A triple box and double-chute planting system, which seems to work best. The triple box mixing N and P (urea and DAP[10]) allows for an easier changeover between feed barley and canola, and so further improves the efficiency of the planting operation.

The aim of this planting method is to obtain less than 20% soil disturbance. The cropping paddocks have shown increases in soil biota and crop residues retained on the surface, leading to improved soil friability and structure. The problem in recent times has been to assess how the farming system will improve in a reasonable rainfall season.

[9] See glossary.

[10] See glossary.

As with Property 1, a major challenge is occurring with the development of a hard pan, and so the use of controlled traffic with tram lines is being assessed.

41.3.2.2 Controlling Soil Erosion

When traditional farming was practised, contour banks were put in to control erosion. Now that no-till has been used for a number of seasons, the crop residues have been allowed to stay on top of the soil surface and the family is removing the contour banks. Water erosion is not a problem as rain is soaking in rather than running off the slopes. Wind erosion has also been eliminated because of crop residues on the soil surface.

41.3.2.3 Improving System Efficiency

The biggest business challenge is to make the cropping system efficient, with the ever-increasing costs of machinery and limited labour resources. The financially challenging seasons of the 2000s makes the timing of machinery up-grade important.

A suite of machinery that has been purchased by the family for the no-till system includes a 12 m (40′) Flexicoil with 23 cm (9″) spacing and a triple box. Their main tractor is a Case STX 242 kw (325 hp) four-wheel drive and their spray rig is a 33.5 m (110′) Sonic with 5,000 L capacity pulled by a Case CVX 1190 142 kW (190 hp) tractor. They have recently purchased a New Holland CR 970 header with an 11 m (36′) Mid West fabricated centre mount draper front and a spreader to evenly distribute the chaff.

The recent purchase of a 'belly dumper'[11] to assist planting (delivery of fertiliser) and harvesting (carting grain) operations has further improved cropping management and greatly improved the occupational health and safety of these operations. The 35t capacity allows 20 h of sowing time and operates in high wind conditions. The belly dumper assists with freighting the grain to either silo or on-farm storage.

41.3.2.4 Responding to Varying Seasonal Conditions

Implementing the new tillage system during a run of late seasons in the 2000s has meant the pressure of getting the crop in has been challenging. No-till allows sowing on the first rain which means a better use of moisture, while in late seasons, sowing is not much delayed compared to the traditional workup and workback tillage system.

The application of nitrogen and seed in the one pass is being used to cut down the cost of the extra working of the paddock.

[11] Truck or trailer designed for fast emptying through the floor or 'belly' of the tray.

41.3.2.5 Communications

This is an area that requires continual effort and refinement; regular meetings with workmen have greatly improved communication.

41.3.3 Owners' Assessment of the Outcomes

41.3.3.1 Advantages of the New System?

The major advantages are the improvement in soil health, less soil erosion and overall improved sustainability. This has made farming more enjoyable and decreased the stress associated with seeing country being damaged. It has also improved productivity and profitability.

41.3.3.2 Challenges of the New System?

One remaining problem is less associated with no-till and more with the farming system itself. With a larger cropping program there is a lot more pressure at planting time when a greater area of crop is being planted.

41.3.4 Economic Impact of the Changes

While the move to no-till has demanded larger, expensive machinery, one of the motivations to make no-till work was to alleviate the problem of labour shortage and costs. The equipment now used in the no-till operation means more cropping can occur with minimal labour. Under a similar cropping program with traditional tillage, multiple seeding implements would be needed – which would require more labour and a far greater fuel cost.

The family has examined differences in variable costs between the old and present farming systems. With traditional tillage, there was less use of chemicals and fertiliser whereas with no-till less fuel is used. The cost saving from less fuel use with no-till is about the same as the additional chemical and fertiliser costs, so the cropping variable costs would remain approximately the same. The seasonal rainfall effects on the productivity of both systems are provided in Table 41.8 which also shows the differences in composition between the 1982 and 2006 systems.

Average and potential yields in 1982 and 2006 are illustrated in Table 41.9. There has been an increase in cropping intensity and area, (less pasture) and improved water use efficiency of wheat and feed barley.

Table 41.8 Cropping programs and grain yield expectations of the 1982 and 2006 farming systems, at three levels of seasonal rainfall

Season	% of farm (area 2,835 ha)	Bad season (decile 3 rainfall) t/ha	Average season (decile 5 rainfall) t/ha	Good season (decile 7 rainfall) t/ha
1982 Program				
wheat	21	1.3	2.5	3.2
Feed barley	21	1.3	2.5	3.5
Pasture	57			
2006 Program				
Wheat (year 1)	14	1.4	2.8	3.5
Wheat (year 2)	14	1.3	2.6	3.3
Malting barley	7	1.8	3.0	4.0
Feed barley	7	2.0	3.2	4.2
Canola	14	0.8	1.0	1.4
Peas	14	0.6	1.0	2.5
Pasture	28			

Table 41.9 Actual and potential crop yields and WUEs from both Humphris farming systems

	Average yield (t/ha)	Potential yield (t/ha)	Water use efficiency % (average/potential)
1982 Cropping program			
Wheat	2.5	4.0	63
Feed barley	2.5	4.4	57
2006 Cropping program			
Wheat	2.8	4.0	70
Malting barley	3.0	4.4	68
Feed barley	3.2	4.4	73
Canola	1.0	2.0	50
Peas	1.0	2.7	37

The increased cropping area has provided the significant improvement of whole-farm profits (before tax) as shown in Fig. 41.4. The 2006 system provided greater profits (or less loss) under all seasonal conditions assessed showing improvements both in profitability and in the management of seasonal risk. There is a greater diversity of enterprises, with the opportunity for break crops and herbicide variation and with a reduced reliance on sheep (Table 41.10).

41.3.5 Future Plans

- The Humphris family feel a degree of optimism for their farming business – even though most seasons in the 2000s have been challenging. They see the following opportunities in the future: The prices for grains are likely to increase with the recent developments in fuel prices and potential for biofuels.

Fig. 41.4 Whole-farm relative financial results (see Table 41.10 for detail)

Table 41.10 Whole farm and individual crop gross margins (AUS$) from both Humphris farming systems, at three levels of seasonal rainfall

	1982 System			2006 System		
	Poor (decile 3)	Average (decile 5)	Good (decile 7)	Poor (decile 3)	Average (decile 5)	Good (decile 7)
Return on capital (%)	–3.5	–0.6	1.4	–3.4	1.8	7.0
Gross margin ($/ha)						
Wheat	$12	$216	$335	$29	$250	$369
Malting barley				$138	$342	$512
Feed barley	$27	207	$357	$132	$312	$462
Canola				$27	$120	$249
Peas				–$147	–$59	$271
Sheep	$84	$84	$84			

- Their significant on-farm grain storage provides an opportunity to respond to grain market trends (selling or storing depending on price) and enables them to institute a feedlot as a possible diversification.
- They see potential for GM crops, with possibilities for resistance to frost and drought, along with the possibility for using cheaper chemicals (see Chaps. 31 and 49 for North American experience).

The use of auto-steer and the next generation of robotics and the possibility of driverless machinery may be able to assist with the labour shortages.

A challenge for this farming business is succession planning and organising the passing of the business from one generation to the next. This will obviously require sound communication and planning. However, if past business performance is any indicator of management ability, a successful succession planning process will be achieved.

41.3.6 Summary and Conclusions for Property 2

The Humphris family feel they have significantly improved the farming system so that it is now more economically and environmentally sustainable. This is due changing the rotation and to introducing such technologies as no-till (low disturbance and press wheels), precision farming and feedlotting sheep. These have resulted in reduced erosion and improved soil structure and health. The planting and harvest operations are at an efficient level due to the machinery purchased and the practices instituted.

The story of this family is largely one of continuing innovation. They are receptive to new technology often being amongst the first to trial it. As a family unit, they have not only advanced the farming operation, but have also spread into tillage component distribution and rural computing. This has provided a stimulating working environment for all members of the family, and continues to provide new ideas to be considered to further refine the farming business.

41.4 Property 3 – Low Rainfall (350 mm)

41.4.1 Introducing the Business

Gary and Janet Flohr (Fig. 41.5) who manage this business began with 408 ha (1,000 acres) near Lameroo in the South Australian Mallee in 1983 in addition to off-farm income from the husband shearing and the wife nursing in the local hospital. They were aware they needed to ‘get bigger or get out’. In the early days, they did not know where the opportunities lay. In 1988 an opportunity came to move into Janet’s family homestead, share-farm the family land and maintain the family’s sheep stud (Table 41.11). They managed this new land as well as maintaining their own farm (Krause 2006c).

Fig. 41.5 Gary and Janet Flohr

Table 41.11 Property 3 details

Area	1,915 ha present area
Soil	Mallee dune swale – Sandy loam dunes with clay flats. Alkaline
Vegetation	Mallee[12] scrub
Water	The property is on the western fringe of the Murray Darling Basin underground water. The water quality is suitable for livestock and winter irrigation of seed potatoes.
Topography	Dune swales with east west sand hills
Rainfall	Mean annual rainfall – 350 mm; growing season rainfall – 250 mm

A further challenge has been to provide the children's education in their rural area, and it has been a top priority. Recent budgets have had to include sending children to boarding school in Adelaide (200 km west).

The decline of the wool price in the late 1990s brought enormous pressure to this strong wool-growing district and was a major catalyst for change in the farming business. As Gary and Janet had been moving into cropping in the years leading up to the wool price crash, this meant there was no going back.

All these challenges have encouraged them to adopt innovative cropping methods to maximise the returns from their family business.

While continual management changes have been made, the system used in 1984 was deemed 'traditional' and it has evolved to the current farming system. The choice to concentrate on cropping was made back in the mid 1980s before the wool price crash. Luckily there were a few good seasons in the late 1980s which allowed the cropping skills to improve and mistakes were not as costly. However, the best strategy has been to use consulting agronomists to guide the business through cropping and tillage evolution.

While the switch to more cropping was occurring before the wool price collapse, the change in the wool market was the catalyst to pursue a 100% cropping program (Table 41.12).

1984 farming system – Cropped (wheat and barley) half of the arable land using conventional tillage. Managed 700 self-replacing Merino ewes plus 1,000 other sheep. These were agisted in the scrub country on a neighbouring farm, mostly for wool production.

2006 farming system – The crop selection (wheat, barley, vetch and oaten hay) is made on the basis of bioassay reading indicating the incidence of cereal root disease. The improved planting timeliness of no-till has increased productivity by 8%. The cropping program consists of 70% minimum till and 30% direct drill.

Along with improved economic and environmental sustainability the family goals include: (1) to accumulate more land in the long-term to achieve the benefits of economies of scale. This is one of the major drivers of the business. While the move to the parent's farm has achieved this to some degree, growth is still important in the business, and could involve off-farm investment. (2) The farm business is

[12] See glossary.

Table 41.12 Time line of management developments 1984–2006

Year	Development
1984	Galleon barley sown into wheat stubble using a two-way disc (to cope with trash) attached under a conventional combine seeder. First vetch crop sown with disc attachment. Glyphosate was expensive so applied at 350 ml/ha
1986	Hired tandem disc to assist in operating through stubble. Normal practice was discing before sowing. Attempted No-till for the first time but with not enough N, just 80 kg/ha of DAP applied at planting. A good season with wheat yielding 1.6 t/ha. Sheep were profitable
1988	Joined consulting group and gained valuable agronomy advice which significantly improved the cropping system
1990	Purchased tandem disk in shares with a neighbour. Wool price collapsed so sold most of the sheep. Also a poor cropping season and finances were tight
1991–1992	All sheep have gone and grew first crop of direct-drilled peas. Crops direct drilled (not 100%) using narrow points. At this stage, 100% cropping with wheat–barley–grain legume rotation and all urea pre-drilled. A wet harvest meant the vetch was spray-topped for the first time with SpraySeed
2001	Spray-topping continued but concerned that it was knocking the crop down. Did not appreciate how effective it was for ryegrass control
2003	First crop of canola produced 0.7 t/ha and gave a better gross margin than sheep. Glyphosate becoming cheaper so increased summer spraying
2004	Tried peas, beans, lentils, chickpeas, vetch, canola and lupins, but all are high risk for the farm's low rainfall
2005	Purchased 9000 series Morris cultivator, Harrington points, press wheels and coulters fitted to the front. Now direct drilling the entire cropping program. Canopy management being used for the first time and grown first crop of export hay
2006	Began clay spreading

now in a consolidation phase. A more accurate seed planter may be necessary but the cost may not deliver the yield benefit to offset the cost of the investment. (3) The children's education is also an important goal and so they are in Adelaide for their senior years.

41.4.2 Issues Faced and Strategies Used to Manage Them

The issues faced by the Flohrs include: (1) maintaining the fragile sand dune soils, (2) controlling weeds and root diseases, (3) managing risk. Strategies to deal with them are as follows:

41.4.2.1 Maintaining Fragile sand Dune Soils

Intensive cropping and multiple workings are not an option on the sand hills with their wind erosion problems; a one-pass tillage system is needed. This is achieved using no-till with knifepoints and press wheels. However hay production needs a prickle chain to level the soil post-sowing, so that the ground is suitable for haymaking.

These sandy soils are prone to leaching so a complete fertiliser is essential. The new system is more robust and the last few seasons have shown that reasonable crops can be grown with less moisture. While there have been no scientific trials, the Flohrs put this down to the use of narrow points and press wheels – which seems to concentrate the moisture through capillary action and some 'water harvesting'.

Wind erosion is no longer an issue on this property, following the successful implementation of no-till, the maintenance of a cover of crop residues on the soil and with less impact from livestock.

41.4.2.2 Controlling Weeds and Root Diseases

The current farming system needs to control summer weeds to conserve moisture and remove hosts of root diseases.

Ryegrass was, and still is, the main growing season weed problem, and crop-topping[13] was being used before it was on the chemical label – giving a head start in the battle. There was initial resistance to adopting this practice but it has helped enormously. Being proactive with this method of ryegrass control has provided another 10 years with minimal rye grass problems.

Growing vetch (for hay), lupins and peas have fitted in well with the crop-topping. Although risky in our rainfall these crops generate yield while allowing the ryegrass to be killed before it sets seed. There are yield losses from crop-topping but this is a small opportunity cost compared to the benefits of controlling ryegrass. The introduction of export hay into the system is also a tool to fight ryegrass.

41.4.2.3 Risk Management

In the early days, grain legumes proved a risk management strategy along with the sheep. However, the low rainfall seasons have shown legumes are a greater risk than sheep, but remain in the rotation for their ability to provide a disease break.

Wheat has been a solid performer and the best enterprise of the farming system. The opportunity of having various price risk management tools (forward selling, swaps, options) available for wheat has also meant this enterprise is the backbone of the business risk management strategies.

While it has taken some time to perfect the no-till and 100% cropping farming system, which includes weed, soil fertility and moisture management, this system is shows signs of being robust. Mistakes can be made now with less effect on yield potential than would have occurred in the early days. The Flohrs put this down to having the right rotation and an appropriate planting system (no-till). The proprietors are happy that they persisted with the intensive cropping system in the late 1980s as these were reasonable seasons in which to learn the management of intensive cropping.

[13] See glossary for explanation.

Frost in spring has been an issue in the district so planting is not begun before 20th May each year, allowing flowering to occur at a less vulnerable time of plant development.

41.4.3 Economic Impact of the Changes

The following were seen as the major economic differences between the two systems:

- The 1984 system used about 45% of the chemical costs of the 2006 system.
- Due to the increased number of cultivations, the 1984 system is estimated to have used twice as much fuel per hectare as the 2006 no-till system.
- The 1984 system used only 80% as much fertiliser as the 2006 system. Fertiliser in the current system requires more intensive management. The aim is to replace the nutrients removed by the previous crop. N and P are added strategically. The application of N in particular is related to canopy management (planting date and variety) and growing season rainfall.
- The header was the only machine that significantly changed the value of machinery. The current system, with its larger cropping program, would require a header valued at $300,000 whereas the 1984 system would require only a second-hand header valued at $150,000. The capital values of the tillage machinery would differ between the systems, but not significantly.

The seasonal effects on the productivity of both systems are provided in Table 41.13. This table also illustrates the cropping variation between the 1984 and 2006 systems.

The increase in cropping area has resulted in a significant improvement of whole-farm profits (before tax) (Fig. 41.6). The 2006 system provided greater profits at all levels of seasonal rainfall assessed showing the better management of seasonal risk. Return on capital is also greatly improved; if the business had not changed, its financial viability would have been doubtful, as shown in Table 41.14.

Table 41.13 Cropping program and grain yield expectations of the 1984 and 2006 farm systems, at three levels of seasonal rainfall

Season	% of farm area (1,915 ha)	Bad season (decile 3 rainfall) t/ha	Average season (decile 5 rainfall) t/ha	Good season (decile 7 rainfall) t/ha
1982 Program				
Wheat	33	1.2	1.6	2.2
Barley	17	1.0	1.4	1.9
Pasture	50			
2006 Program				
Wheat	70	1.4	2.5	3.0
Barley	5.5	1.6	2.5	3.0
Vetch	9.5	0.5	1.0	1.5
Oaten hay	15	2.0	3.8	5.5

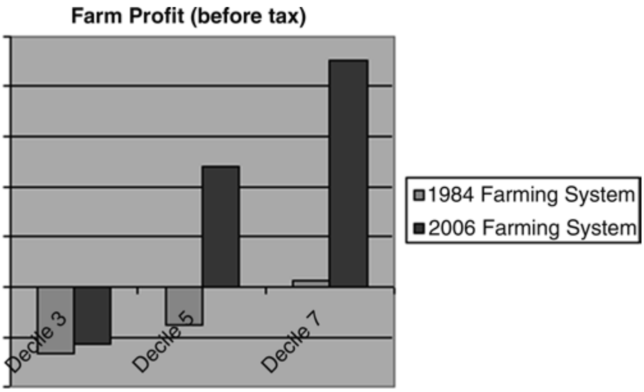

Fig. 41.6 Whole-farm relative financial results (see Table 41.14 for detail)

Table 41.14 Whole farm and individual crop gross margins (AUS$) from both Flohr farming systems, at three levels of seasonal rainfall

	1984 System			2006 System		
	Poor (decile 3)	Average (decile 5)	Good (decile 7)	Poor (decile 3)	Average (decile 5)	Good (decile 7)
Return on capital (%)	−3.3	−1.5	1.2	−2.7	8.4	15.0
Gross margin ($/ha)						
Wheat	$35	$103	$205	$54	$241	$326
Barley	−$32	$15	$83	$34	$155	$223
Vetch				−$39	$111	$261
Oat hay				$66	$291	$503
Sheep	$84	$84	$84			

While the 2006 system provides more whole-farm profit, the total expenses are also higher – which may be viewed as higher risk. However, the results in Table 41.14 indicate that the 2006 system still outperforms the 1984 system in a poor season (decile 3).

41.4.4 Future Plans

The partners believe most of their farming system is now in place and their business is entering a consolidation phase. Their future plans include:

- Decreasing the business debt.
- Assessing ways to improve the seed and fertiliser placement, although they are still not convinced that the technological advancements will achieve the necessary financial improvements.
- Placing more resources in off-farm investments to allow the opportunity for one or more of the children to take over the family business.

- Adoption of technologies for precision, site-specific farming, auto steer on all machines and for GM seed varieties in the fight against weeds and climate change.
- "Never say never." Sheep may well become part of the system again with the ever-increasing input costs and pending changes to the grain marketing boards. Adapting to change will be a top priority.
- Better management of fertiliser and cereal disease with better seed placement and in-crop herbicide and fertiliser application.
- Renewable fuels may be an option given that the USA, Canada, Europe and South America are encouraging ethanol, and farmers are getting increased competition for their grain.

41.4.5 Summary and Conclusions of Property 3

The story of the business is one of persistency, with a firm focus on improvement in its financial performance. While they did not start their business journey knowing where they would finish up, their positive attitude mixed with new business skills has helped them along the path of achievement.

Key aspects of the evolution of this property include increased scale (through moving to Janet's family property), the move from wool to continuous cropping (driven by the declining economics of sheep) and the need for innovative methods to produce profitable crops in low rainfall on their fragile sand dune soil. No-till (with stubble retention) was the most significant of these innovations. However, it was the complete farming system including continuous cropping and diversification (vetch and oaten hay replacing pasture), that they adopted that contributed to their business success and financial viability. They now operate more land, more efficiently and more profitably. Their philosophy of doing more with less has held them in good stead and will continue to guide their business in the lower rainfall district.

As there has always been a need to be viable, the motto used by Gary and Janet is 'to do more with less'. They have been happy to drive their business hard, but also to assess the risks. They decided early that cropping was providing the best return for the dollar invested and also that no-till would allow them to spread their machinery over a larger area and get economies of size and improved timeliness.

They obtained some farm management training early in their careers and farm decision-making is based on assessing which options will provide the best financial reward.

41.5 Comparing the Systems

Each of the three properties has improved their system over the period reviewed in both a financial and environmental sense. Several common elements were:

- Taking a business-like and innovative approach to farming.
- Adopting no-till and stubble retention. In all cases this was important in preventing erosion and improving soil health.

- Reducing or eliminating sheep because of reduced returns when the wool price collapsed.
- Cropping area increased with more diversified rotations made possible by the adoption of conservation farming techniques.
- Improved financial returns, with a likelihood they would not have been viable if they had not changed the system. All properties have adopted a form of conservation farming with an emphasis on increased, diversified cropping a rotation suitable to their rainfall.
- Interest in new technologies such as controlled traffic, auto steer and site-specific farming techniques such as yield mapping. The adoption of some of these technologies has been greater where higher rainfall and hence higher yields warrant the extra cost.
- All have increased their land area through inheritance, purchase or leasing; however, the comparisons between systems were made on a constant total area.

Table 41.15 compares the different properties. The higher the rainfall the more alternative crops are available. Wheat and barley are the common crops, with canola and hay being important on two of the three properties and vetch and peas on one property each. Communication, with more formal meetings is important when additional family members are involved. All the properties also used consultants and other advisors to advantage.

Table 41.15 Comparison of properties

	Property 1	Property 2	Property 3
Area (ha)	1,258	2,835	1,915
Growing season rainfall (mm)	400	300–320	250
Initial crops	Wheat, malting barley, seed oats, canola, seed triticale, peas, lupins, clover seed, pasture	Wheat, barley, pasture	Wheat, barley, pasture
Current crops	Wheat, durum wheat, feed barley, seed oats, canola, oaten hay, pasture	Wheat, malting barley, feed barley, canola, peas, pasture	Wheat, barley, vetch, oaten hay
Pasture reduction (%)	41–6	50–28	50–0
Off-farm income	No	Yes	Yes
Other family involved	Parents	Parents and brother	Succession planning being considered
Communication	Important meetings held	Important meetings held	
Change in return on capital (decile 5) (%)	–2.6 to 2.0	–0.6 to 1.8	–1.5 to 8.4

41.6 Conclusion

Developing a sustainable farming system is a process that takes time. It requires the operators of the farm to be receptive to innovations and careful in their financial planning. The properties show that if this is done the operation can be financially and environmentally improved over a range of rainfall and soil conditions. The economic analysis of these three properties shows that without their changing their systems, embracing technology and adopting conservation farming techniques they would not have prospered and may not have survived.

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Chapter 42
Ruradene, South Australia

A Case Study of Farm Expansion and Diversification

Ian Rohde and John Rohde

Abstract This case describes the development of a mixed farm in the mid-north region of South Australia. It is a story of continued expansion through land purchase and the development of an efficient and productive system by adopting appropriate technology. Sheep and poultry production are integrated with a cropping rotation. The farm has a larger than average workforce, mainly due to the poultry enterprise.

Keywords Farm expansion • Integration

42.1 Introduction

Being raised on a small farm, Ian never considered any occupation other than farming. In 1955, his father paid for him the deposit on a small farm of 166 ha near Tarlee in South Australia, which is in the Gilbert Valley 80 km north of Adelaide. Ian and his wife Jill moved in to Ruradene in 1957, and started married life and farming with great enthusiasm. Over the years, he has made a conscious effort to involve his family in the management of the farm. Their children, two girls, a boy and then another girl, all shared in the life of the farm. Ian believes this has been beneficial in giving broader insights into management decisions, made the family feel they were part of the management team, and has allowed his offspring to decide if they wanted a career in agriculture.

Their eldest daughter Mary became a nurse and married a farmer nearby and is highly involved in their farm. Their second daughter Julie, an agriculture graduate, is married and works with an agricultural company in Perth. Their third child, John, graduated in Farm Management at Roseworthy Agricultural College and now manages Ruradene with his wife Angela—who is also actively involved.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_42,

The youngest daughter Paula, who studied secretarial work, married a local vigneron and is office manager of an artificial breeding station for pigs. So it can be seen that the whole family has retained an interest in agriculture.

42.2 The Farm Environment

The mid-north of South Australia has one of the more reliable climates in the state. The risk of frost is rare, and drought is often less pronounced than in other areas. The home farm is gently undulating (180 m above sea level) with a mean annual rainfall of 460 mm. Later land purchases are in more hilly places hillier with higher rainfall (up to 490 mm).

Soils are hard-setting red-brown earths with a sandy loam texture (Soil Taxonomy classification—fine, mixed, thermic calcic palexeralf). In the mid-1970s (after the cereal–pasture rotation was introduced for restoring soil fertility and structure, following the earlier cereal–fallow rotation), analysis of the top 10 cm of soil showed organic carbon of 1.00%; total nitrogen 0.10%; available phosphorus 54 ppm; pH 6.8; and clay content, 14%. Organic carbon has now risen to about 1.2%, total nitrogen by 20–30%, available phosphorus ranges from 40 to 60 ppm across the property while pH ranges from 6 to 8.5 (Table 42.1).

42.3 The Early Years, System Structure, Enterprises and Management

Ruradene was some of the earliest land to be cropped in South Australia, being settled in the 1850s (Fig. 42.1). The early cropping rotation of fallow–wheat–volunteer pasture had a disastrous effect on the soils that were very low in organic matter. Multiple cultivation of the fallow with tynes made the soils impervious to rain, resulting in

Table 42.1 Farm facts

	Ruradene home farm	Later land purchases
Area	166 ha	1,755 ha plus 300 ha leased (see Table 42.2)
Soils	Terra cotta over limestone	Terra cotta over limestone and sand over clay
Mean annual rainfall (mm)	460	460–490
Growing season rainfall (April to October) (mm)	350	350–380
Vegetation	Blue gum (*Eucalyptus leucoxylon*) and wattles (*Acacia* spp.)	Mallee (*Eucalyptus* sp.)—Blue gum and wattles—Native pine (*Casuarina* spp.)
Topography	Gently undulating	Gently undulating to hilly
Water supply	Mains and bore	Mains, bore, river, dams (latter unreliable)

Fig. 42.1 Land clearing in the area, 1890

increased runoff and erosion. They were often referred to as ‘Sunday soils’—too wet to work on Saturday and too dry on Monday.

Fertiliser (superphosphate) was applied at high rates to build up soil phosphorus to encourage good crop and pasture growth.

Before the Rohdes bought Ruradene, it had been operated traditionally by ploughing in July, cultivating and harrowing numerous times in the bare fallow over summer and planting in June. Ian has said:

> Since we purchased the property, we have never ploughed. We initially attempted minimum tillage by cultivating (tyne cultivator) only twice prior to seeding in May–June and began to use herbicides. We have never burnt stubbles but have slashed it so that the planting equipment could get through without blockages.

This system improved the soils. However, since the adoption of direct drilling, stubble retention and use of seeding equipment which can handle straw, the improvement in soil structure has been dramatic. The earthworm population has built up to a significant level, and the soils are no longer called ‘Sunday soils’. By this stage (mid-1960s), the rotation was sown pasture (based on subterranean clover) followed by crop (wheat, barley and peas). The Rohdes followed the varieties recommended by the agriculture department but also tried them out ourselves.

42.3.1 Poultry for Cash Flow

A greater cash-flow was needed than was provided by the traditional cropping and sheep to pay for developments such as sowing clovers, applying fertilisers and improving fencing. They obtained advice from a Department of Agriculture poultry specialist on starting up an egg production enterprise. Starting with one shed of 800 fowls, they then built two more sheds to hold 2,400. For many years, the hens were housed in barn lay[1] sheds but were changed to free-range in 1975. The original sheds were built cheaply from reject steel tubing, second-hand timber and iron sheeting. All the grain (wheat and barley[2]) for feed was sourced from the farm. This proved to be a success, providing the regular income for development and eventually, purchase of more land.

At this stage, they ran 400 Merino ewes for wool, mating them to Dorset rams for prime-lamb production. During the late 1970s, they learnt how to feed poultry litter as a feed supplement to sheep. This allowed a 50% increase in sheep numbers and better control of pastures by set grazing.

42.3.2 Increased Labour

As life became busier and Ian was elected to local government, extra help was needed; so they employed young, but mainly inexperienced, labour. Farm labour for such a small operation was difficult to find, and it often proved disastrous. As the enterprise expanded, Ian was able to select better staff and to train some good workers.

42.3.3 Sharing Equipment

Ian's brother Ross (who worked the home farm 5 km away) agreed that although they were operating the properties separately, it would be financially wise to share farm equipment. Ian says:

> We hooked up our two tractors in tandem, pulling two cultivators or two seeders with one driver and taking turns in working 8 hour shifts 24 hours a day. This proved to be so efficient that we took on extra share farming (Fig. 42.2).

Ian and Ross also shared harvesting equipment, trucks, bins, and other machinery from the time they started farming.

42.3.4 Weed Control

Soursob (*Oxalis pes-caprae*) is a weed, propagated by bulbs, which is very competitive to crops and pastures; and cultivation merely transplants the bulb. Heavy grazing exhausts the bulb and encourages the sown pasture to grow through it.

[1] A deep litter system whereby birds are free to move within a shed but not permitted outside.

[2] See glossary for botanical name.

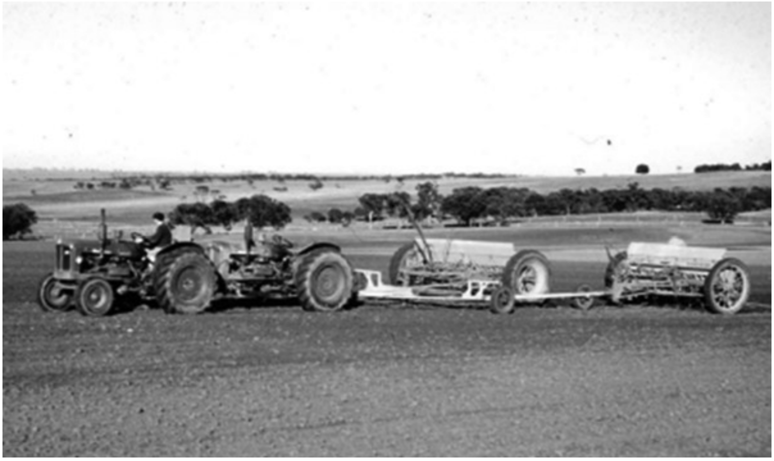

Fig. 42.2 Tandem tractors

In 1976, the herbicide, Glean,[3] became available; application of 10 g/ha at small cost, gave outstanding control of this difficult weed.

Control of soursob by Glean meant that crops could be sown a month earlier, increasing crop yields by up to 50%. Sub-clover pastures became much easier to establish, and soil fertility was lifted. Thirty years later, soursob weed has still not returned—which cannot be said for many other weeds, particularly in annual ryegrass (*Lolium rigidum*), as herbicide resistance developed.

42.4 Drivers of Change

One of the main drivers of change was the need to retain economic viability. This was increased when more members of the family wanted to become involved in the farm. Economic viability meant that it was necessary to (1) maintain and improve the soil through cultivating less and retaining organic matter; (2) devise a system that put nitrogen into the soil then made best use of it in growing crops; (3) combat weed and disease problems, preferably by preventing their build-up; and (4) continually expand the farm size to benefit from economies of scale, particularly in the use of machinery. The change process was facilitated by an active interest in agriculture and membership of organisations such as the Agricultural Bureau, Crop Science Society and Australian Farm Management Society which brought the family into contact with the latest ideas and technology.

Basically, the Rohde's plan has not changed. They have slowly expanded in size and introduced the most appropriate technology for the area; they have

[3]Chlorsulfuron—see glossary for detail.

experimented with alternative crops and livestock, aiming for the best possible combination for their situation, both economically and environmentally.

42.5 Pathways Chosen to Improve the Farm System, and Achieve Goals of Profitability and Sustainability

The first step in improvement was to reduce tillage and improve soil organic matter as described earlier. One-pass seeding systems are now the normal approach, although herbicide resistance in weeds is still a big challenge. As the system was developed, other choices had to be made; for example, they concluded that vetch[4] was better than sub-clover as a single-year legume in the rotation. It produces well in terms of feed or hay, was a good source of nitrogen and fitted in with the control of weeds such as herbicide-resistant ryegrass. The sub-clovers used previously seemed to need several years of a pasture phase to produce well.

For a while, chickpeas were a viable part of the rotation as a legume crop but, over time, were dropped because of problems with disease and a variable market.

Durum wheat has proved to be profitable. As a ‘hard’ wheat, it gives the best return for the nitrogen built up in the soil through legumes. Export oaten hay has also proved profitable and suitable to the environment and the rotation. Faba beans also provide nitrogen to the soil and then prime lambs can be ‘finished’ on the crop residues.

The Rohdes have developed their property and management steadily over the years, not necessarily being the first with new technology, but keeping abreast of change. Where they saw possibilities they started on a small scale, and then built up as their expertise grew and as they concluded that the innovation suited their farm system. They could then invest in the machinery or facilities that were required for efficient operation.

Overall, they aim to control weeds and diseases, vary chemicals (to avoid problems such as pesticide resistance) and minimise costs. This enables them to meet challenges or take advantage of opportunities as they occur, including increasing the size of the property.

42.6 Building up the Farm

Additional land has been purchased over more than 40 years (Table 42.2). The opportunity for purchase has required having both good advice and the right lender, as well as persistence in following this pathway to farm viability. In 1966, a neighbouring property of 150 ha became available for sale. As Ian could not

[4] See glossary for botanical names.

Table 42.2 Land purchases showing rising land values

Year	Block	Acres	Hectares	$/acre	$/ha
1955	Home	411	166	70	173
1966	Kidmans	351	150	90	222
1973	Edwards	300	121	100	247
1974	Thomas's	420	170	140	346
1979	Arnolds	120	49	300	741
1984	Kellys	200	81	660	1,631
1987	Saunders	80	32	800	1,977
1989	Kochs	167	68	814	2,011
1998	Pine Ridge	1,360	550	1,100	2,718
1999	Lynch's	91	37	900	2,224
2000	Meaneys	198	80	900	2,224
2003	Lightford	746	302	1,400	3,460
2006	Bransons	284	115	2,500	6,178

afford it himself, he and his brother bought it together. Ian needed to borrow not only to buy a share in the land, but also to buy extra sheep, and to rebuild his old house. Unfortunately 1967 saw a disastrous drought. Ian told his banker that not only could he not meet his existing loan payments but that he wanted to borrow even more money, to continue improvements. Fortunately the banker agreed—which indicates the necessity of maintaining a good relationship with your banker. After 5 years, Ian was able to buy out his brother's share of the 150 ha so that his brother could buy land closer to his farm.

In 1974, a farm of 200 ha adjoining their property came up for sale. This farm had been auctioned 4 years earlier and although Ian was interested, his farm advisor and banker both restrained him from bidding. Fortunately it was passed in and taken off the market. In 1974, it was advertised for sale at $65/ha. After some months without sale, Ian agreed to a price of $57/ha. Rushing to the agent to pay a deposit, he arrived just ahead of two other farmers with the same idea. Looking around for a source of finance, Ian discussed borrowing Swiss francs as advocated by some advisers. He was advised that it was not the right time, and to use other sources of finance. Good advice! From then on, although the interest rate stayed low, differences developing in the exchange rate between the Australian dollar and the Swiss franc meant that the loan amount would have doubled in a few years. Ian had some good friends who lost their farms through overseas borrowing. Financing was eventually solved by selling the house and 32 of the 200 ha and the bank financing the remainder.

42.7 The Value of Good Information, Advice and Farmer Co-operation

For good information and co-operation, many South Australian farmers join the Agricultural Bureau. It is a non-profit farmer organisation, unique to South Australia, that helps bridge the gap between scientist and farmer and assists its members to work together on issues such as management and marketing. Ian was secretary of his local (Stockport) Branch for 44 years. He organised various agricultural specialists to speak at monthly meetings. These speakers, who often had to travel some distance, would be invited to share dinner and a bottle of red wine with Ian and Jill before the meeting. In this way, he built up a friendship with many advisers and experts who he could readily contact for advice.

In 1960, a group of about 40 farmers in the district got together to employ a farm consultant.

> Our first job was to provide well-prepared figures of production and cash flow for the consultant to compile a comparative analysis of all the farms. This was exceptionally helpful as it quickly showed our own strengths and weaknesses.

These yearly figures showed that, to remain viable and successful in farming, Ian had to increase farm size. The use of consultants remains an important part of managing Ruradene.

In his search for farming information, Ian kept in contact with agricultural organisations. Since being chosen, at the age of 20, to attend a short course for young farmers at Roseworthy Agricultural College (now the Roseworthy Campus of the University of Adelaide), Ian has maintained contact with the College through field days and meetings. Its students have visited their farm regularly over the last 40 years. In 1973, Ian joined the S.A Branch of the Australian Farm Management Society, eventually becoming State President and then National President in 1984. His wife Jill also became a member and served on the State and National Executive. They benefited from meeting rural scientists, lecturers and other interested farmers.

Many Department of Agriculture farm trials such as weed control, nematode control, new pastures, fertiliser rates and the 10-year Tarlee Cropping Rotation Trials were held on 'Ruradene' (Schultz 1995). Ian is sure that being involved in these trials helped their decision making.

42.8 The Current System and Its Management

Ian and Jill have endeavoured to simplify their system over the years to make management easier and to make the various parts of the system complement each other. The current system has a variety of crops chosen in line with the aims described earlier. The base rotation is legume pasture–canola–durum wheat–oaten hay–wheat–grain legume–durum–bread wheat–malting barley–pasture. The Vicia[5] pasture carries 18 D.S.E/ha[6] in the winter to produce prime lambs. It also provides

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[5] *Vicia sativa* variety—Morava, a rust-resistant variety with good herbage and seed production released in 1998.

[6] Dry Sheep Equivalent—see glossary for explanation.

a high input of nitrogen into the soil for use by following crops. Canola uses this nitrogen and acts as a good ‘break crop’ for cereal disease and grass-weed control. Then follows Durum wheat, a high-value crop with potentially the highest net return if the conditions are right. This is followed by oaten hay for the export market. Cutting for hay helps control weeds by restricting their seed production and the oat crop can be grazed early to allow vetch to become established. The fifth crop of bread wheat (APW[7]) is followed by Faba beans, which provide nitrogen and act as another break crop for control of cereal diseases such as cereal cyst nematode (CCN) and grass weeds The nutritious bean residues are used for finishing lambs for sale in Jan/Feb, running at ten lambs/ha. Then there is another Durum crop (high value), another bread wheat crop, then barley for malting.

The year after the crop rotation is completed, the land is put back into vetch pasture. The wheat and barley crops contribute to the poultry feed along with any screenings[8] or downgraded crops. While the poultry were originally introduced to provide cash flow to enable build-up of the farm, they are now a separate business in their own right. However the integration of the cropping and poultry enterprise has been a financial success and fits the Rohde’s farming system.

The whole rotation is integrated, each successive crop preparing in some way for the next one. For example, cereals and canola use the nitrogen fixed by the legumes in the rotation while grazing the legumes also recycles plant nutrients. Almost all the land is included in this rotation, with approximately 200 ha in each phase. An exception is 65 ha of the property at Lightford, which is operated separately as non-arable, grazed pasture. The sheep enterprise, which produces both prime lambs and wool, is low input. It fits in with the cropping program—utilising residues or early weed growth and occasionally early crop growth—and does not have conflicting labour requirements, as shearing is after harvest and lambing in early spring between sowing and hay making.

Right from the start, good physical and financial records have been kept, as initially prompted by a farm advisor; good budgets and financial records continue to this day. Membership of a ‘benchmarking’ group allows inter-farm comparisons that make the owners aware of where they are in terms of profitability, efficiency, scale and sustainability. The use of computers has been essential since the 1980s to cope with taxes, invoicing and the payroll. The farming operations have averaged about 5% return on capital over the last 30 years, with capital gain on the land adding a further 8% per annum. The poultry business has a return on assets of about 20%.

Ruradene now has a ‘board’ to help make important strategic decisions. It includes three outside members—their accountant, the head of an agricultural consulting firm and a marketing manager of an agribusiness.

[7] Australian Premium White—a classification of Australian Bread Wheat.

[8] Undersized or pinched grain screened out during harvesting.

42.9 Non-farm Activities

Following the purchase of Lightford, the house was rented by a television production company, Millenium TV, which used the house and surrounding farm to produce a television series. The relationship was good and the company has used the property, surrounding land and house without disturbing farming operations too much. The Rohdes received a good income from these activities and from showing 'tourists' through the area used. Ian mentions one incident:

> Generally they were well organised and we were able to schedule farm operations around them, but on one occasion we were tailing lambs and the noise of this activity conflicted with their filming nearby.

This is an example of how sometimes it is possible to take advantage of an opportunity as long as it can be fitted into the farm system.

42.10 Challenges for the Future

Current challenges are many and probably have not changed much for a long time. The Rohdes are continually attempting to maximise production while reducing inputs, with water still the most important limiting resource. Continued increases in input costs mean production systems have to be well managed to achieve optimum yields and quality. Despite the cost/price squeeze, profits are still being made in their area. The challenge is to remain as efficient as possible, with continued growth in both the poultry and farming side of the business.

Land prices have become very high, with a 100% increase in the last 5 years—but the neighbours keep purchasing—and the Rodhes believe they need to continue to expand if they wish to stay viable. This may mean leasing rather than owning land. In the future, there may be opportunities to use their management skills to operate land owned by investment funds.

Labour is another challenge—they have three farm employees and the competition for labour from the mining sector continually puts pressure on the farm to retain good employees. The needs of the labour have to be catered for as the business cannot continue to grow without skilled labour. Thus, managing labour effectively has become vitally important and takes most of their time. They have had to learn the intricacies of position descriptions and employment contracts and to develop standard operating procedures—quite apart from getting the best out of employees with a range of personalities and abilities. They will have to continue to hone their ability to manage this vital resource.

The egg production system used to be an important adjunct to the broad-scale farming programme, to aid cash flow. However, it is now a stand-alone business that sells 14,000 dozen free-range eggs each week under the 'Ruradene Free Range' brand. It employs the equivalent of seven full-time people for collecting, grading and marketing the eggs. While separated financially, it is still an integrated part of the system. Grain produced on the farm is fed to the layers, and manure is spread on the fields.

Sheep have remained in their farm system because they compliment the crops, as explained earlier. The pasture/grazing phase assists in weed control and adds nitrogen. Wool and prime lambs provide reliable income in most years.

There will be more challenges in the future: climate change, genetically modified crops, precision farming and other new technologies will all have an impact and will have to be evaluated for their benefit to the farm. The family is considering whether the next generation will want to continue the business, and importantly what training they will need. Ian learnt 'on the job', with only a few weeks of formal training. John has a diploma in Farm Management along with practical experience, but the business has changed and managers of the future may need different skills. John and Angela have four children aged between 11 and 17. All can be part of the business in one way or another, but will be encouraged to receive education to their level of potential before returning to the farm. Management of both the farm and poultry enterprises will be encouraged. With the current Board in place, the four children will have the opportunity to be involved in the future years.

42.11 Conclusion

Over the years, the family business has remained viable, and Ian and Jill believe they have improved the soil fertility, as well as other aspects of the farm environment through planting of shelter belt trees and by virtually eliminating blowing dust. It has not always been a smooth path. They have had their share of family conflicts, but have been able to work their way through them. Succession planning has been important to ensure that the non-farming members of the family received something while enabling those who stayed on the farm to be secure.

The capital value of the farm has grown greatly with the increase in land values over the years. Good management is required to ensure there is an adequate return to this capital.

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Chapter 43
Lindene South Australia

From Tradition to Innovation

Dean Wormald

Abstract This case study describes the development of a farm in one of the drier areas farmed in South Australia. The owners are convinced that the move to no-till and continuous cropping has produced a more sustainable farming system for their farm.

Keywords No-till • Continuous cropping • Farm development • Mallee

43.1 Introduction

Lindene was first settled by my grandfather Lloyd Wellington Wormald in 1913; he pioneered settlement and farming in the Caliph district which lies 40 km south-west of Loxton in South Australia.

The Lindene property covers 1,214 ha (3,000 acres) of undulating land with sandy rises and was covered by low Mallee[1] scrub. My grandfather and father cleared the scrub with axes and then pulled a scrub roller behind a team of eight to ten horses. Later the stumps had to be hand 'picked'. They are a prized form of firewood and provided income when money was tight. Not all the area was cleared and around 400 ha of the original Mallee remains today.

The low rainfall makes it 'marginal' for farming and it certainly provides a challenge for those trying to crop it. Water supply came initially from wells in the district, until windmills and bores were sunk by hand.

[1]See glossary for scientific name.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_43,

43.2 Climate and Soil

43.2.1 Climate

The mean annual rainfall is 270 mm, with growing season rainfall (April–October) of 170 mm. However, the rainfall is extremely variable and ‘droughts’ are an ever present spectre. Other climatic problems include frost, which can occur as late as mid-October (spring) and can adversely affect the growing crops. Conversely, hot spring winds as early as the first weeks in September can severely reduce yield.

43.2.2 Soils

The soils are a sandy loam with clay subsoil but with some heavier clay flats and limestone outcrops. The subsoil can store water to a depth of 25–30 cm—up to 100 cm in places. High levels of subsoil boron can limit the depth of crop root growth and hence the ability to use available water.

The soils are not particularly fertile, and the original rotation of one crop every 3 years did not raise the nutrient level significantly. However, since we began continuous cropping and adding fertiliser each year, phosphorus levels have increased. The result is a good crop if we do get good rain. The soils are highly alkaline with a pH 7.5–8 in surface soil and up to 9.5 at depth. Soil organic matter is low with organic carbon of 0.5–2%. With our move to continuous cropping and no-till, we hope to boost OC in the long term.

Wind erosion is a problem with the light soils. This was particularly so when early methods of cultivation reduced plant cover. Some small (2–10 m diameter) patches of salinity have been caused by low rainfall limiting leaching out of salt, and by the rising of saline water tables after clearing of scrub vegetation. Surface limestone also limits production; we may reduce inputs in stony areas because of lower yield potential on these very harsh soils.

43.3 The Early Years

Initially, traditional district farming practices were followed, by Lloyd and then my father Ken, with 810 ha (2,000 acres) cleared and one third of that land cropped each year. The land was cultivated, sown and harvested with horse-drawn equipment and the bags of grain were carted by horse and dray. A railway was built from Wanbi to Yinkanie—going through Caliph—in 1926 and this made cartage of inputs and grain much easier. Superphosphate was also introduced about that time and this increased yields. The farm bought its first tractor in 1942—a Case model LA. There were 300–400 head of sheep which grazed volunteer pastures until suitable varieties of medics (*Medicago* spp.) were introduced in the 1950s.

The family was fairly self-sufficient, with a milk cow, pigs, chickens and a vegetable patch. In that era, it was possible to survive with only one good harvest in three or four. This was due to the relatively low cost of inputs relative to the price of wheat. For example, you could get a tonne of fertiliser for less than the price of a tonne of wheat—now a tonne of fertiliser costs five tonnes of wheat! Similarly, after a good year, 30 or 40 years ago a farmer could go out and pay cash for a new tractor—now it requires a number of good seasons to pay one off.

I returned home to the farm at the end of 1980, joining my elder brother and father, 1 year after a further 1,600 ha (4,000 acres) had been purchased to expand our holding.

At this stage, most of the crops were established using disc plough fallow, followed by multiple workings for weed control. We continued to use the 3-year rotation (one crop and two pastures). Although machinery had improved and fertilisers and herbicides had been introduced, the system still had problems with erosion, low soil fertility, restricted flexibility in choice of crops, and rising costs.

43.4 Drivers of Change in Recent Years

In 1993, I married Jeanette, who came to the district as a journalist (Fig. 43.1). We took on the original holding of 1,214 ha while my elder brother took on the 1,600 ha block.

At this stage, I was completing a Certificate of Rural Management which followed on from an on-farm training scheme. I believe this training, combined with Jeanette's support for innovation and new ideas, encouraged me to seek improved farming methods, some previously untried in the Mallee.

I read about farmers in other areas of the state moving into continuous cropping and questioned whether it might work in the Mallee. Our soil types were similar to those of the Upper Yorke Peninsula, and I could see no point in cultivating paddocks four or five times to control weeds in order to grow one crop, only to let the paddocks go back to weeds before starting the process again.

This led to the idea of keeping weeds under control through sowing crops every year and using herbicides. For example we have been able to eliminate onion weed (*Asphodelus fistulosus*) from our paddocks by continuous cropping and use of chemicals (Group B sulfonylureas—SUs).

In the early stages, our plans for continuous cropping were limited by the machinery we had and by finance. A cost-effective seeding machine that could handle more stubble was seen to be a necessity. In the early years of continuous cropping, a Conner Shea wide-line air seeder was the only cultivator used to work with stubble. This had poor trash handling ability, so hydraulic harrows were used to break down remaining stubble. However this consumed too much time between harvest and planting, so an old chisel plough was bought. The treatment of crop stubble at harvest was also a high priority in this new system: an even spread of crop residue and no header windrows allowed a much more even flow of trash through the sowing rig. We had previously seen that leaving windrows from the last harvest meant that the crop growing in it

Fig. 43.1 Dean Wormald and family

next year was poor; so a header which could handle a large amount of straw was also very important. This was an improvement, but we realised that we would eventually need more specialised equipment.

43.5 Pathways for Change Chosen by the Owners to Improve Their System

The decision to adopt continuous cropping in place of the crop–fallow system led to further changes aimed at improving the system. By 1997, the shopping list had expanded to a larger capacity header that could cut the stubble lower and spread chaff and straw evenly over the full cutting width. We also needed a cultivator that had good trash flow and could be used for a number of jobs, mainly primary and secondary tillage and sowing, with the capacity to be converted to no till at a later stage. A 40 ft (12 m) Morris 9000 with 9 in. (23 cm) row spacing was the answer (Fig. 43.2).

Even though the improved farming methods, increased use of fertiliser and better grain varieties had increased our yield expectations from an average of four to six bags/acre (0.8–1.2 t/ha) in a good year to 8–10 bags/acre (1.6–2 t/ha), we needed to spread the capital outlay of new machinery over more crop area for greater returns, to justify our machinery costs.

Fig. 43.2 Air seeder and storage

We had already taken on an extra 1,200 ha in 1995 by share-farming the property next door. In 1997, we were approached to crop another 243 ha, and then the following year asked to do 400 ha for a third neighbour. This amount of cropping led to new challenges. While we had also employed a full-time employee, we needed to ensure that we worked efficiently to ensure that all paddocks were sown in the optimal time frame (25th April to 20th May—mid-autumn) to achieve our yield potential. This optimum time is determined by the timing of the ‘break of season’ when effective rain begins, and allows time for the crop to establish before winter cold slows down growth.

No-till seemed to be the best way to ensure timely planting. Herbicides were becoming more economical to use so no-till offered a more time-efficient method of getting over our cropping country while protecting the soil from erosion. We also hoped to spend less time on the tractor. We also believe that over the long term, no-till will improve our soil water-holding capacity (through minimal soil disturbance and crop residue reducing evaporation) and general health (increased organic matter and microbial activity).

The property now has no livestock. We believe to have stock would compromise our ability to produce the best crops possible as they would compete for our time and other resources at critical periods. The only time stock would be on the property would be if we agisted neighbours’ sheep on our stubbles as a favour.

43.6 Putting It All Together—Managing the Whole

The most important part of putting it all together is having a plan. We have a 3–5 year plan for every field on the property. This plan is constantly reviewed. We consider:

- The rotation—with a view to controlling weeds and diseases
- The mix of crops—always looking for the opportunity to economically introduce a weed and disease 'break' crop of canola or a legume. Canola and lupins can be grown but it is difficult to produce a profitable return with them with our climate and soils. Depending on moisture reserves and the seasonal outlook, we may be financially better off with a chemical fallow providing the break.
- The mix of herbicide chemicals—in order to combat herbicide resistance in weeds.
- The grain marketing mix—with the deregulation of grain marketing in Australia, there are an increasing number of marketing alternatives and means of 'hedging' crop prices. The latter all have their own risks however, and so far we have yet to decide how useful they are in our situation.

One of our key considerations is flexibility. We need to be able to respond appropriately to our current situation in terms of stores of soil moisture and the seasonal weather outlook. At the same time we need to conserve our soil and endeavour to increase soil nutrients and organic matter.

When purchasing new equipment, we also have flexibility as a priority along with considering our specific constraints, the area to be covered and the need to match with existing equipment.

We make use of consultants—for agronomic advice and for grain marketing—and we need to maintain good communication with our bank manager.

As mentioned above, a portion of our land remains uncleared. For example, there are large blocks of the original vegetation at either end of our home farm. Over recent years, we have planted a vegetation corridor to link these to allow native fauna to move freely from one end of the farm to the other. The purpose was also aesthetic and we also hope to have some wind break effect as the trees grow.

43.7 The Current System and Looking to the Future

Today, we spray summer weeds after harvest as needed, then leave standing stubble until the break of season. Once weeds have germinated after the break, these are sprayed with glyphosate. Although we have no glyphosate-resistant weeds at present, they are elsewhere in the state and this is a potential challenge. Once weeds are sprayed, the air seeder can start the sowing program without having to cultivate all the country as would have happened with traditional practices.

In the past, the Northern Mallee has not been seen as having the potential for high yields or returns to farmers. This is despite the 'Hundred of Mantung', where our farm is situated, long being recognised as growing excellent high-protein wheat in high demand by bread millers. Today, I believe we are not receiving the premiums for this better quality.

District practice has generally been conservative and the no-till, sustainable farming and continuous cropping approach is still regarded as very new. In 2002, there were a number of high wind events and only half the average growing-season rainfall which severely tested our farming management. However, it demonstrated to us that no-till and sustainable farming methods are the way of the future, even in such adverse conditions. We believe our average yields are consistently better than the district average and we have less soil erosion.

We are now looking to new technology to help us farm better. We want to know more about our subsoils and are using electromagnetic induction technology (EM38 mapping) to map soil properties. In particular, we are interested in subsoil sodicity which is linked to boron toxicity—10 ppm of boron restricts root growth. We have started yield mapping with an aim of applying inputs to match crop needs and using variable rate technology to achieve this. However, good equipment is expensive!

One of the challenges of the future will be climate change as this may alter our rainfall pattern. However, our task will continue to be to turn summer and winter rainfall into grain. This, in turn, depends on the ability of our soils to store water (particularly from larger rainfall events in January, February and March)—a function of our soil health and our management practices to control weeds.

More farmers of our district appear to be moving to reduced tillage or no-till. This has resulted in fewer fields eroding and will hopefully lead to a more sustainable future for the district.

A key aim for the future will be economic sustainability despite the cost of inputs rising faster than the returns from crops. We hope to be able to keep farming through continuing to adjust management to adapt to changing circumstances, and to produce to the capacity of the whole system. The world needs food and if farmers over the world are not adequately rewarded for their efforts they will decide to go and do something else.

Chapter 44
Developments in a Mixed Farming System in Southern New South Wales, Australia

A Case Study

Derek Ingold

Abstract This Case Study shows, from a progressive owner/manager's point of view, how a mixed farming system in southern NSW has developed in response to climate and soils, livestock and cropping patterns, personal goals, external influences, innovations, opportunities and limitations. The operation of the farm is considered in relation to, and the need for, production, sustainability, economic and social imperatives. Future goals and improvements are outlined.

Keywords Mixed farming • Wheat–sheep system • Pasture phase • Crop rotation • Direct drilling • Weed management • Take-all • Fertilisers

44.1 Introduction

The Ingold farm at Dirnaseer is located on a flat to rolling landscape that is typical of mixed farming country on the southern slopes of NSW. The first purchase of 400 ha was made by my father and mother, John and Beverley Ingold, in 1959. This land was originally a 'soldier-settler' block, carved out of the Dirnaseer Station (a large, sheep-grazing property with share-cropping) in 1919. The block was marketed as 'safe wheat–sheep country' to my family, who saw potential in the red loam and red earth soils, an average annual rainfall of 540 mm, and the strategic location of the property in relation to agribusiness, markets and communities in Temora (25 km NW), Cootamundra (35 km E) and Wagga Wagga (70 km SW). The farm is now operated by my wife, Susan, and me on behalf of a partnership with my parents, who are retired and live off-farm but retain ownership of some of the land. The farm currently comprises 1,600 ha of freehold land, almost all of it arable, plus a long-term lease on another 400 ha.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_44,

In this account, my purpose is to outline the evolution of this family farm over the last half-century, from a simple wheat–sheep operation to one that is now more efficient in terms of labour inputs, as well as having higher crop yields and sheep carrying capacity. I describe a series of steps involving technical change and integration that have progressively transformed the sustainable use of the plant, livestock, soil and water resources of the property. Its operation is now more satisfying and stimulating, but there are some ongoing concerns that we must address in future years.

44.2 The Farm Environment—Climate, Soils and Vegetation

The average elevation of the property is 350 m with all but a high hill (430 m) being arable. The mean annual rainfall is 540 mm and is spread fairly evenly throughout the year. The May–October rainfall (about 60% or 325 mm) is sufficient to produce a consistent growing season for temperate crops and annual pasture species. Rain over the remainder of the year also allows the persistence and year-round production of deep-rooted, sown perennials such as phalaris (*Phalaris aquatica*) and lucerne (alfalfa, *Medicago sativa*). Winters are normally cool (mean maximum/minimum temperatures in July 12/2°C) and summers are hot (32/18°C). Around the main flowering period for crops (late September to early October), frosts are rare but they can occasionally be damaging in the lowest pockets of our country.

Most of the soils on the property are kandosols[1] that are typical of the main cereal-growing districts in central and southern NSW. They comprise surface soil of sandy-loam or clay-loam over subsoil that grades into a medium clay. These topsoils are acidic (pH 4.5–5.5) and they are relatively low in the major plant nutrients. The landscapes are prone to erosion by wind and water. In the valley floors, the soils tend towards vertosols[2] with clay topsoils that have a higher water-holding capacity and better natural fertility.

The original vegetation, which in this district was substantially cleared during the nineteenth century for grazing and then for cropping, comprised an open woodland community dominated by yellow box (*Eucalyptus melliodora*), grey box (*E. microcarpa*) and river red gum (*E. camaldulensis*). In lands protected from ploughing, the understory consisted of species that resisted sheep grazing; these included the native grasses wallaby grass (*Austrodanthonia* spp.), spear grass (*Stipa* spp.) and red grass (*Bothriochloa macra*), volunteer grasses (annual cool- and warm-season species) and herbs. The local grazing lands and croplands suffered from decades of over-ploughing, soil erosion, nutrient decline and weed invasion, e.g. skeleton weed (*Chondrilla juncea*). During the relatively prosperous rural

[1] Soils which lack strong texture contrast, have massive or only weakly structured B horizons, and are not calcareous throughout. Australian Soil Classification http://www.clw.csiro.au/aclep/asc_re_on_line/ka/kandsols.htm

[2] Clay soils with shrink-swell properties that exhibit strong cracking when dry and at depth have slickensides and/or lenticular structural aggregates (ASC).

times of the 1950s, these areas were in part rejuvenated through the widespread addition into the agricultural system of subterranean clover (*Trifolium subterraneum*) and superphosphate fertiliser.

44.3 The Early Years—System Structure, Operation and Management

After our family first took over the farm in 1959, we cropped around 40% of it to cereals and grazed a self-replacing Merino sheep flock for wool production. The wheat–sheep system was a simple one to operate, with several years of crops (90% wheat + 10% triticale, sown in May and harvested in December) followed by a 3–4 year pasture phase. The final crop was always undersown with subterranean clover which, when grazed more or less continuously at stocking rates around 10 sheep/ha, became dominated in the third or fourth year by volunteer annual ryegrass (*Lolium rigidum*, a common weed of crops) and barley grass (*Hordeum leporinum*, a problem for lambs in late spring due to sharp pointed grass seeds). Grass dominance was a sign to plough up the pasture for the next 3–4 year cropping phase, which could then capitalise on the nitrogen added by the pasture. The areas of crop stubble were an additional source of feed for livestock in summer and autumn and, in poor seasons, we relied on feed grain stored on the farm rather than hay. We sometimes bought and sold Merino wethers and always had a few cattle on the place.

In the mid-1970s, I graduated from Wagga Agricultural College with a 3-year diploma in agriculture and began fulltime work with my father. At the time, there were several farm issues of interest to me:

- The most important was the problem of soil erosion.
- I also suspected that there were aspects of soil health that were limiting production, such as declining soil pH and the amounts and types of fertilisers that we applied annually, in relation to nutrients available in the soil and those required by the crop.
- Then, there was the high labour demand of the traditional farming methods, which involved sowing the cereals into ground that was cultivated regularly in the summer–autumn months.
- With the sheep enterprise, the price of wool was declining.

During the 1970s and 1980s, our objective was to generate increased cash flow, enhance soil fertility and consolidate an asset base for the future operation of the farm. We set about increasing the proportion of the farm that was cropped, moving towards 80%. Also, we switched our sheep flock to lamb production, mating our Merino ewes to Border Leicester rams and then putting a Dorset Horn ram over the F1 ewe. However, our sheep enterprise was constrained by a chronic feed gap in late autumn and early winter, a feed shortage that was aggravated by a late arrival of the main rainfall season ‘break’ in late autumn.

I thought about all of my concerns and discussed them with a network of leading farmers and agricultural advisers. This network, comprising farmers such as Bernard and Anne Hart and agricultural advisers such as Geoff Pitson, is still of real value to me.

44.4 Drivers of Change During the 1980s and 1990s—New Strategies and Pathways

My first innovation, implemented in the early 1980s with reluctant agreement from my father, was to experiment with direct drilling (sowing into crop or pasture residues without prior cultivation). This innovation was aimed mainly at reducing or preventing soil erosion from both wind and storms in summer–autumn. There were many problems to overcome in order to sow through crop residues and into soil that had received little or no prior cultivation. My discussions with like-minded people intensified and gradually we sorted out most of the problems involved in managing our crop stubbles, dealing with weeds, and adapting our seed drills. A better range of 'knock-down' herbicides (glyphosate replaced the earlier paraquat/diquat mixtures) and selective in-crop herbicides (e.g. diclofop-methyl, 'Hoegrass') helped make direct drilling feasible. A side benefit from the combination of chemical weed control and direct drilling was a considerable reduction in the time that I spent on the tractor seat each autumn. I used this time to attend field days and demonstrations and gather further ideas for the refinement of our operations.

Unfortunately, the expected yield advantages from direct drilling, through timely sowing and improved soil structure and water storage, did not eventuate. My farmer friends and I, in consultation with research and extension officers of NSW Agriculture at Wagga Wagga and Cootamundra, reasoned that soil nutrient imbalances and crop diseases such as take-all (*Gaeumannomyces graminis* var. *tritici*), which is the main constraint to cereal production in this area, were limiting the soil benefits from reduced tillage.

I became interested in the current research on the availability of major and minor nutrients for crop and pasture production, and alternative crops to cereals. Such crops included rapeseed/canola (*Brassica rapa*, *B. napus*) and lupins (*Lupinus angustifolius*). I began my program of crop diversification by growing lupins as a leguminous break crop for the cereals and as a source of high-protein grain for use in supplementing the diet of pregnant ewes.

However, another problem also attracted my attention; the pH of our soils had declined towards pH 4. At the time, the problem of soil acidification was gradually being unravelled. This pH decline did not seem to affect either wheat or lupins but it did affect lucerne and canola, which were soon to become vital components of my pasture–crop rotation cycle. Phalaris, which is a useful perennial grass on non-arable country in this environment, is also affected by soil acidity. An application of 2.5 t lime/ha was necessary to adjust the soil to pH 5, which apparently prevented the adverse effects of aluminium and/or manganese ions on plants when the pH values fell towards pH 4.5. These ions are toxic to sensitive plant species. Liming, a practice that I enthusiastically adopted when the soil pH reached 4.5, ushered in one of the most stimulating phases of the development of our farm by removing the main constraints to the growth of lucerne and canola.

From the early 1980s, I was growing areas of lucerne, using the new winter-active and aphid-resistant varieties that were then available for the pasture phase of the rotation. I was attracted to a mixture of lucerne and subterranean clover (with volunteer grass species) as a ‘pasture for all seasons’. Once I understood the soil nutrient issues, I limed the low-pH paddocks and was pleased to find that lucerne became much easier to establish. Lucerne became a key component of my plan to enhance both the livestock and the crop sides of the farm business. The winter-active lucerne varieties also responded well to summer rain, improved the autumn–winter feed situation, provided a hay cut from excess growth in spring and, we were told, fixed plenty of nitrogen. Even though we increased our cropping intensity towards 80% of the farm, we were able to increase the sheep stocking rates and maintain sheep numbers throughout the 1980s and 1990s.

I regularly monitored soil pH and phosphorus levels, and we progressively applied lime to all of our paddocks. I drilled in more superphosphate with the last crop in the cropping phase to ensure that plenty of P was available for my pastures, which were sown with a mixture of lucerne and subterranean clover. Every few years, we applied the trace element molybdenum, either with superphosphate or as an ingredient in insecticide spray.

I first grew canola in 1993, after watching several farmers in the district growing small areas of rapeseed during the 1970s. Their crops succumbed to blackleg disease caused by the fungus *Leptosphaeria maculans*. This pioneer group of rapeseed growers persisted with their efforts through the 1980s, enhancing their knowledge of this new crop. Then, several factors came together. New brassica varieties, resistant to blackleg and low in their erucic acid and glucosinolate content, were developed for canola production. These varieties thrived on limed soils.

Farmers and researchers found that the production of cereal crops was enhanced considerably on land that had previously grown canola. This effect was subsequently shown to be a consequence of the improved control of grassy weeds and of the canola crop reducing the presence of the cereal take-all fungus. Once I introduced canola into the crop rotation, I was immediately pleased with both its performance on the limed country and also with the enhanced productivity of the wheat crop sown after canola. In order to satisfy the high requirement of canola for sulphur, I applied gypsum at recommended rates.

During the late 1990s, I lengthened the crop section of the rotation towards several sequences of canola–wheat, with an occasional crop of N-fixing lupins. Nitrogen fertilisers were relatively cheap and we routinely applied up to 100 kg N/ha to the non-legume crops. Initially these ‘ingredients’ worked well together. Wheat yields were nearing their potential—a benchmark of 4.5 t/ha (20 kg/ha grain/mm of growing season rainfall) is expected in a good season.

Cash flow during the 1990s was excellent due to the high crop yields and I was able to address another problem—since good farm labour was very hard to get, further increases in my own productivity were essential. I invested in a 12 m air seeder to replace my 4.7 m combine drill, set up a boom system that sprayed an 18 m swathe (previously 12 m) and purchased a 'new' second-hand header (harvester). Although these machinery improvements were expensive, they increased considerably the efficiency of the sowing, crop management and harvesting operations.

I dreamed about similar developments that might reduce the labour input per sheep but I have yet to find a drenching gun that could treat five sheep at once! During the 1990s, we switched to Merino wethers in order to reduce the complexity and time needed to run the sheep enterprise. However, I was keen to build up a flock of Border Leicester × Merino ewes again for fat lamb production.

As we approached 2000, a number of new problems were appearing in our farming system. On the cropping front, we had experienced the resistance of ryegrass to Hoegrass and similar Group A herbicides in the late 1980s and now resistance to the Group B herbicides was increasing. I resolved to try even harder in the new millennium.

44.5 Putting It All Together in the New Millennium

During the early 2000s, we responded to a new set of problems. It was clear that we had to redouble our efforts to develop an integrated system of weed management. Also, we were relying too heavily on the canola–wheat combination, as canola was proving to be a weak link. If the season was late in breaking, canola and lupins were either not sown or sown too late. Diseases of canola such as sclerotinia (*Sclerotinia sclerotiorum*) were increasing. In our district, an unfortunate run of droughts in 2002, 2004, 2006 and 2007 seemed to affect the broadleaf crops, especially canola, more than the cereals. On the other hand, in 1998, 2001 and 2003, late frosts had devastating effects on our cereal crops.

Our current approach is to base the cropping enterprise on cereal crops, since wheat and barley are cheaper to grow and more reliable in performance than canola and lupins. My philosophy is that the management of each crop, including lupins and canola, must create an environment that is beneficial for, or at least not antagonistic to, the planned following crop(s). This approach also ensures that I have maximum flexibility in my crop rotation, creating crop choice options and management strategies for the future. For example, I need a flexible, integrated approach to the problem of take-all. Thus I do not apply lime before a wheat crop, since the take-all fungus is favoured by higher soil pH levels. Again, if I grow a canola crop that is free of grassy weeds, I might consider growing two wheat crops in this paddock. Then, as long as control of grassy weeds is again excellent, I might even grow wheat or barley after two wheat crops, sowing the third cereal crop late and using an in-crop fungicide to help protect this particular crop from fungus infection. This wheat-on-wheat option is tailored for unreliable seasons and tight finances, as costs can be kept down and receipts relatively high. A flexible rotation that includes broadleaf crops that are tolerant of grass herbicides also helps broaden options for herbicide use, since the post-emergent grass herbicides available for use on cereals are rather limited and expensive.

I am willing to explore all available rotation and management options to minimise the risk of herbicide resistance developing in weeds. I am particularly concerned about the possibility of future restrictions on the use of triazine group of chemicals, which are useful for the control of weeds in broadleaf crops. I aim for total control of broadleaf weeds in cereal crops and grassy weeds in broadleaf crops, but I do not rely too heavily on particular herbicides or herbicide groups. I would like to see Roundup-Ready canola released, in order to extend my range of options for weed control.

Another example of my philosophy of *integrated flexibility* is in the application of fertilisers during the cropping phase. For all paddocks, I keep records on all operations, soil test values and key indices of crop productivity (plant density counts, yields, grain quality). Since animals grazing pasture tend to recycle P, I apply all P fertilisers in the cropping phase. I have maintained soil test values in the 40–80 ppm P range (Colwell test), well above the critical value of about 32 ppm.

Years ago, I sowed crops at seeding rates that were too high and fertilised with excessive quantities of bag nitrogen. Now that the organic matter (OM) and mineral N status of my soils has been built up through the use of lucerne and subterranean clover, the supply of available N is usually adequate for canola, the first crop after the pasture phase. For cereal crops, I sow with a little N fertiliser—perhaps 6–10 kg/ha of N in mono-ammonium phosphate (MAP). Then, I closely monitor their tiller development to determine a seasonal N fertiliser strategy. I aim for 500–600 tillers/m^2, perhaps down to 450 tillers/m^2 for a late-sown, rapidly-maturing wheat such as H45. If tillers are appearing at a reasonable rate, I do not apply any additional N until August. In August, if the tiller numbers are on target and the soil moisture levels are good (measured or estimated), I will apply 50 kg N/ha as urea. In early October in a good season, I might add a second application of urea to wheat crops if all of the indicators (tiller number, soil moisture, forecast frost risk) are favourable.

Financially, the reliable pasture–livestock components of our farming system and favourable prices for lamb have pulled us through the recent unfavourable seasons. Lucerne has proven to be an excellent base for our livestock operations, which now comprise:

- A flock of 850 Merino ewes, which produce fine wool as well as being mated to Border Leicester × Finn rams to produce replacement F1 ewes for the prime lamb enterprise. The Finn infusion is a little unusual. It is based on my belief that Finn genes will reduce the size of the F1 ewe (and so the amount of herbage that each ewe eats) as well as make the ewes more fecund.
- A prime lamb-producing flock of 1,100 Merino × (BL × Finn) ewes, mated to Dorset Horn rams, to lamb in early August.
- A small herd of 20 Shorthorn cows, which are those remaining from a small herd that previously numbered up to 100 cows.

With the increasing value and importance of lambs, I have extended the length of the pasture phase to 5–6 years, instead of the 4-year phase that it was in the 1990s.

The extension gives me time to reduce the density of the lucerne, which is hard to kill with herbicide and which potentially empties the soil profile of water for the first crop in the cropping phase. I am happy that barley grass and other annual grasses appear in the later years of pasture, as they are good feed for the lambs, at least until the grass seeds appear, when I switch the lambs to cleaner lucerne paddocks. I encounter occasional outbreaks of red-gut and bloat in lambs grazing legume dominant pastures—a common occurrence in this district—and the annual grasses help counter these outbreaks.

My challenge with the livestock enterprise on the farm is to expand production and maintain diversity without increasing too much either the overall enterprise complexity or the per sheep labour requirement. A constraint is the great difficulty in attracting good farm labour—many of the young rural women are attracted to professional work in the cities and the young men like the high wages paid by the mining industry. We cannot hope to match those wages. The lack of both skilled labour and professional agriculturalists is a problem throughout Australian agriculture that governments need to address, since it has implications for current operations and future farm succession.

In summary, at the heart of my success so far has been the mixed farming system, in which crop production and livestock production are integrated. We have built on this basis by seeking and finding improvements from:

- genetic diversity (crop types, new pasture varieties and livestock breeds),
- refinements to our operational methods (direct drilling, flexible crop rotations, willingness to vary the length of the pasture phase),
- fine-tuning our management strategies (through crop monitoring, fertiliser applications, herbicide rotation).

My tactical approach to management includes a preparedness to wait for opportunities to buy assets (update machinery, purchase additional land) at the right price. My tractor now is used for only about 160 h/year so it will be good for a long while yet. Likewise, I anticipate years of reliable service from my well-maintained header-harvester, which I bought second-hand and which is now 10 years old. New machines inflate costs, so maintaining good-quality machinery is a sensible policy.

For all of our crop and livestock options, the asset base—our soil—is crucial. We have halted our soil pH decline with up to three applications of lime. Soil salinity occurrence is unlikely because deep-rooted perennials (lucerne, phalaris) are used on this property and on properties around me, thereby minimising water recharge and discharge. I would like to buy more land but, as with machinery, one has to be patient and wait for opportunities, at the right price.

44.6 Looking to the Future

At this time, the farm and family are secure environmentally, financially and socially. I still gain satisfaction from operating our farm. My son, Alexander, plans to come back and work with us next year, which gives me an opportunity to implement plans for expansion and eventual succession. If we are successful in the farm business, I am willing to diversify our asset base by investing off-farm into something with which we (the family) feel comfortable.

Currently, topics for thought are greenhouse gas abatement, especially the alternatives to burning some heavy cereal stubbles in late autumn, (to enable handling by tined implements and also how we might create opportunities for carbon sequestration. We believe that climate change is a reality and we must learn to live with it. Rising fuel prices are another threat to profitability and farmers have to ensure that we retain an operating environment that is fair in terms of our access to fuel supplies for food production and to satisfactory terms of trade.

The Farm Management Deposit Scheme[3] is crucial for us—it enables us to deposit money after good seasons and withdraw it when we need it. This stops us spending money, when we have it, just to gain a tax break. The Exceptional Circumstances Scheme does provide some relief from drought in the form of interest rate subsidies and other concessions. These days, there are not many bad farmers left farming. I am always willing to help out a fellow farmer with advice.

We do face a labour problem, which I have mentioned before, and we need to encourage young people into farming. Perhaps the federal and state governments could explore possible schemes to reward farmers for their contributions to landscape

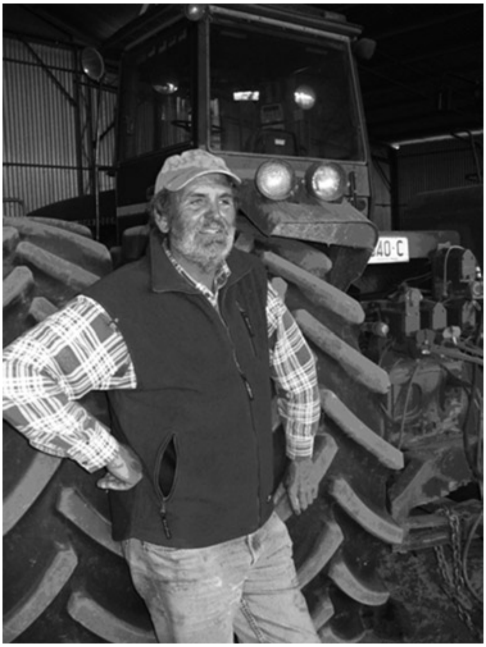

Fig. 44.1 Derek Ingold

[3] An Australian tax concession to primary producers that allows them to deposit funds in a good year, tax free. They pay tax on these funds in the year they withdraw them.

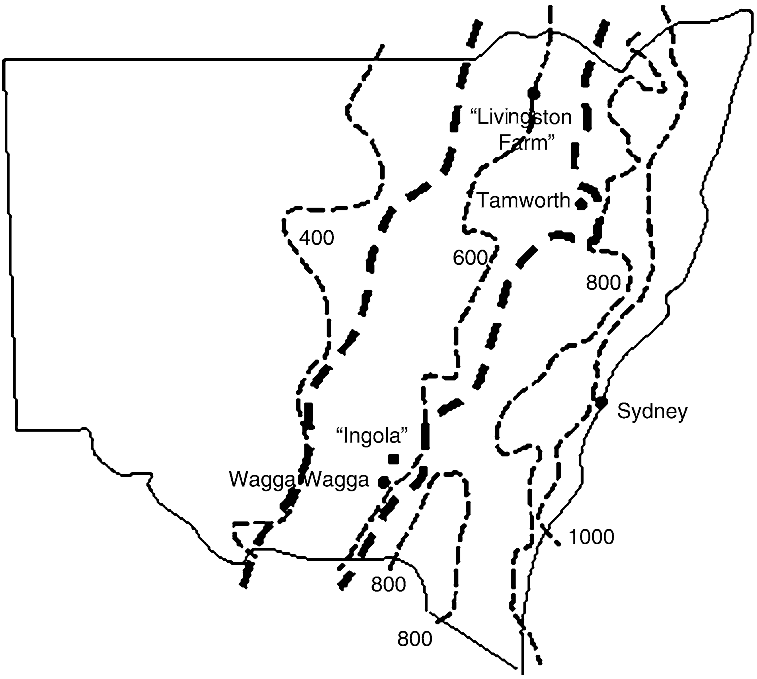

Fig. 44.2 Map of New South Wales showing the location of the farms 'Ingola' and 'Livingston Farm' (Chap. 45) in relation to average annual rainfall isohyets (mm) and the rainfed mixed farming zone (wheat–sheep belt, within *heavy dashed lines*)

management, greenhouse gas abatement and the protection of biodiversity. However, such schemes often come with an expanded bureaucracy to run them, and the paper work is distracting.

I am still thinking about changes that may be made to our livestock program to deal with complexity and labour issues. I have endeavored to keep the livestock enterprise simple but diversifying from wool-growing wethers to wool and fat lamb production has increased complexity. It would be easiest for me if my son preferred livestock management over cropping operations but not many young fellows think that way! Another possibility might be to contract out some of the tasks involved in breeding, maintaining and marketing our animals to working partners. This strategy would preserve our energy for crop production and resource management issues. The synergies and conflicts between diversification and specialisation are at the heart of our farming system (see Chap. 11), and I look forward to an interesting future.

Acknowledgements I thank Emeritus Professor Ted Wolfe for the opportunity to describe our farming system and the editors for their decision to include this case study in their book. Ted was responsible for Figs. 44.1 and 44.2. I am particularly grateful to Susan, my wife, for her personal support to me in terms of a willingness to discuss matters, her teamwork and her astute judgment.

Chapter 45
The Development and Operation of No-till Farming in Northern New South Wales (NSW), Australia

A Case Study

Jeff Esdaile

Abstract This case study describes the development of a farming system, based on no-till methods, that has enhanced the productivity and sustainability of a demonstration farm on the NSW northern plains—an area with a number of severe climate and soil constraints. Stubble retention, no-till seeding and opportunity cropping were the key steps in developing a system to minimise soil erosion, conserve soil moisture and enhance the reliability of growing productive crops. This system is continually evolving, and it faces several challenges in the future.

Keywords No-till • Crop rotation • Pasture phase • Weed management • Conservation farming • Controlled traffic • Sheep • Cattle

45.1 Introduction

As a long-time farm manager and agronomist, my focus of interest is on the farming systems of the North West Slopes and Plains of New South Wales. These areas comprise the farming lands of the North West Plains that stretch from Narrabri westward to Walgett and northward beyond Moree into Queensland; the Liverpool Plains around Quirindi and Gunnedah; sections of the Northern Slopes around the main towns of Tamworth, Manilla, Bingara, Warialda and Inverell; and the undulating arable land on the western fall of the Northern Tablelands (see Fig. 44.2). For decades, these areas have been prized as a production zone for high-quality wheat since the clay-loam and clay soils are, by Australian standards at least, high in natural fertility and water-holding capacity.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_45,

I was employed as the Manager of farms owned by the University of Sydney, first at the Plant Breeding Institute (PBI) at Narrabri (1967–1976, 400 ha property) and then at Livingston Farm at Moree (1976–2000, 4,700 ha property, 4,000 ha cropped). The PBI had a strong emphasis on wheat breeding and research, whereas the Moree farm was run as a commercial operation for the University. The University wanted Livingston Farm to operate as a profitable model farm that demonstrated the principles of scientific agriculture to local, regional and national farmers. This vision and modus operandi ensured that that my University colleagues and I were both active as leaders in, and accountable to, the broad agricultural community.

At the time that I began my work with the University, the main farming system in northern NSW and southern Queensland was a traditional monoculture of continuous annual wheat with bare fallow. The fallow was used to control weeds by cultivation and accumulate soil moisture, but this system caused a reduction in the chemical and physical fertility of the soil, resulting in a decline in crop yield and quality.

The topic of this case study is the process, over the next four decades, of developing and adopting new farm practices that elevated the productivity and sustainability of farm production. This account nominates several problems and describes several innovative practices to overcome them. These practices included those that stemmed primarily from contemporary research and others that came about through trial and error between farmers, machinery firms and agribusiness. The study ends with a consideration of future challenges for researchers, farmers and advisors in this farming system.

45.2 The Farming Environment

45.2.1 Climate

The climate of north-western NSW can be described as mild in winter with a few frosts, hot in mid-summer with maximum temperatures averaging over 30°C, and with an annual rainfall of between 450 and 600 mm annually. Although the rainfall pattern is generally summer-dominant, the production of winter cereal crops under traditional farming systems has been regarded as more reliable than that of summer crops such as grain sorghum. This is due to the capacity, under clean cultivation (fallow), to store some summer rainfall for winter crop production and to the significantly lower evapo-transpiration rates in winter (Fig. 45.1).

Furthermore, farmers can experience considerable difficulty in achieving good stands of weed-free summer crops using conventional fallowing methods. At the time when winter crops need to be sown into moist soil, a layer of dry topsoil often covers the surface. The moist soil is overlain with 3–10 cm of dry soil (depending on when the last rain fell) which the seed drill must penetrate to plant the seeds into the moist soil (Fig. 45.2).

Other climatic constraints are the risk of unseasonal frosts in late September or early October that may disrupt the flowering and grain development of winter cereals, cold soil temperatures (<10°C) that reduce sorghum emergence in October, and a relatively sharp cutoff to the growing season in late spring for winter crops.

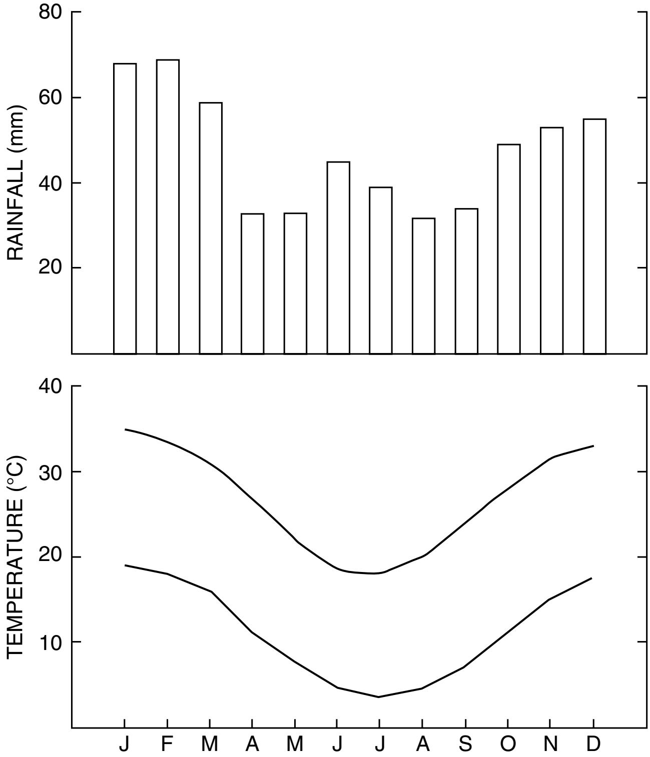

Fig. 45.1 Long term mean monthly climatic data for Moree. *Top*: Rainfall. *Bottom*: Maximum and minimum air temperatures (Crofts et al. 1988)

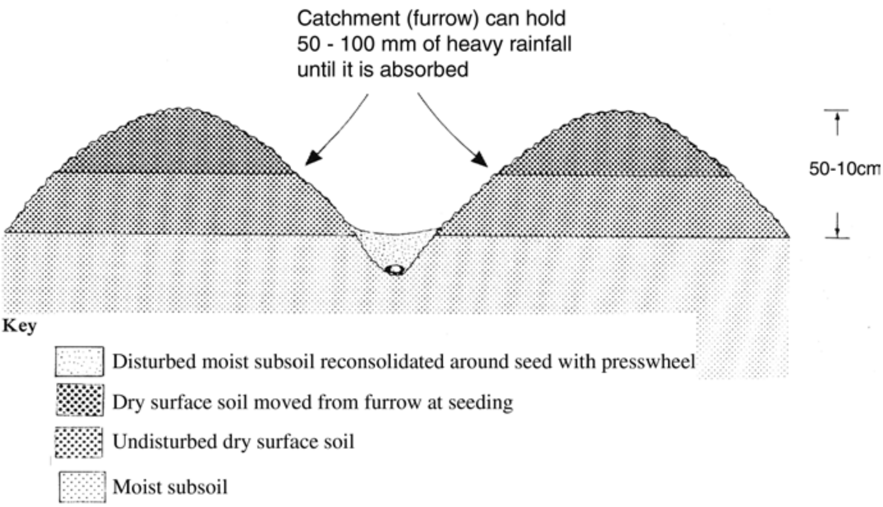

Fig. 45.2 Diagrammatic illustration of seed placement into moist subsoil overlain by dry surface soil, by a deep-furrow seed drill. The furrow is consolidated by a presswheel pressing the disturbed moist subsoil around the seed (Crofts et al. 1988)

45.2.2 Soils

Livingston Farm is representative of the North West Plains in that it mainly contains flat, arable land in a medium rainfall area, with predominantly black self-mulching soil. There are smaller areas of hard-setting, dark grey clay soils that do not crack in their native state.

The self-mulching soils of the area vary in depth from 0.5 to 3 m or more, and are generally alkaline in reaction, with surface and subsoil pH levels ranging between pH 7.2 and 8.3. In their native state, they are high in organic matter, have a high base exchange capacity[1] and are well supplied with all essential plant nutrients, except zinc. They crack freely when they dry out, have a high moisture-holding capacity and, at field capacity, can store up to 150 mm of available moisture per metre of soil depth. They are cloddy when dry and very sticky when wet. Given adequate moisture, they will grow most common crop and pasture plants except those adapted only to acid soils. These soils are relatively easy to cultivate at intermediate moisture levels but difficult to cultivate when dry, and impossible to cultivate when wet. Their high draught requirements ensured that they were not developed for extensive cropping until the advent of powerful tractors after World War II. The soils are highly erodible during the fallow periods between crops and they are prone to the development of plough pans,[2] particularly if they are cultivated when too wet.

45.3 System Structure and Limitations

The key limitation of the system is the highly erratic nature of the rainfall. Average rainfall data are only a rough guide to the probability of successfully growing a particular crop in any given year in this region. A long fallow is needed to accumulate sufficient soil moisture to sow either a summer or a winter crop. Rather than rely on past rainfall statistics, it is considered preferable to farm according to the amount of moisture in the soil at planting time. This amount is the main determinant of whether a summer or winter crop, or no crop at all, is planted in a particular field. Fawcett (1969) developed a simple and cheap soil probe to measure the depth and distribution of water in the profile. Probing is an essential part of the process in deciding what crop to sow, and when to sow it, in a particular field. In some years, it is possible to grow two rainfed crops in one field in 1 year (summer and winter), while in other years it is impossible to grow even one crop successfully.

The main crops grown in the area are wheat and barley in winter–spring (sown May, harvested November) and sorghum in spring–summer–autumn (sown October,

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[1] See Glossary for explanation.

[2] See Glossary.

harvested April). Due to the unreliability of pulses such as chickpeas and faba beans, these are grown only as minor winter crops.

Some parts of the Northern Slopes and Plains, especially the areas that are less suitable for the regular production of crops (steeper slopes, floodplains and/or poorer soils) have a long history of producing sheep (wool, mutton and lamb production) and cattle. Some farms mix livestock production with cropping activities, while other farms are run as specialist livestock or crop farms with some integration of these enterprises through stock agistment or share-farming arrangements. A few farmers retain grain for feeding in feedlots. Along the floodplains of the Namoi and Gwydir rivers are located tracts of irrigable land for cotton production, an industry that is more or less independent of the rainfed farming and pastoral enterprises.

45.4 The Drivers of Change

Even before the 1970s, the time was right for some serious changes to the farming systems in northern NSW. Soil erosion on the slopes was so rampant in the 1930s and subsequently that a Soil Conservation Service was set up to manage the problem through the construction of banks and waterways to control run-off. However, little was done at the time to preserve vegetative cover on the landscape to minimise the impact of sudden storms. Furthermore, although scientists had drawn attention to a decline in the organic matter (SOM) content of cropped soils, farmers had done little to restore SOM or to replace the soil nutrients, especially nitrogen, exported from the system in soil and wheat grain. At PBI Narrabri, Fawcett (1972) demonstrated that, instead of burning wheat stubble and cultivating the fallow to eliminate weeds, retaining crop stubble and eliminating tillage through use of herbicides would prevent erosion and result in an extra 30–50 mm of water stored in the soil during the fallow.

Armed with the convictions generated by these results, I set about changing cropping practices on Livingston Farm in order to reduce erosion, enhance water storage, and hence elevate the potential for crop production. The issue was becoming urgent, in part due to the range of large tractors and new machinery available (disc and blade ploughs, rod weeders[3]) that placed further pressure on the fragile soils. The urgency was also due to official concerns about the declining quality of the grain produced from these so-called 'prime' areas. There were doubts about the practicality of stubble retention, especially regarding sowing into residues left from the previous crop. Further, little was known about how stubble retention might change the spectrum of weeds and diseases that affected the 'monoculture wheat' and 'wheat–fallow–sorghum' systems.

At this point, I emphasise that the issue of farming sustainability was by then (late 1970s) well-recognised by local State agencies (NSW Agriculture, NSW Soil

[3] See Glossary.

Conservation Service, Queensland Department of Primary Industries) and, during the 1980s and 1990s, considerable funds were invested in research and extension by teams at Tamworth, Narrabri, Toowoomba and Warwick They:

- developed and evaluated no-till[4] practices for weed control and crop production (Felton et al. 2001),
- investigated the nitrogen and phosphorus balance of local soils (Holford and Doyle 1992),
- developed alternative crops especially pulses (chickpeas) and pasture legumes (lucerne, medics) (Elias et al. 2004) for inclusion into the crop production systems,
- bred wheat varieties for tolerance to whatever threats arose (such as crown rot of wheat) (Burgess et al. 1993).

Also at this time, agribusiness interests were active in promoting new methods of farming in northern NSW and southern Queensland. For instance, Monsanto released glyphosate as a new type of broad-spectrum, systemic herbicide and Incitec, a manufacturer of fertiliser, promoted the link between soil fertility (and fertiliser use) and wheat quality. In the context of all these changes, my role was twofold: (1) to liaise with these teams and with leading farmers who were open to the new ideas, and (2) to construct the new system at Livingston Farm.

45.5 Developing the No-till System at Livingston Farm

A new system was seen as necessary to minimise soil erosion and to increase the reliability and productivity of crops. The basis for such a system at Livingston Farm was, we reasoned, the retention of the full residue of the previous crop, so that soil moisture would be available near the surface for establishing a winter crop at the optimum time (late April to late May) in most years. This aim sounded simple but, at both the research and farm management levels, it involved considerable trial and error, embracing everything from developing specialised seed drills, to controlling weeds with herbicides during the fallow period and spreading the residues from the harvester evenly on the soil surface. Some of the steps along the way to a no-till system are described below for Livingston Farm.

45.5.1 The Development of Specialised Seed Drills for Reduced- and No-till Farming

I realised very early that a new style of seed drill would be necessary to plant crops successfully under the extremely variable environmental conditions. Doyle and

[4] The terms 'no-till' and 'zero tillage' are synonymous. They refer to a system of farming in which the land is fallowed chemically rather than mechanically, and each crop is sown with a specialised one-pass seeder (drill).

Marcellos (1974) had demonstrated in NW NSW that each winter cereal variety (short, mid and long season) should be sown in a 10–20 day 'window'. By sowing later, farmers would suffer a 7% per week yield penalty. Yet our experience indicated, (later verified by the 'Australian Rainman' (1999) climate analysis program), that for the 30-day optimum planting period (26 April to 28 May) for all wheats at Moree, there is only a 50% chance of receiving a planting rain of 20 mm. The problem was how to plant on time and optimize yields in those 50% of years without such a planting rain. An implement was needed that could place seed at a depth of 5–7.5 cm and 2–4 cm into moist soil. Other requirements for this machine were:

- Soil openers with a high breakout pressure to penetrate into moist soil
- The ability to place seed and fertiliser at the bottom of the opened slot
- Minimum soil disturbance to deter the excessive loss of moisture around the seed
- Individually sprung soil openers that could follow the land contours and ensure that all seeds are placed at an even depth
- Individual press wheels that would press the seeds into the moist soil, even when the topsoil was dry.

In 1981, a Noble 2000 deep furrow drill was imported from Western Canada, and this proved very successful. The first real test of the worth of no-till farming was in 1982. The season started well, with around 250 mm of rain from November 1981 until late March 1982. The rain stopped in late March, and it did not rain significantly again until April 1983. Despite the dry conditions, we commenced planting in April, and continued until June of 1982.The mean results of the alternative planting methods used are shown in Table 45.1.

The results gave tangible evidence to the farming community of the worth of the no-till system, and interest grew enormously. However, the clearance of this drill was insufficient to deal with heavy crop residues. So in 1987, an Australian-built chisel plough/air seeder was modified to carry out planting operations, using the principles demonstrated and described by Lindsay Ward (Ward and Norris 1982). This unit was fitted with moisture-seeking spear points and press wheels. A six-row, no-till row crop planter with tyne openers was also imported from USA around the same time. After several years of successful use, a detailed report was made on the progress with no-till at Livingston Farm (Crofts et al. 1988).

During the 1980s and 1990s, several local machinery manufacturers further developed the heavy-duty, tyne-opener seed drill. Disc-opener drills (both double and single disc type) were tried in the early years, but they were not successful; they

Table 45.1 Results of 1981 alternative tillage practices

Treatment	Wheat yield	Plants with secondary roots
No-till, using deep furrow drill (200 ha)	2.2 t/ha	80%
Stubble mulch tillage using sweep implements and 'combine' drill (1,000 ha)	1.5 t/ha	20%
Traditional tillage (1,000 ha)	Crop failed	Nil

would not penetrate dry topsoils and, in wet conditions, soil stuck to the discs rendering the implement unusable. However in 2000, a range of Canadian 'Barton' type single disc opener drill units became available on the Australian market. These were proved successful and several locally made units are now available. Their success is, at least in part, due to the change in the physical condition of the topsoil after several decades of no-till. The soil is much more friable, the moist soil layer is nearer the surface, and the soil is usually well covered with residue. This allows the disc opener to penetrate adequately and place the seed and fertiliser into the moist soil. The residue acts as a mulch 'blanket' to support the various depth wheels on the opener and prevent soil adhesion. This style of implement has now been widely adopted in northern NSW and southern Queensland. Machines are available with a range of tyne configurations, many styles of points to suit various soil types, and a range of press wheels with different profiles to firm the seed in the planted row. Optional cutting coulters are also available. Seed drill development will continue, for example for inter-row sowing in controlled traffic systems.

45.5.2 No-till (Ecofallow) Sorghum

Also in the 1980s, Australian sorghum growers became aware of the 'ecofallow' system used on the US Great Plains (Nilson and Phillips 1978). The system used a 10-month no-till fallow, with atrazine as the main herbicide, followed by grain sorghum planted into this fallow. A no-till row-crop planter was used, leaving the winter cereal stubble undisturbed. Grain sorghum with wide row spacing (60–100 cm) was easier to plant than a close-spaced crop like wheat. Much of this technology has since been applied to grain sorghum production in Australia. On Livingston Farm, we have successfully used the technology for 27 years (Esdaile 1992) without experiencing a single complete crop failure. Although sorghum was the first ecofallow crop grown on Livingston Farm, this no-till system has since been successfully modified for many other row crops such as corn, cotton, soybeans, mung beans, sunflowers, chickpeas and faba beans.[5]

45.5.3 Sprayer Technology

Although it initially took time for some farmers to substitute glyphosate for the traditional practice of tillage, this herbicide quickly became the main method of controlling weeds in the summer fallow period before the wheat crop was planted on Livingston Farm. We had traditionally used a standard boom spray for pesticide and herbicide application, with the spraying units either mounted on or drawn by tractors, or fitted to farm vehicles. Although satisfactory in performance, I was

[5] See Glossary for scientific names.

aware of the serious shortcomings of the standard boom spray in that, once the droplet left the nozzle, we lost control of the herbicide.

In 1989, I became aware of the work of Geoff Furness (1990) from South Australia who developed the concept of the ‘bluff plate’ boom spray. He proposed that, rather than using air-generating units to propel droplets to the target, the same job could be done by using the disturbed air from the forward motion of the boom. No moving parts would be required. Generally, the bluff plate principle performed as well as expected. However, mainstream boom manufacturers showed no interest in further development, and the farm reverted to the conventional boom spray system in 2001.

45.5.4 Changes in the Weed Spectrum

Very early in the development of the no-till system, shifts in the weed spectrum became evident. Some of the easy-to-kill crop weeds now became of minor importance, whilst other species, which were insignificant in fields that had been tilled, now assumed greater importance. Along with researchers and other farmers, we soon learned which species were easily killed by glyphosate, and which species needed a tank mix of glyphosate with other herbicides to achieve effective control. In some cases, adjuvants were used to achieve an improved result. It was essential that we needed to have a good working knowledge of weed species and their control measures to do a good job in weed control each time a spraying operation was required.

Some of the weeds, which changed in importance and are still sometimes a challenge, included:

- Prickly paddy melons and afghan melons (*Cucumis* spp.). If these are missed by an after-harvest spray they can be troublesome for many weeks afterwards.
- Common sowthistle (*Sonchus oleraceus*). This species can be killed well in the seedling stage when conditions are right. However once it becomes larger than about 10 cm diameter it has some tolerance to glyphosate, even when additional herbicides are added to the mix. Control is also made difficult when the fluffy seeds blow across the landscape and quickly infest a whole district.
- Flaxleaf fleabane (*Conyza bonariensis*). This species also is difficult to control once it has passed the seedling stage. It colonises gaps in the field where crop establishment has been poor. Again, seed dispersal by wind across large areas has caused it, in the space of a few years, to become one of the worst weeds in northern NSW.
- Native grasses such as ‘blowaway grass’ (*Panicum* spp.). The seed heads blow in from adjacent wasteland or pasture areas, and catch in the crop residues. Once established, they can be difficult to control as the dead and decaying leaves at the top of the plant protect the new green leaves from spray droplets.

Over the years, there has been a strong shift from annual weeds to perennial weeds, and a move to the ‘harder-to-kill’ species, some examples of which are outlined above. In addition, northern NSW has seen an increasing incidence of herbicide-resistant weeds due to the continued sequential application over many years, on some farms, of herbicides of the same group. Vigilance will be needed to overcome this challenge to no-till farming. Techniques such as the regular rotation of herbicide groups, the 'double knock'[6] system of weed control, improved spraying techniques, the use of selective weed sensing where necessary, new and innovative tank mixes of herbicides, and new products will hopefully alleviate the problems now being experienced.

Weed control using alternative methods to tillage (mainly herbicides) is a complex business. Farmers must have an expert eye for recognition of weed species (both seedlings and advanced plants) and an expert knowledge of herbicides to know which products will control which weeds. Also a good working knowledge of meteorology is required to ensure that herbicides are applied under optimum weather conditions, to control the target weeds, and also ensure no drift off target to contaminate the environment (or kill the neighbours' crops).

45.5.5 Sheep in No-till Farming

Some farmers have an additional weapon that can greatly assist in many parts of the no-till operation. For example on Livingston Farm we have had up to 5,800 sheep. The main purpose of the sheep is for fallow weed control. In this role, sheep can significantly replace herbicides as a method of weed control in the fallow. Sheep are introduced (from pasture fields, or other grazed fallows) after harvest, and again after each weed germination, and the field is 'crash grazed' for periods of 6 h to 10 days. The aim is to heavily graze out all the weeds and remove the animals before they start to eat significant quantities of residue. Although many farmers dislike sheep in farming systems, I consider that, properly used, sheep can be very valuable. Along with the rotation of herbicides for wheat and for sorghum and for other crops, sheep grazing of weeds became an integral part of our integrated system of weed management, which is designed to reduce the risk of developing herbicide-resistance. At the high stocking rates mentioned, the sheep eat all of the edible weeds quickly. Wethers are purchased at 1–2 years of age, used for 5–6 years, and then sold. Income from the sheep enterprise is significant.

45.5.6 Moree Conservation Farmers and Community Involvement

During the 1980s as the movement towards conservation farming gained momentum, I joined with other leading farmers from the Moree district to increase our

[6] 'Double knock' is the use of a second herbicide to eliminate survivors of the first herbicide.

'information sharing' about no-till and other forms of conservation farming. This activity started as an informal group that met regularly in the library of the Moree High School. Whenever a visiting scientist or local research worker was in the area, he (or she) would be invited to chat with those at the meeting. Information sharing and farmer discussion groups (also involving state extension officers and agribusiness advisors) is a vital part of the system to keep farmers' confidence up.

As our membership grew, we registered as a Landcare group, part of the National Landcare program and, in 1991, we gained funding for a project officer. This enabled a broader range of activities to be undertaken. In addition to the evening meetings, field days, seminars, and bus tours were conducted and a regular newsletter published.

A succession of project officers came and went, and we continued to be funded by Landcare until the year 2000. Later that year we amalgamated with similar bodies from southern Queensland to become Conservation Farmers Inc., an umbrella group based in Toowoomba. This farmer-controlled group now has several sources of funding and, as well as serving its members, conducts small research projects for other organisations.

Such groups are helpful in the introduction of new ideas. While sometimes farmer helps farmer, more often the farmer gets advice from a local Government agronomist or agribusiness advisor. There is also a network of gossip about which systems are working or are not, and which farming implements are good value.

45.5.7 Controlled Traffic Farming

Early in my years on Livingston Farm, the pattern of operations with tillage and spraying equipment was altered from the then traditional system of 'round-and-round' field operations to a 'back-and-forth' method. The reasons included: (1) greater accuracy in the sowing of row crops (mainly grain sorghum); (2) ease of applying herbicides and pesticides to achieve an even dose across the field (especially to prevent the over-application of residual herbicides on headlands, which regularly showed up as bare patches in the next crop); (3) reduce the traffic of vehicles and equipment on the paddock; and (4) facilitate servicing/loading of equipment.

The boom spraying system was adapted so that on the first spray after crop harvest, the field was accurately marked and posted, enabling spraying with an accurate swath width, and no overlaps or missed sections. Subsequent spraying used the same tracks as a marking system. However, crop planting and harvest (although back and forth) was still done in traditional fashion.

In 2001, the initial marking for spraying after harvest was done by a vehicle with a Global Positioning System (GPS) installed. The no-till seed drill was widened from 18 to 24 m, to match the width of the boom spray. Row crop planters were also altered as required to fit in with the modular system being developed. However, by 2008, harvesting equipment had not been integrated into the system fully (since we use harvesting contractors). This remains a challenge for the future.

45.6 Crop Rotations, Pastures and Other Developments at Livingston Farm

45.6.1 Crop Rotations

One of the basic philosophies of no-till farming is always to be in a position to plant a new crop into the residue of a crop of a completely different type. We have always tried to achieve this rule on Livingston Farm. When choosing a crop to grow in a particular field, the following questions provide a checklist to aid the decision:

- What crop did the field have last year?
- What is the subsoil water status of the field?
- What is the fertility of the field (especially nitrogen)?
- What is the disease status of the field (both residue-borne and soil-borne disease)?
- What is the weed spectrum of the field?
- What is the anticipated price and yield of the potential crop?
- Does the potential crop add to the long-term fertility of the field (e.g. a legume or pulse)?
- What is the overall risk factor in the production of this crop (both field risk and marketing risk)?

Based on these constraints (aided by experience and intuition), a decision is made to plant a crop which will give the most profit with the least risk whilst adding to soil health. In practice, wheat has been the main crop grown, with chickpeas, barley and grain sorghum as important subsidiary crops. The list of all of the no-till crops we have grown is extensive—winter cereals (wheat, barley, oats, triticale, ryecorn), winter pulses (chickpeas, faba beans, field peas, fenugreek), summer cereals (sorghum, corn), oilseeds (canola, linseed, safflower, soybeans), summer pulses (mung beans, peanuts, pigeon peas, cowpeas, tepary beans, *Dolichos lablab*) and forages (oats, forage sorghums). Cotton has not been attempted due to the specialised requirements of the crop, and the proximity of Livingston Farm to the Moree urban area. However, other district farmers are successfully no-tilling this crop. We have not grown sunflowers, because of potential bird problems.

45.6.2 A Pasture Phase?

From time to time, lucerne has been grown as a short-term (less than 5 years) pasture on Livingston Farm, especially at times in the evolution of the farm when livestock prices were relatively high and grain prices low. It is planted with the no-till system under a cover crop (wheat, at a reduced planting rate). After the wheat harvest, a rotational system of grazing is implemented (with varying degrees of success) for the next few years.

One difficulty with this system has been that the pasture stand is uneven due to the dominance of the grain cover crop and soil variability. Another difficulty is the susceptibility of lucerne to waterlogging, which occurs from time to time. Lucerne also causes bloat, which is severe at times in cattle grazing lush lucerne. While the lucerne has undoubtedly added to the chemical fertility of the soil (Holford 1981), it has not apparently done much for the physical fertility. So, overall, I have doubts about the value of lucerne when grown in heavy soils on flat plains country. However, I acknowledge that lucerne does well on lighter soils, and on the Slopes.

We never did try long-term perennial pastures (more than 5 years) on Livingston Farm, but at times I wish we had attempted to do so. Research work in a long-term trial conducted by the Queensland Department of Primary Industries at Warra in the 1980s and 1990s (Dalal et al. 1996) showed that, with one exception, all rotational systems grown at that site over an extended period of years did little to increase the physical fertility of that soil. The exception was the pasture treatment, which comprised 5 years of pasture containing perennial subtropical grasses along with annual medic; this treatment showed measurable increases in organic matter, aggregate stability and other physical soil parameters.

One of the challenges for the future for farming in northern NSW will be to decide whether a perennial grass–legume pasture phase will be required for the long-term stability of crop production. Currently no-till in a crop-only rotation appears stable, but long-term stability and soil improvement are uncertain. For degraded soils on the slopes, a period of perennial long-term pasture appears necessary to rehabilitate these soils, despite the difficulty in some years of satisfactorily establishing these pastures. A few farmers in northern NSW have successfully integrated long-term pasture phases into their farming rotation and achieved a stable system as a result (Anderson 2004).

45.6.3 Cattle in the Farming System

When Livingston Farm was taken over by the University in 1969 (as 'Kooroogama'), it was carrying a breeding herd of Shorthorn cattle on partially cleared Mitchell-grass (*Astrebla* spp.) pastures and the stocking rate was estimated to be about one breeding cow to 6 ha. As the property developed towards a grain farm, the beef breeding herd was progressively reduced as livestock did not appear to be complementary to cropping. The wheat varieties left little edible stubble and, in any case, it is necessary to control weeds and retain the residue to conserve moisture for the next grain crop.

Once sorghum was brought into the cropping system, the situation changed dramatically because sorghum stubble was found to have a grazing value when converted to beef by grazing steers. In addition, the grazing of the crop residues made it easier and cheaper to kill the remaining sorghum plants by tillage or herbicides. Experience so far suggests that, in a season of reasonable rainfall, 1 ha of grain sorghum harvested in March or early April will provide about 60 days stubble grazing for one 250 kg liveweight steer, which should gain at least 0.5 kg/day or a total of 30 kg in 60 days. This is a useful addition to the value of the sorghum grain. This is not as good as a grain crop for soil protection as some of the biomass is eaten by the animals. However, if grain prices are low and animal prices high, it increases profitability, and decreases risk.

A further valuable use for livestock in no-till farming, especially when grain prices are low, is to replace cereal (wheat or barley) with no-till oats sown during March or early April at high seeding rates (up to 100 kg/ha) and to graze it from May to June when the green oats reaches a height of 30 cm and yields about 2,500 kg/ha dry matter or 12.5 t/ha green weight. Such a yield should support a stocking rate of 3 steers (250 kg)/ha for 100–130 days at an average liveweight gain of about 1 kg/steer/day. This operation was tested during 1986 on Livingston Farm with a group of 640 steers, producing a gross margin of about $230/ha compared with wheat at $50/ha, and it was continued for several more years. There were some risks, such as dry conditions in spring which sometimes forced premature sell-off of the livestock before they were finished.

Disadvantages of livestock include the risk of soil compaction by animal hooves in wet winters, and the reduction of residue needed to protect the soil in the sorghum field. Moreover, fences had to be secure and watering facilities reliable. Current farming practice is to desiccate the sorghum before harvest to aid in grain maturity[7] and to retain the residual soil moisture at harvest for the next grain crop. Grazing of livestock on the residues of an unsprayed crop prevents this saving of residual moisture to a degree, since it is used to keep the sorghum residues green for livestock fattening.

45.6.4 General Property Improvement

Livingston Farm is divided into fields of 100–500 ha. This results in 1–3% slopes of around 1,000 m length, gently falling into a local creek or waterway. In times of high-intensity rainfall (over 50 mm/h), the rainfall cannot infiltrate the soil regardless of the surface condition. Even under high-residue conditions, water tends to move towards localised depressions in the field and, as it travels down the slope, causes some gully erosion near the bottom.

To combat erosion, many fields were redesigned. Fence-lines and field boundaries were relocated to follow approximately the broad contours of the land, to minimise erosion and facilitate farming operations along the contour. Broad-base contour banks were constructed across some fields to catch excess rainfall during

[7] The sorghum is desiccated when it has ripened and is biologically mature. The plants are sprayed out because sorghum stays green and will continue to grow after biological maturity, if conditions are right.

high-intensity storms, and direct this water to grassed waterways or waste areas where it would not damage crops.

Water points from the grazing area were reconditioned and sited at strategic positions across the farm. Concrete and galvanised-iron structures replaced earthen storage tanks to provide water supply points for spraying operations and livestock watering.

45.6.5 Tree Planting

The Director of University of Sydney Farms told me early in my tenure that ‘every acre on the farm must be earning income’. However, there were quite a few areas of wasteland that were unsuitable for cropping and too great a risk of erosion for general livestock grazing. I decided that many of these areas would be devoted to agroforestry. Accordingly, during the early 1990s, several thousand native trees were planted. The main species used was *Eucalyptus argophloia* (Chinchilla White Gum), recommended by Peter Voller of the Queensland Department of Natural Resources (Voller 1999). Tree seedlings were planted principally in wet autumns (when it was too wet to do any other field work) on a 7–10 m grid. When the trees were around 3–4 m high, livestock could be reintroduced on an ad hoc basis for limited grazing. In addition, rows of recommended native trees and shrubs were planted along major internal roads in the property, and around the administration area for aesthetic reasons.

45.7 What Has Been the Overall Improvement During the Last 30 Years?

45.7.1 The Components of Improvement

There are still some farms in northern NSW that are managed poorly, but most farms have achieved real progress in terms of productivity and sustainability. Through the adoption and refinement of the no-till system on Livingston Farm, we have succeeded in raising crop productivity, grain quality, soil health and production efficiency. The farm continues to be profitable. The components of our success can be summarised as follows:

- Maximum residue retention has reduced run-off and soil erosion. Instead of an erosive event annually, we only have one major runoff occurrence every 5–7 years. Erosion has been reduced by 90%, in accordance with the results of Freebairn (1992).
- Reduced soil evaporation has resulted in additional water storage. This has been expressed in improved crop yields.

- Organic matter and soil structure have been maintained and possibly improved. Preservation of earthworms and mycorrhizal fungi has been assisted. There is less ponding of water on the soil surface after rainfall, and the soils are more trafficable in most weather conditions. However, as mentioned previously, we may be able to do better with an extended grass–legume pasture phase.
- Optimum planting time is longer as moisture remains for a longer time in the seed zone of the soil due to the absence of tillage, and the positive effects of the mulch on the soil. This has allowed a bigger area to be planted and we have been able to farm with less machinery and labour. In the last 18 years we have been able to plant practically all crops on time, giving significant yield increases.
- The chance and reliability of double cropping is increased. An extra crop can often be grown in wet years by sowing into the undisturbed residue a few days after harvest of the previous crop. If one gets unusually heavy rainfall events at or just after crop harvest, there may be enough soil water accumulated to 'double crop' with confidence.
- Reduced tractor hours have meant less machinery repair costs and lower fuel use. At Livingston Farm, we have been able to reduce our major tractor units by one, and instead rent a tractor for a few weeks at the principal planting time.
- The farm is more 'environmentally friendly' with the increased stability of the landscape, together with the effects of tree planting.

However, the process has not been without pain. It seems that every year since we first started, we have taken two steps forward, and one step back, as new problems have appeared. These have to be overcome or sidestepped before we can go forward again. However, we have been able to maintain profitability in the face of stagnant commodity prices, along with increasing costs of inputs and inflationary pressures.

45.7.2 Ongoing Challenges for Farmers in Northern NSW

Our farming system is unlikely to suit everyone. In northern NSW, farmers have achieved productivity and sustainability by a variety of pathways. However, no-till is a common ingredient in successful farms.

For the future, I pose the following questions to agricultural scientists and farmers:

- Can we continue to upgrade the spraying skills of our farming colleagues, enhance their knowledge of herbicides and how they act, improve their ability to identify weeds and choose the correct combination of herbicides to do the best job?
- Can we reduce the shift towards 'hard-to-kill' weeds, especially perennials and weeds that are resistant to some herbicide groups?
- Can we continue the development of resistant crop varieties and rotational strategies to control plant diseases, especially those that are persistent in soils or on crop residues?

- Do GM crops have a role to play?
- Can we continue to improve seed drills? We have come a long way since the first deep furrow drill of 1980. However, is there a unit which will handle wet soils, dry soils, heavy residue, sticky soils and obstacles and achieve a good result every time?
- Can we improve nitrogen application systems in conservation farming? How can we efficiently place fertiliser N near the plant, without sacrificing soil moisture and residue cover under a whole range of conditions?
- Can we manage field fauna, such as mice, which have habitat and food for most of the year?
- Can we avoid the need for post-harvest tillage for the control of over-wintering pupae of some crop insects? Are there alternative ways?
- Are we doing a good enough job of convincing urban dwellers and media people that conservation farming is environmentally friendly? If not, will this translate into pressure on farmers by way of regulation and other measures?

45.7.3 Where to from Here?

Australian farmers will continue to embrace no-till, despite existing challenges. I estimate that in 2007 around 70–80% of the cropland of Northern Slopes and Plains of NSW was farmed using conservation farming techniques and 50% was no-tilled. As the price of fuel escalates, this system of farming will continue to expand.

New pesticides will be found as well as new uses for older products. Unfortunately some of the 'old guard' chemicals may disappear or be severely restricted. We must show the community that we are responsible users of pesticides in order to keep these products as part of our arsenal.

Controlled traffic farming, self-steering tractors and spraying equipment will probably be the norm rather than the exception in the future. I trust that seeder development will continue, and improved spraying technology will become more evident. This will ultimately be translated into lower rates of pesticides being used.

Rotational strategies utilising pulse crops, bio-fumigation,[8] pastures and grazing animals, alternate cereal types and oilseeds will become more important as a means of enhancing soil fertility and the control of weeds, insects and plant disorders. Probably, GM species will play an increasing role here.

Farmers will need to be smarter and more 'switched on' to handle the complexities of modern agriculture. The majority of grain growers in northern NSW now employ consultants, or use local agri-business agronomists, to assist in such things as pesticide strategies. Many farmers will use their own spray rig but contractors are assuming a bigger role in the spraying operation.

[8] See Glossary.

45.7.4 A Vision for the Future

I envisage a future where no-till systems will dominate most of our broad-scale farming operations. No-till will be integrated with diverse cropping and livestock production practices. These practices will be carefully balanced to satisfy the economic and environmental requirements of the day and to achieve long-term sustainability.

Acknowledgements Over my 40 years in grain production, I must acknowledge my many mentors and colleagues from all spheres of the industry. I have continually ‘picked the brains’ of contemporaries from NSW Agriculture, CSIRO, many Universities, Queensland Department of Primary Industries, Queensland Department of Natural Resources, agribusiness, private consultants, the Grains Research and Development Corporation, multinational pesticide and seed companies, agricultural machinery companies, and innovative farmers. People in all sectors have willingly provided research data and information to assist in development and implementation of a sustainable system on Livingston Farm.

I also acknowledge the forbearance and patience of staff at the University of Sydney, especially the Properties Office, my colleagues Professor Frank Crofts and Professor Lester Burgess, overseer Greg Ticehurst and the staff at Livingston Farm. Without their help, the job could not have been done.

In preparing this case study, I appreciated the encouragement and suggestions of Dr Ted Wolfe and Dr Philip Tow.

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Chapter 46
Farming System Development in North Central Victoria Australia

A Story of the Evolution of a Mixed Farming System of Crops and Sheep and How the Farmer Has Adapted to the Challenges of Variable Seasons and the Volatile Markets for Grains, Meat and Wool

Kieran Ransom

Abstract An Australian 'mixed farming' system of crops and sheep in rotation has continually adapted over 25 years to a series of challenges that included maintaining soil fertility and health, managing a highly variable climate, increasing income in response to declining terms of trade and reducing the risks of farming. The changes included replacing annual pastures with a pasture mix of rainfed lucerne and annual pastures, no-till cropping with stubble retention, introducing additional crops and changing the sheep flock from a wool emphasis to a dual-purpose meat and wool flock. An economic analysis confirmed these changes significantly increased whole farm profitability.

Keywords Mixed farming • Dual purpose sheep • Rainfed lucerne

46.1 Introduction

Stephen and Lisa Poole's family farm is on creek flats to moderately sloping sedimentary hill country near Wedderburn in North Central Victoria, Australia (Fig. 46.1). The Poole family has been farming in the area for three generation, with their 'mixed farm' having had two main enterprises, grain and sheep grazing, for over 60 years. Like most farms in the area, the farming system is constantly evolving to meet the challenges of climate, soils and commodity prices. The farm area is currently 800 ha with about 600 ha suitable for cropping.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_46,

Fig. 46.1 The Poole family

46.2 Climate and Soils

The average annual rainfall is 475 mm. About 330 mm falls during the cooler crop-growing season from April to October, while the remainder occurs during the hotter months from November to March (Fig. 46.2). There are normally 12–20 frosts between May and October each year.

The topography varies from flat to moderately undulating. The underlying rocks are of ancient Ordovician sedimentary origin. Soil depth varies from only a few centimetres on rocky outcrops to deep soils on creek flats. The moderately acidic, clay loam topsoils (pH water 5.5–5.9) overlie clay to fractured rock sub-soils (pH water 5.7–6.8). Topsoil organic matter averages 1.5%. No lime has been spread on the property, and little lime has been applied in the district to date.

46.3 Early Years: System Structure, Enterprises and Management

Clearing of the native vegetation of eucalypt trees and scrub bushes started in the 1860s. Originally sheep grazing was the main land use but, since the 1950s, the area cropped has risen from 25% to 35% of the district. A combination of phosphate fertiliser, the trace element molybdenum and subterranean clover has enabled these originally infertile soils to grow improved pastures and crops.

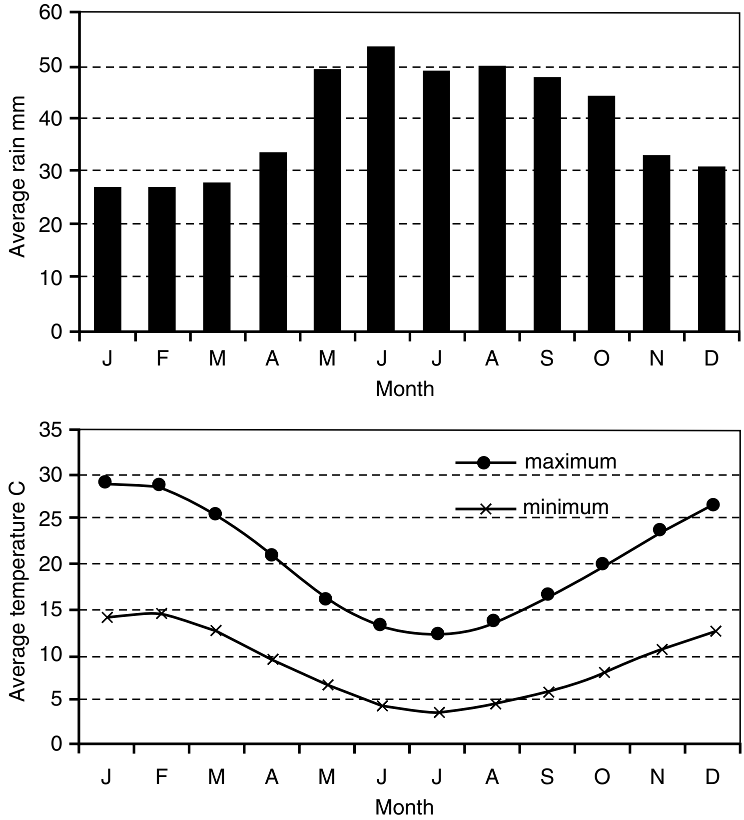

Fig. 46.2 The average monthly rainfall for Wedderburn and minimum and maximum temperatures for the area (Drawn from Bureau of Meteorology Data)

'Mixed farming' of crops and sheep is still the main land use; several years of crop are followed by several years of grazed pasture. Twenty-five years ago the main crops were wheat and oats and the main pasture species were subterranean clover[1], annual ryegrass, volunteer grasses and the perennial grass phalaris. The sheep enterprise was (as for many years previously) a self-replacing flock of Merino sheep with 80% of the income from wool and 20% from the sale of adult sheep.

Challenges of the traditional farming system included the variability of crop yields (especially with traditional cultivation) and winter water-logging. Until the early 1980s, up to ten soil workings to control weeds, prepare a seedbed, incorporate residual herbicides and conserve moisture were commonly used in growing crops throughout northern Victoria. These practices are now known to have caused

[1] See Glossary for botanical names.

a slow but steady decline in soil organic matter and structure that ultimately led to poorer crops and, in the worst cases, complete crop emergence failure. The reduction in cultivation in the district that started at this time was made possible by the new knockdown and soil residual herbicides.

The main challenge to the sheep enterprise was the short annual pasture growing season, with sufficient green pasture to feed sheep for only 4–6 months per year. This short growing season suited wool growing but was not adequate for reliable prime lamb production. Over the last 25 years, the farming system has evolved to meet these challenges. In particular, the Pooles have: (1) effectively replaced their annual pastures with a mix of rainfed lucerne and annual pastures, (2) used no-till cropping techniques with stubble retention, (3) introduced barley and lupins as crops and (4) changed the sheep flock from a wool emphasis to a dual-purpose meat and wool flock. Stephen summarises the purpose of the changes as being to: (1) intensify production to offset the declining terms of trade, (2) minimise the risk by having three reliable income streams—grains, meat and wool, (3) reduce winter water-logging from saturated subsoils, which are effectively dried out by the deep-rooting lucerne, and (4) capture the previously lost opportunity of using summer rainfall. Seasonal rainfall variability also continues to be a key driver for a change to the farming system. From 1950 to 1996, a series of wet winters and the resulting water-logging severely limited crop yields. Then from 1997 to 2007, a series of very dry growing seasons severely reduced crop yields, although rain storms over the following summer months often gave sufficient lucerne growth to finish prime lambs on the lucerne pasture. This confirmed to Stephen that his introduction of lucerne to the farming system had made the farm more financially resilient to the highly variable seasons (Fig. 46.3).

46.4 The Pathways Chosen by the Owners/Managers to Maintain or Improve Their System

Reduced cultivation started in the 1980s and direct drilling (no-till) began in the 1990s. Stephen started growing lucerne in 1993.

Winter-active to highly winter-active lucerne varieties are preferred because of their better winter growth. Stephen has noticed that lucerne dries out waterlogged soils, enabling more reliable cropping. “Before lucerne, winter waterlogging was our major constraint to cropping, especially in very wet winters with conventional cultivation. In some years, summer rain ruined the dry pasture and made the water-logging problem worse next winter.” The sheep enterprise has changed from a wool focus to a dual-purpose meat and wool flock to utilise the high-quality sheep nutrition provided by lucerne after annual pastures have died off.

With the introduction of lucerne and new crops, the rotation system had to be changed. A typical crop–pasture rotation sequence for the traditional annual pasture and current lucerne rotation is shown in Table 46.1. The drivers of the new rotation

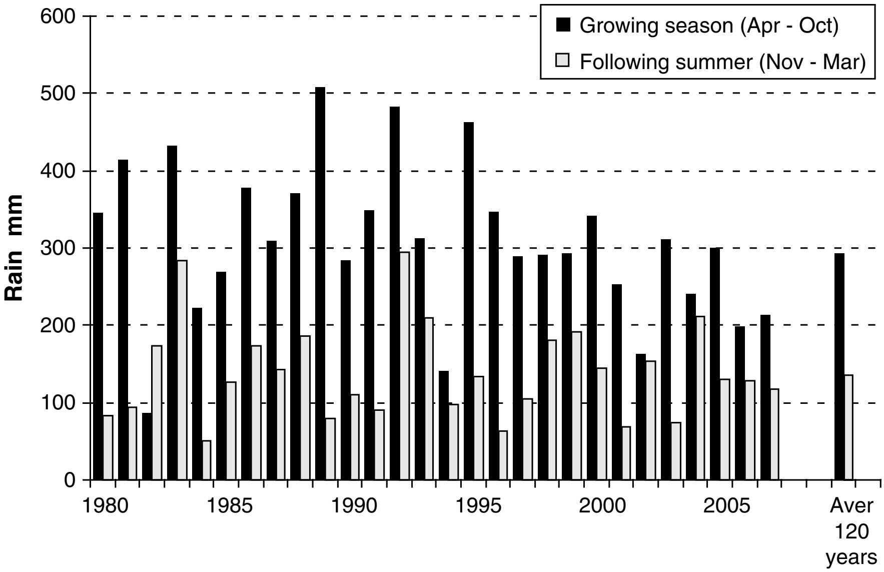

Fig. 46.3 The growing season (April–October) and following summer (November–March) rainfall totals at Wedderburn from 1980 to 2007 (Bureau of Meteorology). It was winter water-logging in the early years, very dry crop growing seasons in the later years and the occurrence of significant summer rainfall that have heavily influenced the continual development of a farming system that is resilient to the highly variable climate

Table 46.1 A typical paddock rotation sequence of the previous farming system based on crops and annual pastures compared to the new crops–lucerne farming system. Typical crop yields (t/ha) and stocking rates (Dry sheep equivalents—DSE[a]/ha) are shown in brackets. Stocking rate estimates do not include an allowance for crop stubble grazing

Year	Annual pasture rotation	Year	Lucerne pasture rotation
Pasture establishment			
1	Annual pasture sown under oats (2.5 t/ha)	1	Lucerne sown under lupins (1.8 t/ha)
		2	Lucerne intercropped with barley (2.2 t/ha)
Pasture phase			
2–6	Annual pasture—average stocking rate 6.3 DSE/ha	3–5	Lucerne pasture—average stocking rate 9.6 DSE/ha
Crop phase			
7	Wheat (3.2 t/ha)	6–7	Wheat (3.0 t/ha)
			Barley (3.0 t/ha)

[a] See Glossary for details

were: (1) the need for very low cost and reliable lucerne establishment under lupins, (2) the cash flow from intercropping and (3) the desire to grow another cereal (barley) to increase returns and reduce build up of cereal disease.

46.5 Putting It All Together, Managing the Whole

Stephen developed his integrated farming system by keenly seeking new information from farm advisors, specialist agronomists, leading farmers in the region and field days. He finds making changes to the farming system stimulating and has readily passed on his experiences to others.

46.5.1 Lucerne Establishment and Management

Lucerne is normally established by under-sowing in a lupin cover crop. Stephen and his neighbour have successfully established 34 out of 35 paddocks with this method over a 10-year period, which included several droughts. Nearby trials have also shown that lucerne can be more reliably established under grain legumes than under cereal crops. This work found that 60–70% of lucerne seedlings emerging under lupin and pea crops were still alive after 1 year, compared with only 1–7% from under cereal crops. There was no ready explanation for these differences. The main practical problem is controlling broadleaf weeds as the chemical used and tolerated by lupins can adversely affect the young lucerne. Stephen overcomes this problem by sowing in stages. The lupins are sown first, followed by the herbicide application and then the lucerne is sown behind a tyne that partially strips away the layer of herbicide-treated soil. Sowing speed is kept moderate to avoid too much soil disturbance, although some soil falls back into the sowing groove to cover the seed and no harrows are used (Fig. 46.6).

In the year after establishing lucerne under lupins, Stephen prefers to direct-drill barley or wheat into the young, 1-year old lucerne stand, a practice known as intercropping. The intercrop year is a transition from the crop to the lucerne pasture phase. This practice aims to provide higher overall returns, as a 1-year old lucerne pasture has a lower potential stocking rate than a mature lucerne pasture. With intercropping, a knockdown herbicide that controls annual broadleaf weeds and grasses while lucerne survives, is applied prior to cereal crop planting in May. Specialist up-to-date herbicide advice is an important part of the system. The crop sowing is cross directional to the lucerne rows and narrow-knife sowing points are used to avoid damage to the young lucerne stand. Stephen has observed that the lucerne plants develop vigorously in the cereal crop and there has been no change in lucerne plant densities from this practice. The aim is to plant early-finishing cereal grain crops that are harvested before lucerne flowering in mid- to late-December, thus reducing lucerne flower and seed pod contamination of the grain (Fig. 46.4). Post-sowing broadleaf herbicides are applied to control volunteer lupins and other weeds. Stephen believes these chemicals also reduce lucerne vigour and its ability to flower and form pods early in the summer, thus ensuring a high-quality grain sample with low pod contamination. Annual ryegrass is allowed to produce seed in the intercrop year, thus enabling its re-establishment to produce a mixed pasture with lucerne, for the grazing phase.

Fig. 46.4 Intercropped cereal after harvest with lucerne ready for grazing

Stephen believes the 1-year old, 30 cm high, single-stemmed lucerne plants (established under a lupin cover crop) provide less competition to following crops than mature lucerne plants. These single-stemmed plants develop strongly in the cereal crop into multiple-stemmed plants about 60 cm high by crop harvest. He estimates that the crop yield is 25% below a similar crop without lucerne competition. However, he believes this yield reduction is more than offset by a number of advantages. These include: (1) "There is good cash flow from the cereal intercrop when the young lucerne could only support a low stocking rate in its first year." (2) "Intercrop stubble contains green lucerne that provides valuable green feed and huge benefits to prime lambs in December. They are ideal for weaning spring-born lambs and are worm-free." (3) "Under the crop the second year lucerne develops into a strong plant." (4) The cereal crop benefits from the grass-free break and the increase in soil nitrogen under lupins in the previous year; (5) "The intercrop year allows the ryegrass to freely seed and form the grass basis of a mixed pasture for the rest of the pasture phase. This inclusion of grass is particularly important in years with a late start to the growing season which would result in capeweed[2] dominance of the pasture and very poor sub-clover growth" (6) Intercropping is an important part of a mixed farm with income from grains, meat and wool (Fig. 46.4).

Stephen prefers a mixed pasture of 5–15 lucerne plants per square metre, together with sub-clover and annual grasses. "The sub-clover and grasses are vital to providing good winter growth and in summer the dead residues protect the soil" (Fig. 46.5).

[2]See Glossary for botanical name.

Fig. 46.5 Lucerne in a pasture with sub-clover and ryegrass during winter

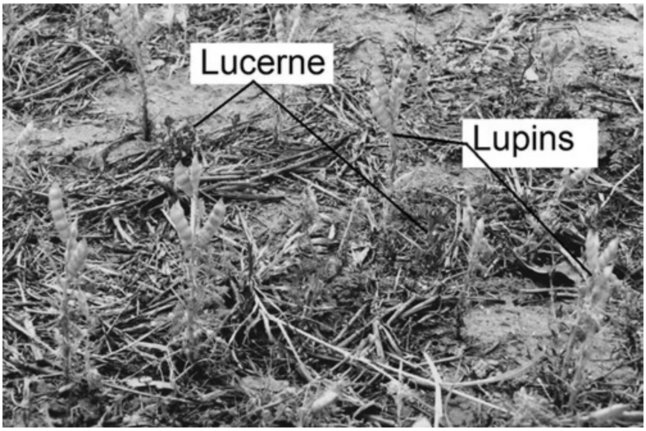

Fig. 46.6 Successful lucerne establishment under lupins in the 2002 drought. Three of the four paddocks established in this way by Stephen and his neighbour under these drought conditions were successful

These mixed pastures are grazed rotationally at very high stocking rates, typically up to 1,000 sheep in paddocks of 20–30 ha for 2–3 weeks, followed by at least a 6-week break. “In summer, the prime lambs are the first to go onto the fresh lucerne to enable rapid weight gains. Merino lambs might follow immediately afterwards. These may then be followed by ewes. After grazing, the paddocks are spelled for 5 to 6 weeks.”

Lucerne removal prior to a new cropping cycle starts with a chemical fallow in spring, followed by cultivation after a good rainfall that could be as early as November or as late as February. This is the only cultivation in the whole rotation as all the other crops are direct drilled.

46.5.2 Lucerne and Livestock

With the introduction of lucerne, the livestock enterprise has expanded from 800 self-replacing Merino ewes to include an additional 600 Merino ewes joined to White Suffolk rams. The time of lambing has changed from April–May to early August, so that the feed needs of the sheep and the spring flush of pasture–lucerne growth coincide. Lambing percentages have remained more or less unchanged (Fig. 46.7).

Before the use of lucerne, Merino wethers were sold at 18 months of age, after being shorn twice. Now, as a result of their good growth on lucerne, they are sold at 12–13 months, still with their lamb's teeth, at live weights of about 50 kg (Fig. 46.8). The White Suffolk first-cross prime lambs are usually sold as heavy weights (22–26 kg carcase) at 8 months of age.

The total amount of hand feeding to ewes in autumn and early winter remains unchanged but, as ewe numbers have almost doubled, the amount fed per head has halved. In recent years, additional grain has been used to finish lambs on lucerne in poor rainfall seasons.

In the recent run of dry years and droughts, the ewes have been confined to stock containment areas after the crop stubble has run out of sheep feed. This process protects the soil from wind erosion, allows the lucerne to recover and finish lambs over the summer, and also increases the capacity of the farm to carry more ewes.

Fig. 46.7 Merino ewes in spring on mixed lucerne–annuals pasture

Fig. 46.8 Merino wether lambs, at 1 year of age, but still with lambs' teeth, ready for market in early August 2005. These dual-purpose Merinos have been bred for both fine wool and body weight. They were grown out on lucerne when the stocking pressure was reduced after the first-cross prime lambs were sold. They were then finished by grazing cereal grain crops until the end of crop tillering and then with grain in the last few weeks before market. Our analyses indicated that this practice increased the whole-flock livestock gross margins by about $8/DSE, compared with a traditional Merino flock of ewes and wethers

46.6 Assessment of the Current System

46.6.1 Lifting Profitability with Lucerne

Our economic analysis indicates that the adoption of lucerne increased profitability of the rotation by 63%.

With lucerne in the system, the average crop gross margin decreased from $281/ha to $233/ha (Fig. 46.9a), assuming both long-term yields and 2000–2007 prices. This was a result of lower gross margins associated with the lupin crop and the lower yield of the inter-cropped barley. However, this was partly offset by the increased cropping intensity (29–44%) with lucerne. Cropping intensity is the number of years of crop expressed as a percentage of the total length (in years) of the whole crop–pasture rotation. For example, in the previous crops–annual pasture rotation there were 2 years of crop with 5 years of pasture, a cropping intensity of 2/7ths or 29%.

The average gross margin of the sheep enterprise increased from $78/ha to $221/ha, an increase of over 180% (Fig. 46.9b). This was the result of an increase in stocking rate from 6.3 DSE/ha to 9.6 DSE/ha and a change to a more profitable sheep enterprise from mainly wool to both wool and prime lambs. Assuming 2000–2007 prices, the Merino flock on annual pastures had a gross margin of $18.20/DSE for wool

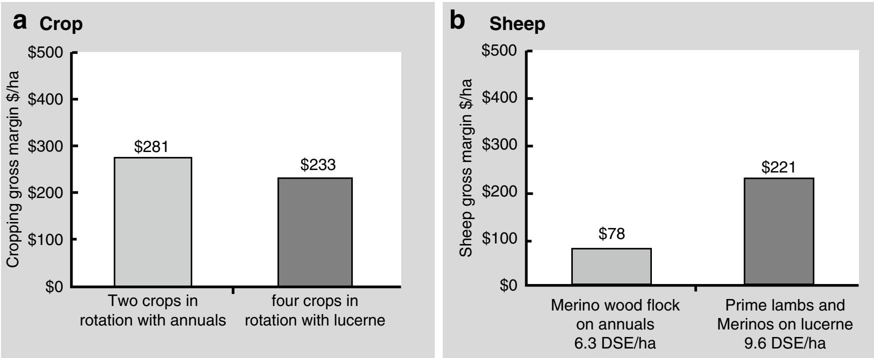

Fig. 46.9 Annual pasture and lucerne average annual gross margins (**a**) cropping and (**b**) sheep

and sheep sales, while the Merino flock selling pure Merino wethers as prime lambs had a gross margin of $26.30/DSE and the Merinos joined to terminal sires (for cross-bred lamb production) had a gross margin of $24.30/DSE.

The analysis of the cumulative net cash flow indicates that there was a consistent positive cash return from making the change from cropping with sub clover to cropping with lucerne. This was because of the low establishment cost of lucerne under lupins, the returns from the lupin crop in the lucerne establishment year and the good returns from the intercropped barley in the year after the lucerne was sown. At the end of the 9-year rotation, the extra cumulative net additional cash flow that was estimated from making the change was $1,035/ha. Some other farms in the study had high lucerne establishment costs and this increased debt took several years to repay from the increased productivity of lucerne.

We estimated the barley intercrop gross margin at $153/ha, which is well below the wheat gross margin of $367/ha. However, this is partly balanced by the grazing value of the green lucerne in the crop stubble and other advantages outlined previously. Even though the intercrop has a reduced gross margin, our analyses indicate it is an important component of a highly profitable system.

Stephen reflects on the change in sheep profitability, "We are now selling $70,000–$80,000's worth of livestock each year, whereas in the old system we were selling only $5,000 to $10,000's worth." Stephen also considers lucerne an important tool to minimise the financial risk of farming; for example, crops were very poor in the 2002 drought but two storms in the following summer–autumn resulted in prime lambs being finished on lucerne and sold for an average price of $101 a head.

Stephen sums it up, "Lucerne gives you a sustainable farming system, a good drought strategy, higher stocking rates, lower risks and good gross margins." When asked about environmental benefits, Stephen replies. "Great for lowering watertables and delaying winter waterlogging. There is a need for grasses to provide feed in autumn–winter and for ground cover in summer, especially after dry spring months."

46.7 Problems and Challenges Remaining and Plans for the Future

The current challenge is the run of 12 dry years where average rainfall has fallen by 25% compared to the previous 50 years. District farmers are debating if this is a normal dry cycle of about 10 years, as has happened in the past or long-term climate change. Management practices that have ‘worked’ in these dry years include no-till cropping and opportunity crop sowing several weeks earlier on a chance shower of rain.

New ideas are constantly being investigated. There is more interest in crops with a winter habit where flowering of early-sown crops is delayed to reduce the risk of frost damage, and also the use of barley that is less susceptible than wheat to frost damage at flowering. Stephen is also considering increasing the area of grain at the expense of sheep. Factors influencing this possible change include: (1) grain prices have increased over the last 2 years, and many market forecasters are indicating this may be a permanent trend, (2) during this same period fertiliser and fuel prices have also increased, while (3) grain yields have been lower due to the dry conditions. In addition, although the price is high, an increasing proportion of the grain grown has been fed back to the sheep, thus foregoing grain income and (4) the benefits to costs ratio of the increased level of grain feeding to sheep have decreased as meat and wool prices have remained stable.

The use of barley for intercropping is being re-examined. In 2004, Stephen intercropped with alternatives such as grazing oats and winter wheats to provide winter feed. “The grazing wheats offer a lot to the mixed farmer. If we can establish wheat crops, graze the early growth and finish lambs on them, and then harvest quality grain without a yield reduction, it is almost too good to be true. We have yet to prove that.”

Stephen is continuing to develop the role of lucerne on his property. He has a developed a preference for the highly winter-active varieties as sub-clover has failed as a pasture legume in the recent dry years. He has introduced South African Merino genetics to increase sheep weights and lambing percentages without compromising the wool returns. The larger Merino wether lambs can be marketed 6 weeks earlier.

Chapter 47
The Jochinke Farm Victoria, Australia

A Case Study of Environmental Adaptation and Evolving Farming Systems Over Three Farming Generations in the Victorian Wimmera, Australia

David Jochinke

Abstract This case describes the evolution of a farm in the Wimmera region of Victoria, Australia over three generations. There has been an increase in the size of the farm and changes in the crops, livestock, rotations and technology, driven by both economic and environmental imperatives. It is an example of the implementation of many of the concepts outlined in earlier chapters.

Keywords Environmental adaption • Stubble retention • Autosteer • Controlled traffic • No-till

47.1 Introduction

In 1950, Albert Victor Jochinke (known as Vic) purchased two 130 ha (320 acres) allotments at Murra Warra located 30 km north of Horsham. Vic was a returned World War II soldier who, with his wife Emily, had previously owned a small farm near the Ebenezer Mission 18 km north of Dimboola.[1] Their son Trevor began working the farm upon his return as a national serviceman in the Vietnam War. He married Elaine and had a daughter Ruth and son David who now operates the farm.

Like many place names throughout Australia, the name Murra Warra is Aboriginal given to the area by the Wotjobaluk tribe meaning ‘place of no water’ which describes the lack of any permanent natural water supply. The original vegetation was of an open grassy nature supporting woodlands of Black Box[2] and Buloke trees and is traditionally considered ideal for annual rainfed cropping and sheep grazing. The area comprises gently undulating to flat plains. The dominant soils are friable, alkaline, calcareous, self-mulching, clay loams which are generally

[1] A town 40 km NW of Horsham and 20 km West of Murra Warra.

[2] *Eucalyptus largiflorens* and *Allocasuarina luehmannii* (Bulloak, Bull sheoak).

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_47,

low in phosphorus and zinc while organic carbon content is less than 1%. Rainfall is winter-dominant with a long-term mean of 410 mm annually, of which 290 mm falls in the growing season.

47.2 The Early Years: First Generation Albert 1950–1970 (259–389 ha, 640–960 Acres)

As a youth Albert, like his father, worked on numerous local farms and learnt most of his formal farming knowledge from his employers. Upon operating his own farm, he adopted the local system of mixed farming, consisting of a 3-year rotation of long fallow–wheat–clover-based pasture and a self-replacing Merino flock for wool. Operating the farm with limited resources was the greatest challenge as machinery was scarce and all farming activities were highly labour intensive. Fields were all adjacent, ranging around 50–100 acres in size. All machinery was powered by two-wheel drive 40 hp tractors while the 9′ (2.7m) combine seeders, 12′ (3.7m) harvesters and 16′ tillage (4.9 m) implements were considered large. Initially wheat was delivered to local rail heads by wagon in hessian bags but was changed to bulk with the purchase of the first trucks.

Tillage was the primary tool to control weeds, capture rainfall and prepare the ‘seed bed’ for the key wheat phase. This tillage method, referred to as a ‘long’ fallow, typically started as soon as the clover varieties in the pasture phase flowered or started to nodulate[3] around August. The process involved 9–11 cultivations over a 10-month period. Wheat sowing was generally delayed until mid- to late-June to avoid damage from late frost and to allow time to kill weeds after the autumn break. Special wheaten or oaten hay varieties were sown around the margins of the wheat crops for baling prior to the grain harvest. This created the outside track which the initially ground-driven, later power take off-driven, harvesters would follow, while assisting to control fence line weeds. Pastures were undersown with the wheat and mainly consisted of ball or woolly clovers[4] which did not contaminate the wool as much as other burr medic varieties.[5]

Burning was commonly used to clean pastures or remove cereal stubbles ready for cultivation. The sheep continuously grazed the pasture phase which often left the fields bare. This process, together with multiple cultivations in the long fallow phase, created hard pans in the heavier clay soils, while increasing risk of wind erosion during summer. Tillage also propagated skeleton weed and hoary cress while wire weed[6] also caused havoc as it blocked up the narrow-spaced, tyned implements. Both skeleton weed and hoary cress were controlled by spot spraying with 2,4-D.

[3] Visual appearance of root-nodule bacteria which biologically fixates atmospheric nitrogen.

[4] *Trifolium glomeratum* and *Trifolium tomentosum.*

[5] *Medicago polymorpha* and *Medicago truncatula* cultivars.

[6] See Glossary for botanical names.

47.3 Changing Practices: Second Generation Trevor 1970–1996 (389–925 ha, 960–2,285 Acres)

Like all farm boys, Trevor constantly helped his parents around the farm and, before being conscripted into the army, he had completed a Diploma of Agriculture at Longerenong Victorian College of Agriculture and Horticulture. The first hydraulic tractor was purchased in the late 1960's and first boom spray in the mid-1970's; both improved efficiencies in labour and dramatically reduced tillage. However, stubble burning and long fallowing continued. Barley was introduced into the cropping rotation following the wheat crop. Most implement wheels were converted from steel to rubber which improved their flotation. The introduction of steel posts and prefabricated wire made erecting fences for livestock quicker and maintenance easier. Increased operating scale was required to lower increasing costs and therefore additional land was purchased in 1972.

When economic returns from wool declined in the 1980's, the Merino ewes were joined to Border Leicester rams to produce first-cross ewes for sale as prime lamb mothers. Diversification of the cropping rotation saw the inclusion of chickpeas to fix additional nitrogen and safflower to help control grass weeds. Canola and sunflowers were also grown if full soil moisture was available before sowing. The increase in crop varieties was accompanied by increased cropping intensity to around 70%. New machinery such as self-propelled harvesters and 150 hp tractors with enclosed cabins increased efficiencies and operator comfort. The early 1990's saw minimum tillage adopted to further reduce the amount of costly cultivation. The combine seeder was converted to handle direct-drill sowing, and slashers were used to lay the stubble residue on the surface, allowing it to decompose. Long fallowing and stubble burning were discontinued in favour of minimum tillage in order to increase soil organic matter content and conserve water stored in the soil. Gradual improvements in both indicators were observed.

47.4 Modern Farming: Third Generation David 1996–Present (925–1995 ha, 2,285–4,930 Acres)

David, like Trevor, completed a Diploma of Agriculture at Longerenong College. He steadily increased direct drilling as seasons became dryer, especially during the critical spring months. As returns from wool continued to decline, the pure Merino wool flock was changed to prime lamb but declining availability of stock water forced a reduction in sheep numbers. Due to drier spring conditions and unfavourable gross margins, canola, chickpeas and safflower were removed from the cropping rotation while lentils and oaten hay were introduced. Additional land was again purchased to gain efficiencies of scale but, due to capital constraints, an increasing amount has been leased. Field sizes also increased, reaching 77–384 ha.

Due to the increased size of the operation and the desire to move towards a no-tillage system, the main tractor was updated to a 300 hp articulated four-wheel drive and an existing 8.8 m-wide chisel plough bar was converted into an air-seeding rig. The bar initially had spring trash harrows attached but, after one season, these were quickly upgraded to press wheels to achieve better seed–soil contact—which improved germination percentage and evenness. A larger combine harvester with better straw handling ability and yield-monitoring equipment was also acquired; this allowed the no-till values of one-pass cropping and full standing stubble retention to be adopted. Visual GPS guidance was first introduced in the early 2000's on the wider 32.5 m boom spray equipment, which prevented overlapping while giving more flexibility for accurate night application. The introduction of full 2 cm accuracy auto steer provided the ability to sow inter-row while maximising machinery efficiency and reducing operator fatigue.

47.5 Putting It All Together for Managing the Farm System

Striving to gain greater efficiencies has been the objective of changing the farming system and adopting different techniques throughout the three generations. The most significant changes have been the evolution in tillage and stubble management practices, along with increasing crop diversity and mechanisation. Drivers of these changes have been both economic and environmental as profitability in increasingly dry seasonal conditions has become more difficult. Dry sowing of crops begins in late April, reducing compaction from machinery and livestock, and retaining standing stubble are all aimed at maximising available soil water for crops.

The path to reduced tillage has shifted weed management from assisting crops to compete with weeds by using narrow-row spacing and high seeding rates, to an increased reliance on herbicides. The obvious negative aspect of this is the increased management needed to be vigilant against selection pressure for herbicide resistance and the cost of chemicals. The removal of tillage and adoption of stubble retention has resulted in a reduction of early nitrogen mineralisation from organic release. Removal of stubble by grazing has also decreased as sheep grazing is less intensive in the larger fields.

The change in cereal stubble management from burning to mulching to being left standing upright has been achieved with seeding machinery that has good trash clearance and residue handling ability with wider row spacing (out to 12 in. or 30.5 cm). Stubble management begins at harvest as straw height needs to be optimal while the residue from the header is chopped and spread. Soil disturbance is reduced with narrow points and fewer tynes, which also requires less horse power. The results from the stubble retention and associated reduction in tillage are seen in improved soil structure, almost doubling of soil organic carbon (an average increase of 0.8–1.4 over numerous fields) and reduced risk of wind erosion over summer. An increase in available water has also been observed, along with more moderate soil temperatures compared to bare fields, as the stubble both reduces evaporation and shades the soil surface.

Maintaining the sowing groove and improving seed–soil contact with press wheels has directed rainfall towards the seed. Water Use Efficiency has also increased with barley reaching 21 kg/ha/mm from an average of 16 kg/ha/mm. David attributes this result to a mixture of increased plant efficiencies in drier seasons, earlier time of sowing, reduced presence of root and foliar diseases and overall improved farming system management.

Auto steer technology has allowed lentils to be sown inter-row between the previous standing cereal stubble, which acts as a trellis to prevent lodging and improves harvestability. The key to adopting this farming system is having accurate and repeatable auto steer on the sowing machinery.

Wool production has been greatly reduced by the shift to increased cropping intensity, larger fields and current low economic return of livestock enterprises. However, a section on the farm has been left with smaller fields and annual feedlotting of purchased prime store lambs still continues.

During the evolution of this farm system, information has actively been sought, initially solely from governmental sources, but changing to the current heavy reliance on private consultants. With deregulated marketing exposing producers to a volatile global supply chain, increasing investment in on-farm storage and market advice are both critical management tools.

47.6 Looking to the Future

Over the past 60 years, most of the changes on the farm have been driven by the availability and adoption of new technologies, leading to increases in efficiencies of use of inputs and labour. Chemical herbicides and GPS auto-steer have provided the critical tools to adopt and continually improve the no-till farming system. Adapting to the changing climate will continue, and some potential changes to the current farm system are being investigated.

Some potential mechanical changes to the sowing operation include fitting auto steer to the air seeder bar to reduce tracking errors from draw bar hitch points and implement crabbing.[7] Improving the seeder tracking is a simple add-on to the system already installed on the tractor that would improve row straightness. This in turn provides greater precision of input placement.

Controlled traffic is another logical step being investigated that involves all equipment wheel spacings being matched by multiples of a set implement width. The promoters of this system assume all operations generate limited compaction. However, a more appealing benefit of the system is the ability to confine harvest chaff onto the defined wheel tracks, in contrast to broadcasting problem weed seeds. This would assist in managing both current and possible new weeds by using

[7] A term which describes undesired off-centre tracking of an implement caused by contrasting soil textures at opposing sides creating leverage resulting in crab-like sideways movement.

the track as a defined control area, which is not too dissimilar to the old technique of using defined hay margins to control fence line weeds.

As increased knowledge is gathered about soil attributes and the effects on yield, site-specific crop management would be confidently adopted. This will require strategic soil sampling to 'truth' soil and yield correlations. Additional equipment such as on-the-go protein mapping during harvest operations and using reflected light patterns from chlorophyll to map and control weed populations during spraying will provide additional management data. Information from satellite imagery along with air-borne remote sensing that monitors crop health and assists in detecting disease and pests will further support site specific crop management. The increase in digital data recording will potentially make traceability of produce an easy process using automatically generated information. Product identification can be provided through application and operation records which may provide premiums but more likely greater access to markets. However managing all of this information in a meaningful way to apply site specific crop management will require integrated data systems. The downside to all this digital technology is the complexity of electronic systems that will be installed into the various farm machines. Breakdowns and troubleshooting will require appropriate after-sales support, especially in the climatic extremes of Australian farming.

Global climate change will be a significant factor in future even if only through government carbon policy. There is no doubt that the farming system has evolved during a significant shift in seasonal climatic conditions; however, how it adapts to national government policy will depend on how much international compliance varies. Policy regarding agriculture production trading may also leave farmers exposed to volatile and sometimes irrational markets. Marketing of produce has become as important as actual production and tools such as non-physical contracts and grain storage need to be constantly reviewed. As terms of trade are tightening operating margins, mistakes in this area are very costly.

Access to improved genetics especially for drought and frost tolerance in plants will greatly assist the farming system. Any improvements in disease and insect resistance which lowers production costs will also be beneficial so long as the technology costs are not restrictive or reduce commodity prices.

All of these future challenges will revolve around building the personal skills and confidence to operate such farming systems in increasingly complex situations. The farm business will continue to draw on external sources of information and expertise to develop and operate the farming system so as to turn increased efficiencies and soil health into reliable, long term, productivity.

Preparation and timing of operations are seen as the two biggest elements to this farming system where soil is considered the biggest asset and available water the largest limiting factor. Making the right decisions to manage the system risks is the greatest challenge.

Chapter 48
The Halford Farm Saskatchewan, Canada

Thirty Years of No-Till at Indian Head, Saskatchewan, Canada

Jim Halford

Abstract 2008 was the thirtieth year of using no-tillage for Jim Halford. Since implementing no-till in 1979, all wind and water erosion has been prevented, especially on the sloping hillsides previously ravaged by water erosion. A hundred years of conventional tillage had reduced organic matter by 30%, but 20 years of no-tillage built it back to 90% of that of the native soils and doubled the mineralisable nitrogen compared to the conventional tillage soils. In 24 hours, water infiltration into already saturated soil was 3.6 mm for conventional tillage soil, 8.6 mm for native soil and 11.2 mm for 20-year no-till soil. Yields of spring wheat and canola are about 40% higher on improved long-term (20+ year) no-till land as compared to short-term no-till on previous conventional tillage land for the same level of all inputs. Band placement of all the crop's fertiliser needs below and to the side of the seed at planting provides optimum fertiliser use. The Halford family owns Vale Farms Ltd. which conceived, developed, tested, manufactured and sold the Conserva Pak® seeder starting in 1983; the technology was purchased by John Deere™ in 2007.

Keywords No-till • Conserva Pak® seeder

48.1 Starting Point

The Halford farm is located south east of Indian Head, Saskatchewan, Canada. This is about 45 miles straight east of Regina, Saskatchewan.

The principal farm of 65 ha (160 acres) was first homesteaded[1] by Jim Halford's grandfather in 1890. He worked off the farm on the nearby Indian Reservation

[1] Homesteading was a process by which people could take up 'vacant' land under a government act, provided they made certain improvements within a specified time (proving up).

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_48,

while slowly 'proving up' his homestead. Jim Halford's father, William and mother Alison, continued the mixed cereal grain and livestock operation (pure-bred beef cattle, hogs and chickens) until they retired in 1966.

Jim attended the University of Saskatchewan, College of Agriculture and received a Bachelor of Science and Master of Science in Agricultural Economics, and started farming in 1962 while still attending university. In 1976, he studied agriculture in the United Kingdom on a Nuffield Farming Scholarship.

The farm had beef cattle, cereals and oilseeds until 1984 when, due to time constraints, the cattle operation was terminated and greater attention was given to developing the Conserva Pak® no-till Seeder (more details later).

Chris Halford, Jim's youngest son, is the main farm operator today; he has been involved with the farm for several years as well as being Operations Manager at Vale Farms Ltd., which manufactures the Conserva Pak® Seeder.

The Halford farm currently consists of 1,175 ha with 810 arable. The non-arable land is leased for pasture and hay production to other farms.

Jim Halford and his wife Dayle Bowman and Chris and Jackie Halford represent the third and fourth generation of Halford farmers.

48.1.1 Climate and Soil

Rainfall: The mean annual precipitation, including snow, is 400–425 mm (16–17 in.) per year. Mean growing season (April 1–September 1) rainfall is 225 mm, but it can vary from 100 to 375 mm.

Moisture stored in the soil from previous fall rains (September–November) and infiltration of snow melt (March–April) is of key importance in determining crop yield. The depth of moist soil at the start of planting has varied from 150 to 1,200 mm.

Temperatures: The normal frost-free period is approximately June 9–September 9. Hence, most crops have to go from planting to maturity in less than 100 days. Typical planting time is in May with harvest in late August or September.

Frost is an ever-present threat and is of greater concern when crop maturity is slowed by a cool and/or damp July and August. In 2004, a serious frost of about −8°C on August 20 affected nearly all crops in the area. Frost damage in the spring is of less concern as most early growth can withstand a few degrees of frost.

Soil conditions: The Halford farm is located in and around the Red Fox Valley. This is a glacier-formed drainage zone with a depth at the farm of about 45 m (150 ft). This has created a valley about a half mile wide with some sloping hill fields and a valley bottom. A creek wanders through the centre of the valley, flowing mainly during spring thaw (April–July).

The soils in the valley fields vary greatly from light sandy soil, to light loam to low-lying boggy areas near the creek. Topsoil or A horizon is typically 5–15 cm deep. The main farming areas on the top of the valley have a light loam soil normally containing 50% sand and limited clay. Some of the hillside ground is too steep to farm and is largely covered by trees and native grasses.

Table 48.1 2002 soil analysis (nutrients measured in kg/ha for 0–30 cm)

Factor	Long-term no-till	Short-term no-till
Number years in no till	20+	2
Soil test NO_3-N	55	41
Soil test PO_4-P	60	25
Soil test K	895	1,200
Soil test SO_4-S	73	69
Soil pH	7.9	8.0
Salinity rating	Non-saline	Non-saline
Target N levels for 2.8 t/ha spring wheat (kg/ha)	39–50	50–63
Soil texture	Clay loam (50% sand 16% clay)	Clay loam (50% sand 16% clay)

The results of a 2002 soil analysis from land at the top of the valley (Table 48.1) come from a research area that has compared the effects of no-till over the long-term (more than 20 years) and the short-term (2 years). (Crop Trial Research results will be discussed later.)

Other features of the soil include:

- Numerous small to large stones.
- The soil profile can store about 15 cm of water in a depth of 1.2 m.
- Drainage is generally good, but some low-lying sloughs or potholes can fill with water at spring snow melt when the ground is frozen.
- There is some salinity on parts of the farm caused by high below-ground water pressure, these areas have been reduced with no-tillage. This is because growing a crop each year keeps soil moisture and salts under control. Also, the no till system has better surface moisture which assists initial plant establishment.
- The soil organic matter content of the original native soil was about 5%, but this had been halved after 100 years of tillage. With no-tillage for 20+ years, some of the soils are again close to 5%.

48.2 Early Years: System, Structure, Enterprise and Management

The following will cover the period of farm management control by Jim Halford from 1962 to 1979.

Jim Halford started farming in 1962 with cereal (wheat, barley and oats) on a half section (320 acres/130 ha) while his father produced cereals on another full section (260/ha). In 1966, Jim took over full ownership and management and expanded the total acreage by purchase and lease until 1979. A 40-cow beef cattle herd was also added in the late 1960s to use the farm's area of native pasture and hay, with extra chaff and straw from the cereal production. It was discontinued in 1984 so that more time could be devoted to development of the Conserva Pak® seeder.

During this period, pedigree seed of cereals and grass was grown. All cropping was done using limited tillage with a Morris Seedrite hoe drill with an attached rod weeder.[2] All fertiliser was applied at seeding in the seed zone; this did not exceed 28 kg/ha (25 lb/acre) of nitrogen (N).

48.2.1 Positive Aspects of the System

The grain–beef combination used the total farm resources more effectively than crops alone. For example, when the grass seed was harvested the residue was baled to form a key part of the beef cows' winter ration. Chaff was collected behind the combine harvester and fed in the field and winter feed yard to the beef cows. This also served to remove weed seeds and light grain from the combine at harvest. In some instances, crops such as oats and fall rye were planted together and served a dual purpose of grazing and grain production the following year. Manure from the corrals was spread on about 12 ha each year.

48.2.2 Negative Aspects

The early tillage system had some serious negative features including serious potential for wind erosion. However, this erosion could be largely contained by keeping surface residues on the fields and using some narrow fields of crops to limit soil drift from light soils.

The major problem was water erosion on hill sides which could occur on fields being tilled during the summer fallow year, or even on stubble-cropped fields (second year of crop). Serious erosion with gullies 1–1.2 m wide and deep still occurred during a single heavy summer rain, even when surface residues were left by using a single pass of the seed drill with hoe openers and a rod-weeder attached. No-tillage showed that it is the roots of the previous crop that anchor and hold the soil. We also encountered an increase in perennial weeds (quack grass, Canada thistle and sow thistle) and annual weeds (millet, wild oats and buckwheat).

Overall we could not achieve stubble crop yields that were more that 60–70% of the yield of crops after summer fallow, even with much higher inputs for fertiliser and herbicides for weed control. However after initiating no-tillage we realised that we simply had not been able to store and retain sufficient moisture for successful stubble cropping when we were using a tillage-based system.

A final key negative aspect was the cost (money and time) of maintenance and operation of the variety of tillage equipment, including heavy and light duty cultivators, rod-weeders and harrows, as well as the seed drill. Our soil is abrasive with an abundance of stones loosened with continual use of tillage equipment.

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[2] See Glossary for explanation.

48.3 Drivers of Change

The changes in direction of the Halford farm production system began in the 1970s. The key reasons for change were:

1. Ongoing problems with water erosion on hill side fields.
2. The desire to incorporate winter wheat as one of the crops grown. This had to be planted into standing stubble so that snow could be trapped to insulate the crop over winter and prevent winter kill, as well as to conserve water.
3. An initial desire was to reduce the total areas farmed and intensify production on the balance of the area with continuous cropping. We believed continuous cropping would reduce erosion problems on land that would otherwise be in fallow.
4. High cost of inputs, such as fertiliser and fuel, especially in recent years.

48.4 Pathways Chosen

In 1979 we chose to reduce our total crop area and initiate continuous cropping on the balance. We believed we could maintain or increase net income by farming a smaller area but applying more fertiliser on that area. Less total farmland also reduced overall farm debt.

We purchased and used a no-till disk drill, intending to adopt no-tillage. We also introduced oilseed crops (linseed and canola) into the rotation, alternating cereal crops and oilseeds.

We planted about half our farmland using a no-till system (spray the weeds, plant with starter fertiliser and apply the balance of the nitrogen in a separate operation); the remainder of the land was pre-worked and then planted with the same disk drill. In 1980, no-till had a net extra cost, over conventional tillage, of $37/ha ($15/acre) believed to be due to the following:

- We used disk seeding equipment that only allowed starter fertiliser to be mixed with the seed, necessitating a second operation to broadcast or band the balance of the nitrogen requirements of the crop. This machine also proved expensive to maintain.
- The quantity and price of herbicides was high. For example for annual preplanting weed control, Roundup® (360 gm/L) costing about $30.00/L was recommended to be applied at 2.5 L/ha in 110 L (1.0 L/acre with 10 gal of water (45 L) per acre).
- The no-till method gave no increase in grain yield over full tillage.

Thus the pathway chosen in 1979 did not appear to be successful. However, we soon learned that Roundup at half the above rate was as effective as, or better than, the recommended rate, and so could reduce input costs. Over 1979–1982, we became satisfied that the no-till system could be successful and economically viable, provided some changes could be made to the seed drill. We decided to make the changes ourselves, test them initially on our own farm, but eventually market our improved machine.

48.4.1 Development and Evolution of the Conserva Pak® Seeder

The Halford Farm adoption and development of continuous cropping and low-disturbance, one-pass planting systems is closely entwined with the Conserva Pak® Seeder development.

We recognised that the first no-till disk drill purchased in 1979 had several limitations. These can be briefly summarised as:

1. There were no features to allow banded fertiliser placement during planting. All the drill permitted was placement of seed and fertiliser together, thus limiting the fertiliser rate. Most of the nitrogen had to be applied in a separate banding or broadcasting operation, resulting in extra cost and decreased fertiliser efficiency.
2. The disk drill failed to consistently penetrate the residue and/or hard soil to place the seed for optimum germination, despite having up to 180 kg (400 lb) of down pressure per opener.
3. After 3 years and planting an estimated 1,200 ha (3,000 acres), we had to replace the disks and many bearing in the disks and packers because our stony and sandy soils were causing excessive wear. The worn openers caused even greater problems for achieving satisfactory seed placement. Overall, our soils were becoming harder because the disks and packer wheels only provided downward forces and there was no tillage effect to loosen the soil.

We concluded that we needed a seeder that had:

(a) knife or shank type openers;
(b) means to place fertiliser separate from the seed, to allow application of all the crop fertiliser at planting;
(c) a packer wheel depth control for at least the seed placement;
(d) an air delivery system for efficient refilling and application of all the fertiliser at planting. Lack of this facility was a limitation of box drills which varied in their weight from full to empty, thereby affecting depth of seed placement.

We developed the Conserva Pak® Seeder to overcome the problems and provide the desirable features (Fig. 48.1). Key events in the evolution of the Conserva Pak® Seeder to its commercialisation are as follows:

- 1983—the Conserva Pak® was first built and used in the fall on Jim Halford's farm.
- 1983–1989—five prototypes built.
- 1989—the first sale of Conserva Paks® in Western Canada.
- 1993—the first sale of Conserva Paks® in the USA (North Dakota) and Australia (West Australia). At that time, 9 in (230 mm) and 12 in (300 mm) spacings were available.

Fig. 48.1 Conserva Pak® seeder

- 1994–1995—research by Agriculture Canada, Westco Fertilizer and Vale Farms Ltd. proved anhydrous ammonia could be applied in the one pass planting operation.
- 2000—the first hydraulic trip system was introduced and sold extensively in Australia.
- 2005—the first openers using separate hydraulic force for the fertiliser shank and seed opener/packer wheel were sold in Canada, USA and Australia.
- February 2007—John Deere purchased the Conserva Pak® technology (Patents, trademark and designs) from Vale Farms Ltd. Vale Farms Ltd. is owned by the Halford family.

48.4.2 Some Opinions Formed from Experience

48.4.2.1 Disk Vs. Knife Soil Openers

Disk drill systems for planting into undisturbed stubble fields have a limited range of soil conditions in which they work well. Knife openers can deal with a wider range of soil conditions.

48.4.2.2 Cool Soil Conditions

Knife type openers provide an advantage over disk openers when farmers seek to achieve germination and emergence under cool soil conditions. Soil temperature in a knife-opened, black furrow has been measured to be 5°C higher than disk-formed, ‘residue full furrows’. This is very important in Western Canada where we start spring with cool soils and need to get rapid emergence.

48.4.2.3 Winter Canola Establishment and Survival

A 2007/08 trial by Oklahoma State University determined that the Conserva Pak opener provided more consistent planting depth and emergence and up to 50% better stand survival over winter. This trial had 10 side-by-side farmer seeded trials with disk seeders for comparison. It appeared that the disk-planted canola crops had their seed planted in the previous crop ‘residue zone’. Thus fewer seeds germinated and emerged; over winter the canola crop roots tended to dry out and lose vigour and then a significant percentage of the plants died. The Conserva Pak® opener allowed the seed to be placed in ‘mineral soil’, permitting good germination and root development which then improved winter survival. As well, in most cases, the furrows did not have any residue in them.

48.4.2.4 Optimum Fertiliser Placement at Planting

The placement of fertiliser in a band 3–4 in. (7.5–10 cm) deep in the soil, below the level of the seed and 1–1.5 in. (2.5–3.75 cm) to the side is optimum because:

- The crop has close and easy access to the fertiliser.
- This can be the lowest cost method because there is no need for extra field operations, expensive separate banding nor broadcasting equipment.
- A fertiliser knife at 3–4 in. (7.5–10 cm) depth can fracture any tillage hard pan. This will allow new crop roots to readily develop downward rather than be forced sideways.

48.4.3 Requirements for Low-Disturbance Dual Openers

48.4.3.1 Factors Affecting the Potential for Seed Damage from Side-Band Fertiliser Placement

Factors include:

- Crop grown: flax (linseed), canola and field peas are very sensitive to concentrated fertiliser. Wheat is the most tolerant but can be injured if separation from seed is inadequate.
- Soil type: the risk of fertiliser damage is greatest in sandy soils and least in clays. The clay will ‘tie up’ the commercial nutrients better.
- Row spacing: the wider the rows the greater the fertiliser concentration and hence the higher the risk of seed damage.
- Soil moisture level: the drier the soil, the higher the risk; conversely, rain shortly after planting will reduce risk.
- Total fertiliser applied—higher rates produce higher risk.
- Fertiliser type—Anhydrous Ammonia is the most likely to cause seed damage, because the gaseous product tends to escape upward. Thus it requires adequate

horizontal and vertical separation from the seed. As well, the gas needs to be sealed in the soil. Visible ‘puffing’ or vapour escape indicates that the fertiliser is not placed deep enough and/or is not sealed down well enough.

48.4.3.2 Depth of ‘Tillage’ of the Openers

- A deeper knife action will fracture any tillage hard pan. This will improve the ability of crop roots to penetrate deeper in the soil profile and thereby explore more total soil area for moisture and nutrients.
- Tillage action of only 1–2 in. (2.5–5 cm) will reduce the amount of soil mixing as most action will occur primarily in the residue zone. The deeper tillage fosters mixing of surface organic matter with mineral soil and can help deepen the ‘A’ soil horizon over time.
- Generally a depth of 4 in. (10 cm) is the maximum required.

48.4.3.3 Residue Clearance by Knife Openers

- If the tips of knife openers are too vertical or blunt, the opener will ‘bulldoze soil’ rather than lift and roll the soil. If run too shallow, they will only contact high organic matter soil and surface residues which do not flow as readily as mineral soil.
- Deeper knife action with a more angled opener will contact more mineral soil. It will also cause the mineral soil to be lifted and rolled which will assist in moving the lighter weight organic matter and residues. Hence, overall better residue clearance is achieved.

48.4.4 Cropping System Changes on the Halford Farm

This evolution of the whole cropping program involved the adoption of pulse crops (lentils and peas) and normally a 4-year rotation of a cereal crop alternating with a broadleaf crop (oilseeds or pulses). This rotation provided excellent opportunity to control broadleaf weeds during the cereal year, and grassy weed control during the broadleaf crop year. As well, it minimises carryover of those diseases which differ between cereals and broadleaf crops. The economics of this No-Till evolution can be further summarised as follows. In 1980, the continuous cropping no-till/stubble retention system cost an extra $37/ha ($15/acre). By 1990, we estimated that our system produced a net benefit of $62/ha ($25/acre). This huge gain was due to:

- One pass only for fertilising, planting and packing, thus reducing fuel, operating and labour costs.
- An average of 10% higher yields due to extra moisture collected and saved and the improved fertiliser use efficiency.

- An average of $10/acre ($25/ha) lower costs due to reducing the herbicide Roundup, and reducing or eliminating some of the other herbicide applications.
- Much of the gain could be credited to increased fertiliser use efficiency and the start of the benefits of 'free' nutrients accumulating in the organic matter from crop residues.

By the year 2000, we estimated that the net benefits of our low disturbance, one pass (no-till) system were $35/acre ($87/ha). Some of the reasons for further gains were:

- Further improvements in soil quality and the combined benefit of one pass fertilising/planting/packing. The soil was continually becoming easier to work with, and water infiltration was improving.
- The ability to use anhydrous ammonia at planting.
- We estimated yields and protein levels were 12–15% higher than those obtained from continuous cropping with tillage.
- Further reduction in input costs such as Roundup® (glyphosate), and the use of pre-harvest Roundup® to control perennial weeds and hasten dry down of mature plants.

The specific levels of soil improvement and crop performance on our farm are based on research findings.

The agronomic changes to farming and equipment design evolved together. Once the Conserva Pak® was being marketed, an even broader exposure to equipment ideas occurred (carbides, large frame tires and hydraulic force cylinders from Australia and side hill hitch from Pacific Northwest in USA). There have been benefits from the exposure to research, extension and farmer experiences in Western Canada, Australia and USA since 1993. Various agronomic and equipment knowledge was exchanged.

48.5 Putting It All Together

The Halford farm has evolved a simple cropping system. This has been based on technologies developed and available and the need to complete cropping activities quickly, so as to be able to spend more time on the manufacture of seeders. A simple rotation has been followed using oilseeds, cereals and pulses and based on market projections. In recent years, the average yields of canola and field peas have been similar to those of spring wheat. The crops vary in input costs and product prices.

48.5.1 Crop Diversification

We have successfully used forages to improve soils and diversify crop production. It is estimated that 1 year of forages is equivalent to 2 years of annual no-till cropping in the amount that soils will improve. The forages are used to produce hay for sale and/or pasture leased to other farmers to graze their cattle.

We have successfully used the following steps to establish legumes and grasses, or a combination, using no-tillage.

1. Grow a cereal crop the preceding year with good weed control management. Avoid using residual herbicides that could retard the following crops.
2. Establish the forage crops with a canola crop. Reduce the planting rate of canola to a third to a half of the normal planting rate but plant the recommended rate of legumes and/or grass seed. The canola and forage seed can be placed together or separately.
3. Fertiliser can be applied as required to grow a canola crop, plus any required for the forage at planting. Be sure all fertiliser is kept at least 1.5–2 in. (4–5 cm) away from the canola and forage seeds.
4. Weed control by herbicides is possible only if the canola and forage crop are both tolerant.
5. The canola crop is not very competitive so it and the forage can be established together. The forage can establish and then grow slowly under the canola canopy. Once the canola stops growing, the forage will grow rapidly if moisture is available.
6. Harvest the canola crop. Spread the canola straw and chaff to avoid retarding the forage crop growth.

The following steps can achieve maximum benefits from growing an annual crop after forage, without tillage in the Northern Great Plains.

1. Apply glyphosate and other herbicides in mid-August to mid-September to remove the forage; this is when forages are storing food reserves for the next year.
2. Apply further herbicide treatment before planting the next spring.
3. Preferably plant a large-seeded crop such as peas, oats or barley. Small seeds like canola will not have enough fine mineral soil for good germination.
4. If a cereal crop is grown, it will probably require 50% more nitrogen than normal, because nutrients are ‘tied up’ in the organic matter in the first crop year after forages.
5. Control weeds in crop as required.
6. Apply pre-harvest Roundup in August to remove any forage regrowth. (Forages are unlikely to be controlled in just 1 year with a single application of herbicide.)
7. The second annual crop can be canola or another oilseed. If peas were grown in year 1, a cereal could be grown in year 2. (Note: There will probably be a large nitrogen release from the organic matter with the second crop.)
8. Other benefits likely to be realised are:

   - The land may be fairly free of weeds for several years.
   - The soil profile will readily absorb water.
   - The soil will warm up quickly.
   - The overall soil quality will have greatly improved with 4–6 years of forage.

48.5.2 No Till and Residue Management

- Proper planting equipment can handle crop residues from a wheat crop of up to 5.4 t/ha (80 bus/acre) if the residue has been correctly managed at harvest.
- It is better and more economical to improve combine residue management, and to use high residue clearance planting equipment than to harrow fields.

48.5.3 Weed and Disease Control

- Using harrows to spread straw causes more weed seeds to germinate and establish because the harrows help bring weed seeds into contact with soil. Without harrowing, many weed seed will desiccate and/or germinate but not establish, as they are stranded in the residue.
- Uniform and undisturbed spreading of canola residue appears to inhibit future weed seed growth.

48.5.4 Summary of Technologies That Evolved Between 1983 and 2008

1. One-pass fertilising/seed placement and packing (Conserva Pak® Seeder).
2. Reducing rates of Roundup and water volumes and reduced price of Roundup (glyphosate).
3. Use of Roundup in crop as a pre-harvest treatment for weeds and to assist maturity/'dry down' of crops.
4. Use of Anhydrous Ammonia (NH_3) fertiliser at planting. This is a lower cost and convenient option.
5. Development of a multitude of optional herbicides, insecticides and fungicides provide more options for post-emergent crop use than do soil-applied herbicides.
6. Multitude of available G.M canola varieties.
7. Optional harvesting of canola by straight cutting instead of swathing.
8. Successful reduction of canola planting rates from advisory recommended rates of 7–8 kg/ha (6–7 lb/acre) to 3.5 kg/ha (3.0 lb/acre).
9. Expanded management knowledge on various rotations of crops.
10. Proven improvement in soil fertility—from information on mineralisation and availability of N and P as a consequence of increased quality and quantity of organic matter, from the no-till system (See Soil and Crop results from Halford Farm in study by Guy Lafond Lafond et al. 2008).
11. Development of rhizobium inoculants for pulse crops.
12. Development of auto steer systems for tractors.

48.6 Current Situation and Looking to the Future on the Halford Farm

In 2008, the Halford Farm was due to crop about 1,800 acres although the equipment, facilities and management available could handle two to three times this area. The limiting resource is manpower for the actual management and key farm activities due to the concurrent operation of the manufacturing of seeders by Vale Farms Ltd.

In 2008/09, Vale employed 40–50 staff involved in the fabrication and assembly of Conserva Pak® seeders for John Deere. Jim and Chris Halford are both heavily involved in the manufacturing, thus limiting the time they have available for farming.

48.6.1 Results of on Farm Research

In 2001, a unique opportunity to quantify the magnitude of the long-term agronomic and economic benefits of direct seeding presented itself when I leased a field adjacent to my long-term (over 20 years) no-till, continuously cropped area. This field had been managed using a conventional crop–fallow system with conventional tillage (Lafond et al. 2008).

Soil was analysed from the two study areas and the adjacent native prairie. Bulk density in the surface soil (0–15 cm) was much less in the native soil (0.99 g/cm^3) than the farmed areas (both about 1.43 g/cm^3). Potential nitrogen mineralisation, determined using the Hot-KC1 extraction method, was highest for the long-term no-till soil (75% of native soil) and lowest for short-term no-till soil (47% of native). Organic matter is shown in Table 48.2.

The experiment below (Table 48.3) was established with five fertiliser levels in such a way that the same fertiliser treatment was applied to the same plot in each succeeding year, i.e. a plot receiving 30 kg/ha of N received that same 30 kg of N each year. This allows the opportunity to measure the cumulative effects of different fertility levels over time on grain yield, grain protein and residual soil nitrate nitrogen.

All plots were planted with a 12-row Conserva Pak plot seeder with a row spacing of 30 cm, in the first week of May—Spring wheat was planted in 2002, 2004 and 2006, and canola in 2003, 2005 and 2007,

Table 48.2 The effects of time under no-till on soil organic matter content relative to native prairie, for the 0–15 and 15–30 cm soil layers

	0–15 cm depth			15–30 cm depth			
Variable	Native	Long-term	Short-term	Native	Long-term	Short-term	p-value
Organic C t/ha	51.4	46.1	37.0	31.5	20.6	18.6	0.06

Table 48.3 The effect of time under no-till on crop yields and protein in wheat

	Wheat (mean of 3 years)				Canola (mean of 2 years)	
	Grain yield (kg/ha)		Grain protein (%)		Grain yield (kg/ha)	
N rate (kg/ha)	Long-term	Short-term	Long-term	Short-term	Long-term	Short-term
0	2,044	1,401	13.0	11.5	684	408
30	2,306	1,719	13.2	11.8	921	574
60	2,807	2,210	13.5	12.2	1,383	983
90	3,149	2,702	14.2	13.3	1,706	1,424
120	3,225	2,713	14.6	13.9	1,789	1,572

Grain yields increased with increasing application of N. At each N level, yields were considerably higher from the long-term than the short-term no-till plots. A similar trend in differences occurred with grain protein levels. As in wheat, canola grain yields increased with increasing N application and were higher in the long-term no-till area. This trial helped to confirm the value of no-till in raising the production capacity of the soil.

48.6.2 Future Prospects

If manufacturing pressures were to decrease, Chris Halford might increase the area cropped; Jim Halford is now at an age when many persons retire.

48.6.2.1 Potential Changes to Our Farm System

- Increased emphasis on the use of forage crops to further improve the soil. These areas could be used for seed production, hay or grazing.
- Adoption and production of some ‘special crops’. This would provide diversification and potentially greater income.
- The available high capacity and precision planting equipment provides an option for custom (contract) planting under certain conditions. As the optimum planting window is about 3 weeks, late spring weather and/or excessive rainfall can put large farms at risk of not getting their planting done on time.

48.6.2.2 Future Technologies We Hope to See Developed

1. Greater accuracy in determining optimum fertiliser application rates. This would take into account the predicted mineralisation from the organic matter. In addition, the fertiliser would have nutrient-release control to meet the needs of the crop during its full growth cycle.

2. Integration of niche marketing opportunities back to the farm. This would mean production and segregation in the marketing channel. This could produce higher net returns than production of ‘bulk’ common products.
3. Further mechanical and physical control of the total cropping process. Examples are: more control over crop residue distribution behind combines, greater accuracy in seed metering (lower seed rates), fertiliser control and precise herbicide management.

These may all be only small gains but would collectively enhance the quantity and quality of output and net returns. It is unlikely that any one new practice will achieve the leap forward in crop production and soil sustainability that low-disturbance, one-pass fertilising/planting and packing have achieved!

Reference

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Chapter 49
Four Farms in the USA

Case Studies of Northeastern, Southeastern, Great Plains and Midwestern Farms

Alan Franzluebbers

Abstract Four case studies are presented that illustrate some of the regions discussed in Chap. 20. These farmers have made technological changes to increase their competitiveness in the marketplace and increase their sustainability in terms of the economic, production, and environmental issues they faced. The four case studies describe approaches to farm systems which feature: (1) integrated cover cropping and conservation tillage in Pennsylvania, (2) self-developed conservation tillage in Georgia, (3) strip-cropping of corn and soybean with conservation tillage and satellite-guided equipment controls in Iowa, and (4) integrated crop–livestock with conservation tillage and crop rotation in North Dakota. Case studies describe the need for change, the drivers of change, and the unique pathways of change adopted on these farms. These working examples of conservation agriculture in the USA will provide hope for other farmers trying to increase agricultural sustainability, will challenge research and extension professionals to further refine conservation agricultural strategies, and will give government policy makers ground-truthed information to encourage sustainable land stewardship around the world.

Keywords Conservation agriculture • No-till • Innovation • Farm management

49.1 Introduction

The four farms, whose locations are shown in Fig. 49.1, are examples of leading farms in the regions discussed in Chap. 20.

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_49,

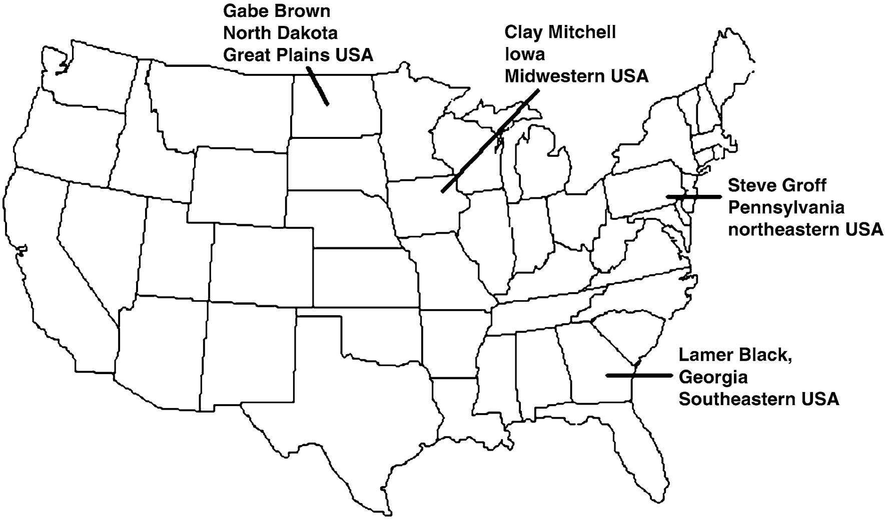

Fig. 49.1 Map indicating location of the four case study farms

49.2 Steve Groff—Northeastern USA

In the historically rich and agriculturally fertile region of south-eastern Pennsylvania USA (Fig. 49.1), Steve Groff has become a pioneer for modern sustainable management practices. While soil is being washed away with frequent heavy rains on neighbouring fields, Steve Groff has protected his fields from erosion by abandoning tillage and planting cover crops—while still producing abundant vegetables and field crops for sale. Steve Groff and his family have meticulously developed innovative small-farm approaches to stop erosion, build soil quality, and create a sustainable farming environment. This is a story of resource-efficient farming practices, combining old and new concepts to achieve conservation and profitability goals, all within a cultural setting rich in tradition.

49.2.1 Background

Steve Groff (Fig. 49.2) owns and operates Cedar Meadow Farm in Lancaster County Pennsylvania. He is the third generation on the farm, working closely with his father, Elias, who owns a neighbouring farm. Vegetables and crops are grown on 80 ha of hilly land in what many consider the most agriculturally productive non-irrigated county in the USA. Lancaster County is composed mainly of highly traditional farmers, descendants of Amish and Mennonite immigrants from Europe,

Fig. 49.2 Steve Groff

who started cultivating this area some 250 years ago. Close association to the Earth and its resources are part of the cultural heritage of farmers in the area. But despite this association, some traditional practices have allowed soil erosion to slowly wash away the rich inherent fertility of the land.

Steve has pioneered the ‘Permanent Cover Cropping System’, which combines no tillage, cover crops, and effective crop rotations as a way to increase profits, enhance soil and water quality, and reduce pesticide applications. The development of this system that maintains continuous soil cover and minimises soil disturbance is described below.

Steve grows corn, soybean, alfalfa, tomatoes, pumpkins, and small grains on his farm—all without tillage. He was the first vegetable grower in Pennsylvania to use a mechanised no-till vegetable transplanter on a large scale.

49.2.2 Environmental Conditions

Climatic conditions (Fig. 49.3) are nearly ideal for many spring and summer crops. Surplus precipitation occurs during the winter and early spring, while a moisture deficit can occur in summer months. Soil is often frozen from December to February.

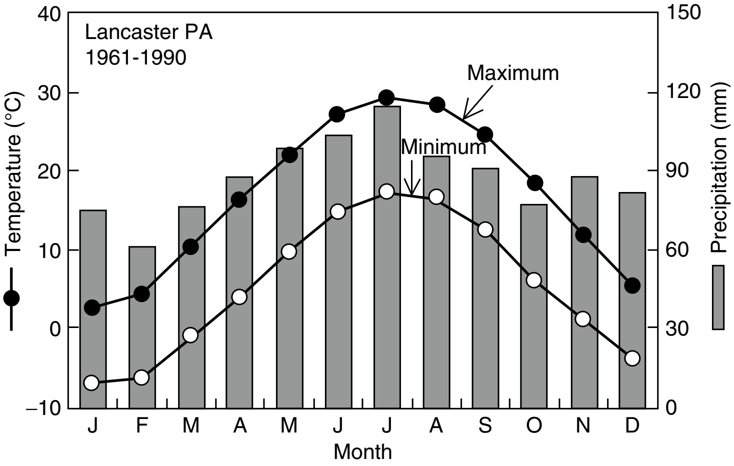

Fig. 49.3 Mean monthly climatic conditions in Lancaster PA (40.05°N, 76.28°W, 82 m above sea level). Mean annual temperature is 10.9°C and mean annual precipitation is 1,047 mm (National Climatic Data Center, 1961–1990)

Soil on the farm is mostly Hagerstown silt loam (fine, mixed, semi-active, mesic Typic Hapludalfs[1]). This soil is very deep, well-drained, and moderately permeable, with moderate to rapid runoff. Slopes are generally less than 15%.

49.2.3 Early Years

Steve Groff took over farming operations on his grandfather's farm in 1988. Ever since he graduated from high school in 1982, he has kept records about the condition of soil on the farm. While in school, he recognised that soil erosion simply could not continue on the farm for it to be considered sustainable. His father began farming on the contour in 1963 to control erosion, but gulleys still developed. In an effort to try something new to control soil erosion, Steve rented a no-till corn planter from the Lancaster County Conservation District.

49.2.4 Drivers of Change

Steve Groff has stated, "Some of my fields have not been tilled in any fashion for about 15 years. The reason I got away from ploughing the soil was because I saw

[1] This chapter uses the US soil classification—see http://soils.usda.gov/.

too much soil erosion. My soil was washing away when we had rain and, since soil is my number one asset, I want to try to manage it in such a way to keep my soil in place." In an interview with Public Broadcasting Service,[2] Steve also stated, "The other thing that the cover crops have done for us is to enable us to reduce insecticide and fungicide use in our vegetable crops. We've done some comparisons of conventional versus no-till tomatoes and, on our farm, we've got about a 10 percent yield increase using no-till. And we've been able to consistently get increased yields consistently ever since. I'm the third generation on this farm and I'm really proud of that, to be able to continue on the tradition of agriculture that has been in our family. And my mission or my goal in life, in regards to farming, is to be able to leave the soil in better condition than when I found it."

49.2.5 Pathways of Change

Steve Groff began farming with no tillage in the early 1980s in a 6-ha field of corn. Within a few years, he took note of the soil improvements that occurred. Today, all of his land is planted without tillage, and fields have been cropped for 25 years without tillage. Those following pasture have been without tillage for even longer. With further research into soil conservation approaches, Steve added cover crops[3] to his list of conservation practices. With cover crops, crop rotation, and long-term no-tillage, total cost of pesticides declined from $80/ha to $42/ha. Initial costs of cover crop seed and establishment can be significant, but these are eventually offset by contributions from nitrogen fixed by legumes, reduction in soil erosion, and better soil tilth. Other benefits attributed to this conservation approach include better water infiltration, greater resistance to soil compaction, better harvesting conditions, and improved soil fertility.

49.2.6 Managing the System

Steve uses a customised Kinze no-till planter with Monosem row units to plant sweet corn, field corn, and pumpkins. This machine has Rawson coulters, Kinze row cleaners, Yetter parallel linkage, Case IH depth wheels, Martin spading closing wheels, Keeton seed firmers and foam markers.

When planting early into heavy cover, he uses a 5-cm-wide, eight wave coulter on either side of the row to clean the row so that the soil can dry and warm quicker. This is essentially a zone-till[4] setup. Later in the spring, he changes the coulters

[2] www.pbs.org/journeytoplanetearth/hope/lancaster.html.

[3] See Glossary for definition.

[4] The indirect loosening of an area of soil between two coulter blades which are stagger mounted on either side of a planter row.

Fig. 49.4 Planting tomatoes with the no-till planter

to a 2.5-cm-wide 13 wave style. He typically applies 90 kg N/ha on the row (or 45 kg N/ha on each side) and 6 L/ha of popup fertiliser[5] in the seed trench.

Cover crops are planted with a John Deere 1560 no-till drill. Steve has replaced the 2.5-cm-wide John Deere seed press wheels with 1.6-cm-wide Case IH press wheels. The narrower wheel has allowed much better pressing of seeds at the bottom of the trench. With a good, thick mulch cover, he has sometimes been able to eliminate herbicide applications during the summer. This system has potential for organic growers when a heavy cover is achieved.

Vegetables, such as tomatoes, are planted without tillage using an RJ Equipment carousel transplanter into killed cover crops (Fig. 49.4). This transplanter has a spring-loaded 50-cm-diameter turbo coulter, followed by a double disk opener and a short shoe to place the transplant into. Angled press wheels tuck the soil firmly around the plant. The package leaves virtually no soil showing after the crop is planted, giving good, full coverage mulch for the whole season.

Fertiliser management has evolved with time during his experience with no tillage and types of cover crops. Steve typically applies ammonium sulfate a few weeks after planting. Foliar feeding is practiced as well.

In driveways, soil can become compacted from repeated traffic during harvest. Steve uses a ripper/stripper to loosen soil in these areas (Fig. 49.5a). He customised a 2-shank Unverferth ripper/stripper, which has a 2-cm-wide shank that penetrates 30-cm deep and has a 5-cm-wide wavy coulter on either side of the shank. This keeps soil from being thrown away from the shank and chops it up a bit. A 30-cm-wide

[5] See Glossary for definition.

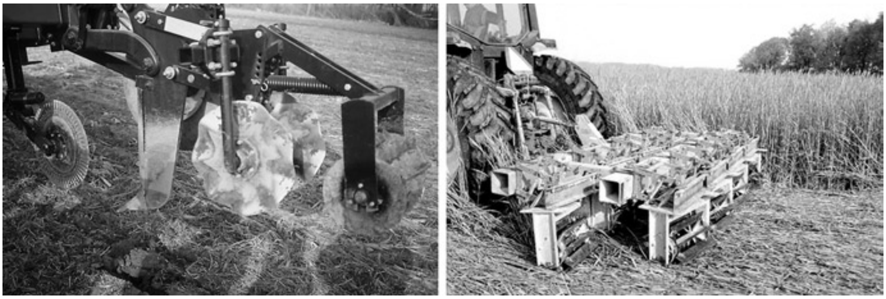

Fig. 49.5 *Left*: Riper stripper unit; *right*: Rolling cover crop

rolling basket follows to further break up clods. He has been able to plant behind this operation without need for further soil preparation.

Steve has modified a Buffalo Rolling Stalk Chopper to mechanically kill cover crops (Fig. 49.5b). The machine has two rows of rollers, four in front and four in back, with eight 58-cm-long blades per roller. The blades crimp the cover crop stem and push it down to the ground, but do not cut the stem. The roller can be operated at 13–16 km/h—fast and economical. He added parallel linkage so each roller floats independently. The versatile machine has been used on more than 500 ha in 8 years.

Controlling perennial weeds can be a challenge, but Steve has observed that intensive crop rotation and occasional spot spraying are effective in controlling difficult weeds. He warns that one cannot count on a cover crop to eliminate weed such as thistles, bindweed and hemp dogbane.

The quality of soil on the (*Convolvulaceae*) farm has greatly (*Apocynum cannabinum*) improved with the planting of carbon-building cover crops and not tilling the soil. Steve was convinced early in his adoption of this conservation approach that these changes would occur. With the collaboration of Dr. Ray Weil at the University of Maryland, these changes in soil quality have been verified. Figure 49.6 shows that soil bulk density has actually decreased with time under no tillage, rather than increased. Some farmers perceive that tillage is necessary to avoid compaction. However, the accumulation of soil organic matter at the soil surface actually buffers the impact of traffic and provides a soft medium for roots to penetrate. Along with an increase in soil organic matter, aggregate stability and microbial biomass carbon have increased. Higher aggregate stability keeps soil from falling apart during heavy rains, thereby keeping soil pores open for water to infiltrate into the soil profile where roots can have access. An increase in microbial biomass carbon suggests that nutrient cycling is being enhanced and that soil has become more living in response to preservation of crop residues at the soil surface.

In other collaboration with Dr. Weil at the University of Maryland, corn yield data were collected from plots established under different conditions in 1999. Corn yield under short-term no-tillage (<10 years) was 4.8 t/ha and under long-term no tillage (>10 years) was 6.8 t/ha. When no cover crop was grown before corn, corn grain yield was 0.2–0.6 t/ha lower than when hairy vetch and rye was a cover crop.

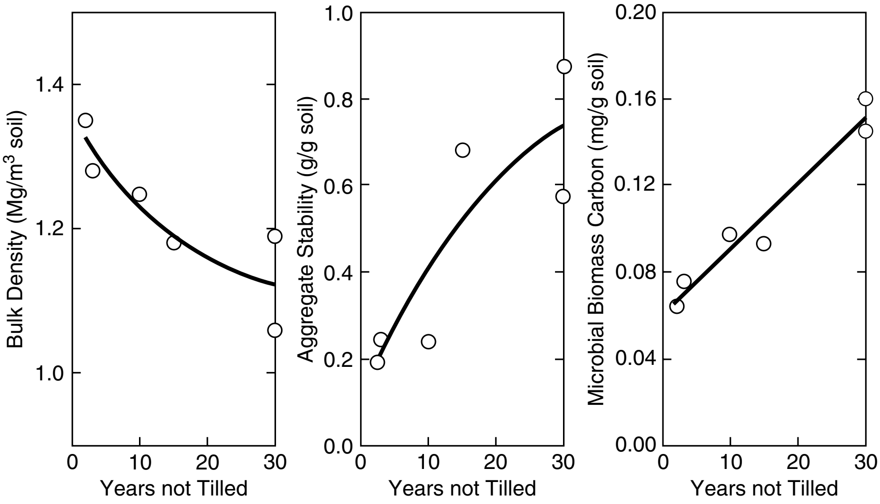

Fig. 49.6 Change in soil characteristic over time with no-till

The benefits of cover crops are:

- Erosion control
- Increased organic matter (although this is negated if you aggressively till it in)
- Removing excessive soil moisture in the spring
- Keeping soil cooler during a hot summer if left on top.

Some challenges with cover crops are:

- Soil stays cooler in spring
- Soil dries out in spring
- Finding time to establish them
- Planting into them without the proper equipment.

Steve has made some calculations on economics of cover crops. He has factored in the extra cost for cover cropping and is sure the benefits of increased organic matter and biological activity, together with reduced erosion and better infiltration, offset the investment cost. Steve has experimented with the following cover crops: (1) fall/winter cover crops [rye, vetch, spring oat (winter kills[6]), triticale (spring triticale winter kills)]; (2) summer cover crops (sudax, German millet[7]); and (3) spring cover crops (oat, spring triticale, field pea).

These are the covers Steve has found to be useful on his farm. There are many more options out there that might be better for other environments or conditions.

[6] Once grown cover crops are chemically or mechanically killed to provide a no-till mulch.

[7] See Glossary for botanical names.

He prefers 100 kg/ha of spring oat planted as soon in the spring as possible. He even plants onto slightly frozen ground as a way to avoid compaction on wet soil in the early spring. Spring triticale is the spring cover of choice, but since he does not grow the seed himself, it is more economical to plant spring oat. Mixing field pea with either spring oat or triticale gives some added N.

49.2.7 The Future

Some common mistakes that have occurred and that can be controlled in future are:

- Allowing the cover crop to lodge before rolling. A cover such as rye is nearly impossible to plant into if the stems are lying across rows rather than in the direction of rows.
- Not enough N is supplied when rye is grown as a cover crop. Rye takes out a lot of N and releases very little during the growing season.
- Improper seed-to-soil contact can occur without proper planting equipment. One needs to do whatever it takes to get the seed in the ground.
- Pumpkins are much cleaner in a no-tillage–cover crop system because the soil does not splash on them when it rains. Steve has found that this is the main selling point of no-tilling pumpkins. He estimates that nearly half of the pumpkin land in Lancaster County PA is now no-tilled.

Steve offers some advice to other farmers interested in making changes to the farming system similar to his:

> Farmers who desire to reduce tillage have some proven options to choose from. Learn all you can about how the system works, make necessary equipment changes, and start on a small acreage.

49.2.8 Information and Support

Steve farms along with his wife, Cheri, and they can be reached at their website at www.cedarmeadowfarm.com. The farm has been honoured with a number of awards, and Steve hosts an annual field day at his farm each year to educate visitors about sustainable agriculture practices. The field day is often attended by hundreds of visitors from the local community, the state, and throughout the region.

49.3 Lamar Black—Southeastern USA

In the Coastal Plain region of Georgia (Fig. 49.1), Lamar Black manages a farm that produces cash crops of cotton, peanut, soybean, corn, and wheat. Water is the driver that has shaped many of his decisions. With an average of 1,200 mm of precipitation in a year, one could imagine that Lamar Black manages his farm to avoid excessive water. While remnant hurricane rain events can contribute to excessively wet conditions in the summer, more often it is the plentiful sunshine and intense summer heat causing periodic drought in these sandy soils that has shaped his management decisions, including use of supplementary irrigation. Managing both excessively wet and dry conditions has been possible with adoption and evolution of conservation-tillage equipment over several decades. Lamar Black has become increasingly more efficient in water use and less environmentally threatening in his approaches to farming.

49.3.1 Background

Lamar Black (Fig. 49.7) has managed the Tilmanstone Farm in Jenkins and Burke Counties near Augusta Georgia since 1982. Samuel Tillman is the owner of the 930 ha farm which was purchased by the Tillman family in 1970. Previously, it had a dairy herd and some cotton was grown.

As a farmer, Lamar Black has followed in the footsteps of his father, grandfathers, and great grandfathers. Lamar was farming at another location in Jenkins County until he was hired as a manager in 1982. His connection to this farm started when his father rented part of the farm in the 1960s and 1970s to plant cotton.

From the perspective of agricultural statistics in the USA, Lamar farms typically for the region, growing cotton, peanut, and small grains like many other farmers in the region.

Fig. 49.7 Lamar Black

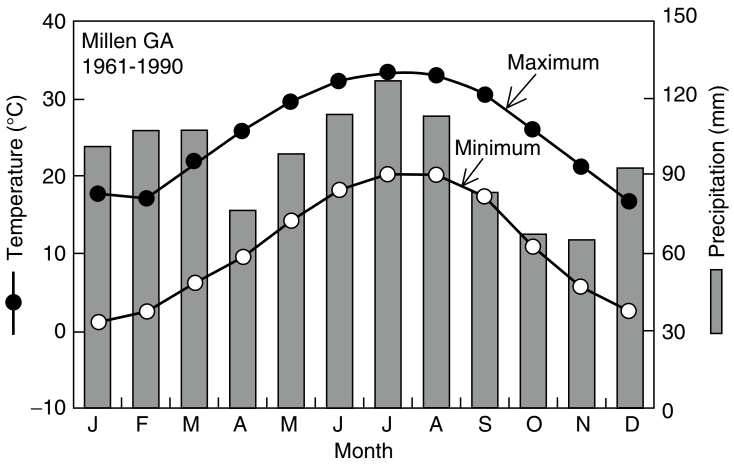

Fig. 49.8 Mean monthly climatic conditions in Millen GA (32.86°N, 81.96°W, 59 m above sea level). Mean annual temperature is 17.9°C and mean annual precipitation is 1,158 mm (National Climatic Data Center, 1961–1990)

49.3.2 Environmental Conditions

Typical of the southeastern USA, rainfall is abundant in the winter and limiting to adequate in the summer (Fig. 49.8). Overnight frosts occur from December to February, but temperature is overall relatively mild in the winter and hot and humid in the summer.

The Tilmanstone Farm lies on typically coarse-textured soils of the Coastal Plain region. They are well-drained, acidic, and generally low in organic matter. Specific soils on the farm include Dothan and Tifton loamy sands (fine-loamy, kaolinitic, thermic Plinthic Kandiudult) and in low-lying areas, Grady sandy loam (fine, kaolinitic, thermic Typic Paleaquults). The dominant soils, Dothan, were formed in thick beds of unconsolidated, medium- to fine-textured marine sediments.

Soils are sampled routinely on the farm following a grid pattern with GPS. Samples at 0–5 cm depth are used to estimate lime requirement, those at 5–20 cm depth to develop fertiliser requirement.

The region is characterised by a relatively flat landscape dissected with multiple streams that channel water to larger rivers (e.g. the Savannah River) passing through the region from the Appalachian Mountains to the Atlantic Ocean.

49.3.3 Early Years

Cotton, peanut, corn, soybean, and wheat are the primary crops in the region, as well as historically on this farm. Although the landscape is relatively flat, soil erosion and excessive water runoff are threats that degrade the environment in this region.

Most of the land on the farm was not classified as ‘highly erodible land’ (HEL) and therefore, a conservation plan was not required. Yet erosion with intensive rainfall events still occurred, especially on susceptible parts of various fields.

Low economic return and its high variability from year to year were concerns. Soil organic matter was less than 0.6%. High costs for inputs such as equipment, repairs, labour, and fuel reduced profit margin before conservation tillage was adopted.

49.3.4 Drivers of Change

Lamar Black began adopting conservation tillage primarily because of a concern with wind and water erosion. Since he felt he could grow the same crops with conservation tillage as with conventional tillage, the switch was a matter of mechanical innovation specific to the conditions on his farm. Although the farm was not classified as HEL, there were times in the summer when intense storm events would cause erosion and this often raised ire with his land ethic. Something needed to be done.

Eventually, input costs were lowered with conservation tillage and this became a talking point to get others to adopt the technology as well. Profitability of farming has increased for Lamar with the adoption of conservation tillage.

Positive outcomes from adoption of conservation tillage include erosion control, cleaner water, better soil quality, and retention of nutrients in the field. Lamar feels that he has become a better steward of the land.

Lamar used conservation tillage successfully before herbicide-tolerant seed technology was developed. He does not plant herbicide-tolerant corn because he can control weeds adequately without the technology. With the high cost of GM seed technology; this strategy is saving him money in the long term. He does plant herbicide-tolerant cotton and soybean because weeds were more difficult to control in these slower-growing, short-stature crops compared with the quick growing, full canopy of corn.

The main reason for switching to conservation tillage was ‘better soil quality’. Without erosion, soil organic matter accumulates and soil physical, chemical, and biological properties and processes improve with time.

49.3.5 Pathways of Change

Lamar Black began experimenting on the farm with conservation tillage in the mid 1970s, inspired by publications of the time on controlling soil erosion. Since fewer field passes were needed with conservation tillage, savings were quickly made on fuel, time, and equipment repairs. Corn was tried first because it was considered the easiest crop to manage with conservation tillage. In 1977, he bought a Brown-Harden Super Seeder. Since then, he has made many modifications to the planter and still uses the same original unit today. Some of the modifications included moving the coulter farther ahead of the subsoil shank, replacing the seedbed coulters with rubber tires, and adding plastic to the front of the subsoiler to reduce soil sticking to it. Subsoilers and rollers are used to provide deep tillage with minimal disturbance of surface residue. A spiked, seed-closing wheel on one side provides better seed-to-soil contact, particularly in wet conditions. Lamar had to devise his own row marker to work in thick cover crops. He says it is not perfect, but works better than anything he has looked at in the market.

Lamar has been able to supply irrigation using two center-pivot sprinklers with almost all of the water being provided by surface impoundments replenished with runoff in winter and supplemented when needed with well water. After continued use of conservation tillage it became apparent to Lamar that irrigation water was able to penetrate the soil surface much more readily and that yields were higher. In effect, more water could be applied at one time before water runoff would occur, which led to better crop performance and less water stress during critical growth periods. As an example, in the dry year of 1990, corn was planted conventionally and irrigated 41 times because only about 10 mm could be applied at one time before runoff would occur due to surface sealing. In 1993, Lamar planted cotton with conservation tillage in the residues of the previous corn crop and was able to apply nearly 40 mm before runoff would occur. This was proof to him that conservation tillage was enabling storage of more water and production of better crops. With rainfall only, crop yields have still improved with conservation tillage, because the accumulation of surface residues protects the soil from drying out too rapidly.

The two main components of conservation employed by Lamar are strip tillage[8] to reduce soil disturbance and winter cover cropping to accumulate surface soil residues. The strip-tillage approach allows him to use a subsoiler to break up the hardpan that forms under these soils. Soil is disturbed only in a 30-cm wide path at the time of planting.

49.3.6 Managing the System

By growing the range of crops mentioned above, Lamar tries to take advantage of the short- and long-term benefits of crop diversity for economic stability. He views the production of a variety of crops as a means to reduce the risk associated with fluctuating commodity prices. In addition, crop rotations and cover crops allow him to take advantage of biological synergies to reduce weed and insect pressures, as well as to build soil quality and reduce the threats to water quality.

Conservation tillage is now used continuously on the Tilmanstone Farm for all crops. Double-cropping with winter small grains prior to summer cash crops allows sufficient surface residue to accumulate so that weeds can be smothered and the soil

[8] See Glossary.

Fig. 49.9 Rolling cover crops

can be protected from erosion. Summer cash crops are planted with a strip-tillage planting system following rolling of cover crops or harvest of small grains.

In the early years of using conservation tillage, Lamar used winter weeds as a cover crop, but as he gained more experience he started planting cover crops, such as wheat, rye, black oat, annual ryegrass, and Cahaba white vetch (cultivar of *Vicia sativa*). Winter small grains are planted with a no-till drill. Some rye is allowed to mature for seed harvest and all wheat is grown for grain harvest. Today, winter cover crops are almost exclusively rye and ryegrass that are rolled down mechanically (Fig. 49.9). Rye provides the most biomass and ryegrass has a dense root system, both of which help to improve the life of the soil.

Plant nutrition is managed according to annual soil test recommendations provided by the University of Georgia. Growing a Cahaba White Vetch cover crop in one year, allowed about 80 kg fertiliser N/ha to be saved on a cotton crop in the following year. Starter fertiliser is applied to corn and cotton. Cotton leaf petioles are sampled to assess N and K status throughout the growing season and if needed, foliar fertiliser is applied. Animal manures are generally not available in the region, and therefore are not applied on the farm.

Pests are monitored by a professional consultant and chemical controls are employed only when necessary. Bollguard®[9] cotton is planted and has resulted in fewer insect applications to control bollworm. Hessian-fly resistant wheat is planted. Fungicide on wheat is applied at boot stage because of the warm, humid

[9] A cotton variety that has been genetically modified by Monsanto to contain bacterial genes that cause bollworms eating the plant to die.

conditions that favour fungal development. Fungicide-treated corn and cotton seeds are used to control seed rot and seedling diseases. Weeds are controlled with herbicides and cover crops as part of the total control package.

Soil quality has greatly improved with long-term continuous conservation tillage on the Tilmanstone Farm. Lamar has collaborated with University of Georgia extension agents, USDA-Agricultural Research Service scientists, and USDA-Natural Resource Conservation Service specialists to validate these changes. Organic matter in the surface few centimeters of soil is now well above 3% compared to less than 0.6% previously. Fertilizer and lime are applied without incorporation and have improved soil fertility. Compared with conventionally tilled fields, soil fertility levels and soil pH have increased to depths of 1 m. Earthworms can be found in the soil because of the rich surface residue layer and lack of soil disturbance. Bobwhite quail have always been on this farm and are not declining because of the soil cover and habitat provided by various crops.

Since switching to conservation tillage, Lamar has been able to achieve average corn grain yield under irrigation of 14 t/ha. Previously with conventional tillage, he was able to get a maximum yield in some years of 11.3 t/ha. Lamar says, "I've never experienced a yield drag with conservation tillage on any of the crops I grow".

49.3.7 The Future

With increased development of guidance systems, conservation tillage will become easier for farmers. With a thick cover crop of rye, a guidance system would be of great assistance for rolling and planting in the same direction, thereby avoiding residue fouling. In addition, the establishment of consistent traffic patterns could possibly eliminate the need for high horse-power tractors to pull subsoilers and make operations even more economical.

The positive environmental impact of conservation tillage will become even greater the longer the system is used. With high fuel price and expensive equipment, conservation tillage will become an even more economical system in the future. Precision application of fertilisers has been used on Lamar's farm and this should contribute to better water quality, because there will be less chance of fertiliser washing away from the farm.

49.3.8 Information and Support

Conservation tillage schools and various other agricultural extension meetings are important venues for Lamar Black to obtain and share ideas. Every farmer has a different approach to conservation tillage. The idea of moving the coulter farther away from the subsoil shank was an idea that came from one of these group meetings.

The USDA-Natural Resource Conservation Service (NRCS), University of Georgia extension service, and USDA-Agricultural Research Service have been supportive in sharing information with Lamar, as well as visiting the farm and offering suggestions. All of them have participated in various field days on the farm during the years.

Lamar Black is a farm leader in his community and in the region. He is a charter member of the Georgia Conservation Tillage Alliance (GCTA) that was formed in 1994 (http://gcta-ga.org). The GCTA is a farmer-led group devoted to improving and sustaining agriculture in Georgia by providing a forum for sharing ideas and research findings. Lamar Black can be contacted at lblack@jeffersonenergy.coop.

49.4 Clay Mitchell—Midwestern USA

In the middle of corn and soybean crops as far as the eye at ground level can see, another 'eye on the ground' is linked to satellites via a geographic positioning system (GPS). With centimetre precision, the GPS system is controlling the movements of 12-row planters and sprayers for strip-cropped[10] corn and soybeans. This is a story of high technological innovation combined with a land ethic to preserve environmental quality, based on a strong family history of rural living in Iowa (Fig. 49.1).

49.4.1 Background

Clay Mitchell (Fig. 49.10) farms with his parents and great uncle on 1,000 ha of land near Buckingham Iowa. The farm has been family owned for more than a century. As with most other farms in the region, corn and soybean are the primary crops. Clay and his family have blended a diversity of modern and historical practices into their farm operations to achieve high productivity, while preserving environmental quality.

Historically, farming in the area included multiple livestock operations (e.g. beef, dairy, hogs, and chickens) combined with corn for silage, pasture, hay, alfalfa, oat and, more recently, soybean. Like the rest of the country, most of the land was historically ploughed with a mouldboard implement.

Clay's ancestors were from northern Europe; most were farmers in their ancestral lands, as well as when immigrants to America. Clay's great-uncle lives on the farmstead that has been in the family the longest. Most descendants bought farmland in

[10] A system that alternates strips of grass or closely sown crops such as hay, wheat, or other small grains with strips of row crops, such as corn, soybeans, cotton, or sugar beets. These are often sown on the contour to reduce erosion.

Fig. 49.10 Clay Mitchell

the area, but land was also rented when needed. Farm leases used to be crop-share, but now they are almost all cash leases (similar to the national trend). More and more land is leased as farms grow in area.

Clay bought some farmland in the 1990s when he was in college. He did not farm the original family land until a few years ago when his great-uncle started farming less intensely.

49.4.2 Environmental Conditions

Precipitation and temperature in this area of the midwestern USA are almost ideally suited to the production of summer annual crops such as corn and soybean (Fig. 49.11). The long days and high temperature in the summer create ideal conditions for crop growth, given sufficient precipitation. Year-to-year variation in precipitation in any month is high. Therefore drought resulting in crop failure is an occasional concern. Winters are cold and the soil is often frozen from November to March.

Soils on the farm include fine-silty, mixed, superactive, mesic Typic Argiudolls in the upland areas (e.g. Dinsdale and Tama silty clay loams, 2–5% slopes) and fine-silty, mixed, super-active mesic Aquic Pachic Argiudolls in the lowland areas (e.g. Nevin silty clay loam, 0–2% slope). Soils are neutral in pH (6.5 ± 0.3). They are kept at optimum-high levels in available phosphorus (34 ± 12 mg/kg) and extractable potassium (192 ± 31 mg/kg) with annual fertilisation as recommended by soil testing. Soil calcium (2,039 ± 180 mg/kg) and magnesium (395 ± 38 mg/kg)

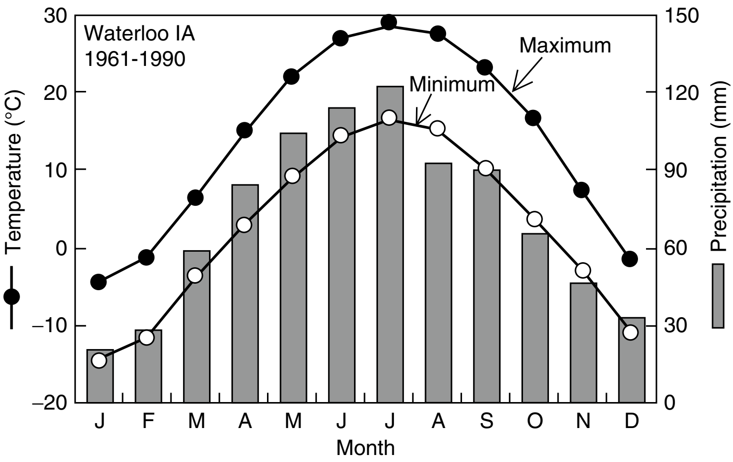

Fig. 49.11 Mean monthly climatic conditions in Waterloo IA (42.55°N, 92.40°W, 264 m above sea level). Mean annual temperature is 8°C and mean annual precipitation is 856 mm (National Climatic Data Center, 1961–1990)

are at optimum to high levels, but are added as limestone when soil pH drops below 6.5. Sulfur (13 ± 5 mg/kg), zinc (4.8 ± 4.5 mg/kg), and boron (0.8 ± 0.2 mg/kg) levels in soil are usually adequate, but added as micronutrient fertilisers when recommended by soil testing. Soil organic matter is 2.6 ± 0.4% and cation exchange capacity is 12.7 ± 0.7 cmol/kg, both indicative of fertile soils.

The region is characterised by a gently rolling landscape dissected by small streams channelling water to the Mississippi River, which drains into the Gulf of Mexico.

49.4.3 Early Years

Land in this region was settled by European immigrants during the latter part of the nineteenth century. Native vegetation was likely a mixture of forest along streams and prairie in the upland sections. During settlement, corn, wheat, oat, and pastures were the primary crops. Mouldboard ploughing was commonly practiced, with rotation of annual and perennial crops. Soil erosion and water quality are serious concerns in this area, which is a part of the Upper Mississippi River Basin. With the shift from fewer sod-based crops in the rotation (e.g. alfalfa, oat/clover, perennial pastures) following World War II, the threat of soil erosion in this area became serious. Permanent grassed waterways were a conservation practice implemented during the 1950s on the Mitchell Farm. Clay's grandfather had the first soil conservation plan in Tama County, in which he surveyed the farm to put in very precise contours. Different crops were planted on the contour to control erosion.

Some estimates of soil erosion in Iowa suggest average soil losses of 20 t/ha/year. Although soils are deep, the on-farm effects from such major soil erosion have eventually been realised in reduced soil quality, loss of potential productivity, and the time and expense needed to fix the gullies. The off-farm effects from such extensive soil erosion include sedimentation of water bodies, high costs to maintain local roads, and nutrient loading of rivers, lakes, and eventually even hypoxia in the Gulf of Mexico.

Because of climate and markets, cropping options are limited. In warmer climates farther south, relay cropping with wheat grown in the cooler months is an exciting option. An important long-term trend is that labour has become valued less than land; competition for land is intense. People in the region also enjoy the farming lifestyle. As a consequence, almost all farm families in Clay's neighbourhood subsidise their farming with some other off-farm income source. For Clay to be able to rent farmland and farm on a family scale without an off-farm income requires precise management. Crop yields above the county average are a part of his advantage.

49.4.4 Drivers of Change

A number of issues have driven Clay towards his current conservation-tillage farming system approach: (1) controlling soil erosion was the largest driver. He had to change his approach to be able to farm sustainably into the future. (2) Labor availability was a big issue. Clay's father has always worked off the farm full time. Clay was in school during most of his farming career. Therefore, less than one full-time person has been available to conduct the business. By eliminating pre-planting soil tillage, significant time savings were possible. (3) Machinery cost. Fewer pieces of equipment without large capital investment and with less operating and maintenance expense have allowed the switch to conservation tillage to be profitable.

Availability of modern agricultural technology has allowed Clay's farming approach to blossom. Herbicide-tolerant crop varieties were half of the technology required to combine conservation tillage with strip intercropping. Real-time kinematic[11] (RTK) control of operating equipment was the other technological wonder to make the system work effectively.

Research on how no-till has performed relative to conventional tillage has suggested that strip tillage would be a suitable alternative for this area. Conventional tillage is still used widely in the Great Lakes area because of the observed yield disadvantage with no tillage. Farmers who use conservation tillage need to look for alternative technologies to overcome this reduced yield. For Clay, the answer was strip tillage and banding fertiliser below the seed. Strip tillage was the driver for RTK auto-steering. With high residue, it was too difficult to see the fertiliser band

[11] A development of GPS that enhances accuracy.

and RTK auto-steering allowed him to do a better job of planting on top of the tilled, fertiliser banded strip.

49.4.5 Pathways of Change

Clay Mitchell became an early user of RTK to move tractors precisely around fields with centimetre accuracy. Tractor traffic can be precisely controlled from year to year to avoid soil compaction and apply herbicides most effectively at the desired point (RTK nozzle control) without harming sensitive field margins. He started using RTK in the fall of 2000. This technology also allowed him to apply banded fertiliser precisely in the anticipated rows of corn, which would be planted in a separate operation later. Seed placement is very important in corn and soybean and staying focused on that operation is critical to success.

Another proven technology adopted by Clay and his family in the 1980s was conservation tillage (in this case, strip tillage). This practice allowed crop residues to cover most of the soil, except in the row where germinating seeds could benefit from a warmer and drier soil environment. Surface crop residue between rows is important to control erosion during early crop development and to reduce drying out of the soil later in the growing season.

Genetically-engineered corn and soybean seeds have been planted since the 1990s so that herbicides can be sprayed over the top of crops at development stages early and late enough for the crops to compete vigorously with both early and later weed threats.

Clay describes historical changes on The Mitchell Farm in the following and in Fig. 49.12. No-till is for soil conservation, strip-till is to bring yields back to conventional farming levels. Auto-steering with RTK is to make the strip-till more effective in terms of fertiliser placement. Controlled-traffic farming follows very naturally from these other operations, but it is also appropriate with no-till because reversing soil compaction caused by machinery is a major reason for conventional farmers to till.

An historical practice of alternating tall and short crops on the landscape has also been made possible on The Mitchell Farm primarily by the adoption of RTK

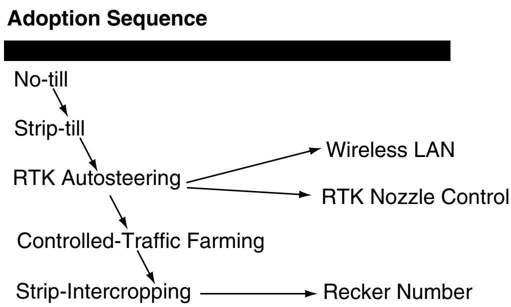

Fig. 49.12 Technology changes on the Mitchell farm

steering of equipment. Alternating 12 rows (9.1 m) of corn with 24 rows (9.1 m) of soybean across fields has helped the Mitchells take advantage of the additional sunlight penetrating exterior rows of corn. With corn being a C4[12] plant, light is a limiting factor for production. The alternating strips of corn and soybean residues on the soil surface are an additional strategy to help to reduce soil erosion. Even with continuous no tillage, some studies have shown significant soil erosion on land previously planted to soybean due to rapid decomposition of the high-N content soybean residue. Although corn–soybean is a simple crop rotation sequence, it provides additional soil conservation and resource efficiency from the reduced commercial nitrogen input needed and beneficial interactions to reduce insect and disease pressures.

Another driver for strip-intercropping is that the taller crop is currently higher value. Yield and grain price for corn have increased faster than for soybean, so favouring the higher value crop is profitable. In addition, there are intrinsic rotational benefits derived from the C3 (soybean) and C4 (corn) crops. The nascent development of RTK and herbicide-tolerant crop technologies came at the right time in Clay's farming career.

A pre-industrial soil conservation approach has been preserved on the farm by maintaining perennial grassed waterways. These waterways are important to stabilise soil in sensitive positions on the landscape. The adoption of RTK and GPS technology has maintained the integrity of these waterways by accurately determining when each nozzle of the herbicide applicator is in or out of an area of the grassed waterway. Without this precision technology, waterways can be invaded by weeds and the surface cover can be eventually compromised.

49.4.6 Managing the System

Strip-tillage and strip-cropping have been possible with the effective utilisation of RTK and GPS technology on The Mitchell Farm (Fig. 49.13). Strip-cropping is a way to keep soybeans in the rotation during a time when economics favour continuous corn. Rather than rotate from field to field, strips of corn and soybean can be present each year in a field.

Nothing tells the story of a farm as much as crop rotation and it seems obvious to judge a farm by the degree of diversity. However, Clay is in a situation where the difference in economic value between primary crops and secondary alternatives is just too large to be ignored. Clay would like to have more crops in rotation on his farm, but current economic conditions and the government subsidy system do not support viable alternatives.

[12] See Glossary.

Fig. 49.13 Strip cropping with advanced machinery

In spite of this, Clay believes in the value of crop diversity and is looking for ways to increase it on his farm. Perennial tall grass prairie and forests have been long replaced with annual crops in Iowa and the region. Looking at his environment, the biggest issue he sees is to avoid fallow periods, in which no crops are grown. In Iowa, the longest fallow period is winter, when the soil is frozen and plant growth is impossible anyway. With modern plant genetics, the growing season has been extended, so that planting now occurs a full month earlier than previously.

49.4.7 The Future

Regarding additional tools for conservation in the area, Clay states, "We really could benefit from a good cover crop here because there is a lot of erosion potential in the short fall and spring periods when the ground is not snow covered, and no crop is established. Our conservation practices are the next best thing, but nothing holds the ground like a cover crop. But as of yet, nobody has come up with anything that doesn't have detrimental yield/economic consequences. If there were a cover crop that could predictably improve productivity, it would be impossible to keep it out of farmers' hands. Perhaps someday that will become a possibility."

49.4.8 Information and Support

Clay Mitchell farms with his parents, Wade and Cynthia, and his great uncle, Philip. Clay has been invited to speak in many places in the USA and around the world, including Australia, Canada, Chile, England, France, Germany, Japan, and New Zealand. He has hosted research from several midwestern universities and is currently a Saltonstall Fellow at Cornell University.

Clay Mitchell can be contacted through The Mitchell Farm website—www.mitchellfarm.com.

49.5 Gabe Brown—Great Plains USA

On the Dakota Plains near the upper stretches of the Missouri River (Fig. 49.1), Gabe Brown has been integrating crops and livestock with success for many years. Although his Gelbvieh[13] cattle are his pride, he has also been overcoming weather stresses typical of the region to produce high-quality, versatile feedstuffs with conservation-tillage production technologies and management intensive grazing. This is a story of environmental stewardship that underpins a diversified farming operation in a harsh environment.

49.5.1 Background

Gabe Brown (Fig. 49.14) and his wife, Shelly, own and operate Brown's Ranch near Bismarck North Dakota. They purchased the farm from Shelly's parents in 1991. The ranch covers 2,225–562 ha family-owned and 1,664 ha leased from various sources. Nearly all of his farm income is from cattle and alfalfa hay and grain sales. He grows 100 ha of alfalfa for hay, 540 ha of various crops (corn, pea, barley, hairy vetch, millet, sorghum-sudan grass, wheat, and a variety of legumes[14]), 205 ha of tame pasture,[15] 1,195 ha of native rangeland, and 185 ha of wildlife cover.

The cattle operation consists of 250 cow/calf pairs with 50–250 yearlings, depending on moisture and forage availability. Fewer yearlings are retained during dry periods so that a constant number of cows can be maintained. F1 crosses of his Gelbvieh cows with Angus bulls produce Balancers. Calves are weaned in early September.

Crops have been grown with zero tillage since 1994. Gabe is a strong advocate of the conservation tillage technology to improve soil, water, and air quality. Fields planted with zero tillage have earthworms and an abundance of other soil organisms. The higher organic matter at the surface allows for greater water infiltration and surface cover for greater diversity and population of wildlife.

[13] A breed of beef cattle with European (Bavaria) origins.

[14] See Glossary for botanical names.

[15] Cultivated fields planted with introduced (non-native) grass and legume species or cultivars.

Fig. 49.14 Gabe Brown

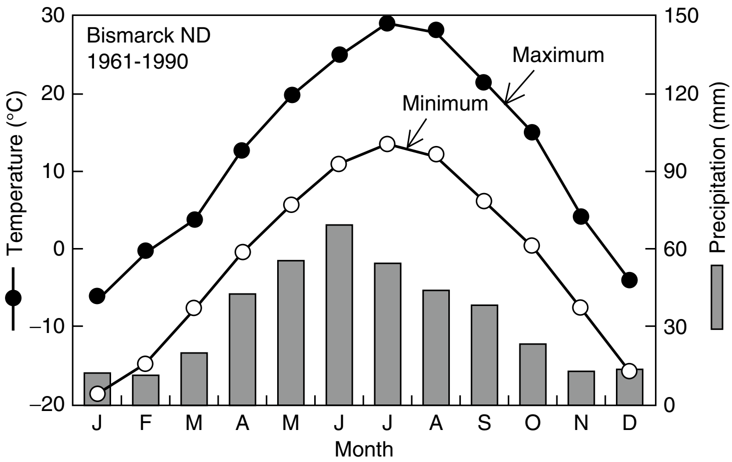

Fig. 49.15 Mean monthly climatic conditions in Bismarck ND (46.76°N, 100.75°W, 502 m above sea level). Mean annual temperature is 5.3°C and mean annual precipitation is 393 mm (National Climatic Data Center, 1961–1990)

49.5.2 Environmental Conditions

Typical of the Great Plains, precipitation generally includes snow in the winter with peak precipitation in the summer. Temperatures are very low in the winter, with near continuously frozen conditions from November to March (Fig. 49.15). The long days and high temperature in the summer create conditions for rapid forage and crop growth, given sufficient precipitation. Year-to-year variation in precipitation in any given month is high, and crop failure is a constant concern.

Brown's Ranch lies primarily on Williams loam soil (fine-loamy, mixed, superactive, frigid Typic Argiustolls). This soil is highly productive, typically producing small grains, flax, corn, hay, or pasture. Native vegetation was western wheatgrass (*Pascopyrum smithii*), needle-and-thread grass (*Hesperostipa comata*), blue grama grass (*Bouteloua gracilis*), green needlegrass (*Stipa viridula*) and prairie junegrass (*Koeleria macrantha*).

The region is characterised by a relatively flat landscape dissected by small streams. These channel water to the Missouri River, which passes through the region from the Rocky Mountains in the west to the Mississippi River and ultimately to the Gulf of Mexico.

49.5.3 Early Years

Wheat, alfalfa, tame pasture, and native rangeland are the primary crops/pastures in the region, as well as historically on this farm. Although the landscape is relatively flat, soil erosion is a major threat to the environment. Before Gabe's ownership, wheat–fallow with conventional tillage was the dominant land use on the farm, and typical of the region.

49.5.4 Drivers of Change

Soil erosion and poor rainfall infiltration were problems that forced Gabe to rethink the management strategies on the farm and he switched fully to zero tillage management of crops in 1994. He also recognised that crop diversity needed to be substantially increased to survive the harsh environmental conditions. All of these changes were important to improve soil organic matter so that crops, pasture, and hay could buffer against frequent droughts in the area.

49.5.5 Pathways of Change

"People get stuck in a rut. They always plant the same things. They're afraid to try anything new. But you can't do what dad and granddad did and expect to earn a good living with expenses what they are today." says Gabe Brown about current farming conditions.

In 1993, Gabe Brown sold his conventional tillage equipment and purchased a John Deere 750 no-till drill (4.5-m wide). He harvested his first small grain crops with no tillage in 1994.

The early years of change did not come easy though. In 1995, he lost 500 ha of spring wheat to hail damage shortly before harvest. The next year a similar scenario of hail devastation stripped his enthusiasm. In an effort to diversify and avoid widespread susceptibility to these vagaries of nature, Gabe started to diversify the crops he grew. He began planting and harvesting alternative crops, including field pea, corn, haybet barley,[16] millet, and others in an effort to diversify his operation. He planted field pea, hairy vetch, and red clover[17] to benefit from their symbiotic nitrogen fixation and contribution to the fertility of his main commodity crops. Unfortunately, even these changes were met by drought in 1997 and by hail again in 1998.

Gabe Brown states "Four years of crop failure was the best thing to ever happen to us. It made us realise that we had to focus on soil health, soil structure, and improved rainfall infiltration. If we did that, the soil would provide us what we needed to produce crops efficiently. We also realised over time that we had to diversify the cropping system to make it more sustainable."

49.5.6 Managing the System

Integrating crops and livestock on Brown's Ranch allows for a diversity of enterprises. This diversity hedges against risks from weather variability, market prices, and input costs. The farm is managed as a whole, optimising not specifically for either livestock or crops, but for the family business, as well as for the environment.

Various legumes such as hairy vetch, field pea, red clover, and sweet clover[18] are planted in combination with small grains as a second-year forage to increase forage quality and build soil fertility. Calving date has gradually been shifted to a later date so that forage quality is at a peak during the breeding season.

Gabe believes in cover cropping[19] and crop rotation for a variety of reasons. He states, "As soon as we get one crop off the field, we're seeding in another crop. In July, we'll seed warm-season cover crop mixes which include pearl millet, sorghum, sudangrass, cowpea, soybean, radish, and sunflower[14]. People say they can't use cover crops, because it's too dry or the growing season isn't long enough, but they're doing it in Canada and that's 150 miles north of here and they're doing it in regions of Africa where they only get two inches of rain per year. If Canada and Africa can produce cover crops in those growing conditions, anyone in the United States can do it. It's simply a mindset. You might as well use the moisture to grow a cover crop and increase organic matter. It's a good way to help alleviate water problems in an arid environment. Our crops are able to withstand drought much

[16] A two-row, hooded cultivar of barley.

[17] See Glossary for botanical names.

[18] See Glossary for botanical names.

[19] See previous case studies and Glossary.

better, because we have increased the water-holding capacity of our soils and we get much higher utilisation of the moisture we do have. We lose much less to evaporation because the soil surface is covered with residue and soil temperatures are cooler." Gabe believes that cover crops offer excellent protection from wind and water erosion. He also relies on deep-rooting cover crops to cycle nutrients within the soil profile, as well as to alleviate hardpans.

Integration of crops and livestock is another important facet of Gabe's operation. He states, "One thing we're doing with cover crops is integrating crop and livestock production. Instead of harvesting by mechanical means, we use our cow herd to harvest for us. Too many people look at livestock separate from cropping. On our operation, we look at the system as a whole. It's about what is best for the resource. When we purchased the farm, we could only run 65 cows. Now we easily sustain 250 cows and have more forage than we ever grew before, because we are able to graze cover crops and rest our pastures. When drought hits, we can easily sustain production because we have a good supply of grass to fall back on."

Grazing on the Brown Ranch starts in mid-May and ends when the snow gets too deep, sometime in January or February. Tame pasture, native rangeland, and cover crops are components of Gabe's planned grazing system. Tame pastures have been interseeded with legumes, including cicer milkvetch, sainfoin, birdsfoot trefoil, alfalfa, crown vetch, hairy vetch and white clover.[20] The purpose of the legumes is to: (1) supply grasses with nitrogen to increase plant vigour and forage production, (2) improve forage protein to enhance herd health and rate of gain, (3) leave additional plant litter at the soil surface to increase infiltration and maximise use of soil moisture, and (4) create a deeper rooting zone to enhance nutrient cycling. Before legumes were inter-seeded, tame pastures produced 1.8 t/ha, but now that legumes are inter-seeded, production is 4.5 t/ha. Tame pastures are divided into multiple paddocks using single wire electric fence. Livestock receive water from rubber tire tanks delivered from a shallow pipeline. Paddocks are grazed once or twice a season, depending on plant regrowth and rainfall. Recovery periods range from 90 to 120 days when paddocks are grazed twice. Careful plant, litter, soil, and livestock observations are used to assure adequate recovery periods. In addition, native grasses from previous Conservation Reserve Program land have been added to the grazing system. Cover crops, provided by the no-till cropping system, is an important part of the sustainability of the grazing systems. Fall grazing is mostly on corn stalks, small grain stubble, and annual forages. Gabe estimates the grazing value of hairy vetch as $65/ha and of corn stalks as $93/ha.

A total of 250–300 bull calves are fed in a feedlot on the farm with feedstuffs produced from the farm. Manure from the cattle feedlot is composted for at least 6 months and applied to cropland to create a synergy of nutrient cycling from livestock and crop operations within the farm. Along with seeding of legumes, relying on more natural nutrient cycling processes has allowed Gabe to reduce commercial

[20] See Glossary for botanical names.

fertiliser application by 90% and herbicide inputs by 75%. Gabe notes, "At the same time, we have seen our yields increase."

Managing the farm for wildlife habitat has also been a priority. The farm has nearly 200 ha of pasture and pond for wildlife use—nesting habit for game and song birds and cover for deer. At least 3% of cropland is left unharvested for wildlife food and cover. Tree windbreaks, planted both in an earlier generation and more recently, have been buffered with additional nesting cover and have created a mosaic of beauty, practicality, and environmental stewardship on the farm.

49.5.7 The Future

Gabe Brown has had to look at profit a little bit differently because of the changes he has made to his operations. Field pea is not a particularly profitable crop but it helps to lower input costs by biologically-fixing its own nitrogen and leaving behind nutrient-rich residues for subsequent crops.

Gabe also looks to the future, rather than just for today. He wants to improve the soil as much as possible so that he can leave his farm in better condition for his son, Paul. Gabe is passionate about this and makes the claim, "I'm a conservationist first and a farmer/rancher second. We need to improve the resource for future generations. Fortunately, if you do that, it also will improve your bottom line." He elaborates on this when recalling the changes he has made during the years, "We were on the verge of going broke after those four years of crop failure, but through the changes that situation brought on, I've seen the profitability that can come from improving the soil health. In 2007, it cost us only $1.19 to produce a bushel of corn [$46.85/ton]. Farming is much more profitable for us today."

49.5.8 Information and Support

The Browns' have been honoured with a number of awards. To better their conservation approach to farming, they have enrolled in the Environmental Quality Incentive Program and Conservation Security Program administered by NRCS.

The Brown's have hosted visitors from all 50 states and 14 countries. Gabe helped initiate the Grazing Management Mentoring Network for the North Dakota Private Grazing Lands Coalition to give ranchers opportunities to teach and learn from each other's experiences. Other mentoring networks have since become established in other states.

Gabe has worked with researchers on the effects of his integrated crop-livestock system on soil organic matter and nutrient cycling.

Gabe and Shelly Brown can be contacted at brownranch@extendwireless.net. Other information about their farm can be accessed on their homepage at http://www.sustainableranching.com.

Chapter 50
Summing Up

Philip Tow, Ian Cooper, and Ian Partridge

Abstract A summing up of the key themes of the book.

Keywords System • Systems approach • Farming system • Farm system structure and operation • Boundary • Feedback • Effective interactions • Productivity • Profitability • Efficiency • Sustainability • Adaptability

50.1 Introduction

This book provides an understanding of the *structure* and *operation* of rainfed farming systems, of their diversity around the world, and of what farmers, researchers and agribusiness operators are doing to achieve *productivity*, *profitability* and *sustainability.* The definitions and concepts in Chap. 1 and the classification in Chap. 2 provide a basis for the analysis and understanding of the systems, and how the integrated parts combine to operate as a whole. It is this requirement for integrated operation and management on farms that shows the need for a 'systems' approach in agricultural production.

While defining the farm system in mainly production terms is useful, it becomes clear in this book that including the farm 'family' and its personal goals within the system boundary is often a more appropriate way to operate, and that widening the boundary to include the environment and other members of the community such as researchers, agribusiness and policy makers may sometimes yield a more complete understanding for the purposes of overall farm management. Moreover, as Chaps. 13, 16, 22, 30 and 38 indicate, cultural, community and social factors can have a strong modifying or limiting effect on attempts to design, operate and

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P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_50,

improve farming systems. Whatever the boundary set for the system and because of the interdependence of all its parts, the definition of a system, based on that of Spedding (1988), has proved relevant to the goals and contents of this book, i.e.

> A system is a group of interacting components, capable of reacting as a whole to external stimuli applied to one or more components and having a specific boundary based on the inclusion of all significant feedbacks.

This is a useful definition; it provides a base for understanding and working with the structural characteristics, relationships, operation and management of a farm(ing) system, for achieving the goals of the owner or manager and for understanding the place of a farm in the wider social and physical environment.

50.2 Types of Rainfed Farming Systems

Chapter 2 describes a classification of farming systems based first on climate and then on *productivity* and *farming intensity*. Chapter 13 reminds us that other factors related to non-agricultural members of the community also need to be considered in designing new systems. It also stresses the need to incorporate changes in systems that take into account the effects of climate change and the need for change to be multi-directional (having multi-criteria to connect the goals of farmers, agribusiness, researchers and public policy makers). Importantly, also, the author of Chap. 13 explains the need for farming systems to change from being ‘leaky’ and oriented to focus on inputs and outputs, to being semi-closed or *regenerative*, with more recycling and less waste and less use of fossil fuel-derived inputs. This hope is echoed in the ecosystem approach to farming systems promoted in Chap. 21. At the same time, Chap. 1 and many other chapters discuss the need for Farming Systems to be profitable and sustainable, and to have other characteristics such as efficiency, stability, flexibility, equitability and resilience.

Many chapters illustrate how the crops, pastures and livestock that can be produced and the type of farming system that can be operated in a given area depend on climate—particularly rainfall and temperature. These external factors determine the time of year, starting point, length and reliability of the growing season. However, as discussed in Chap. 2, growing-season attributes are affected not just by amount of rainfall, but by its effectiveness, as defined by the Precipitation/Potential Evapotranspiration (P/E) ratio; P/E generally has fairly low values (often around 0.5) in areas of rainfed farming. Further, in discussing the management of climate risk in rainfed farming, Chap. 3 points to the limited value of climatic averages. It is vitally important to determine probabilities of high or low agricultural performance through estimating rainfall variability and the occurrence of climatic extremes such as dry spells, drought, heat wave and frost. Such probabilities are important to any kind of forecast or predictive modelling of production (as in Chap. 37). While these just-mentioned climatic variables may not alter the general, annual or seasonal pattern of production, they may have significant effects (along with length of growing season) on the types or varieties of crops and pastures, and the types and breeds of livestock that are best adapted to the region.

The productivity and intensity of farming have always varied widely throughout the world, and still do, as illustrated in the chapters of Part II. These differences have been linked to variations in rainfall, soil fertility, availability of scientific research and technology, infrastructure such as railways, markets and marketing and even culture and social tradition. Chapter 2 discusses these and other factors in current contexts. At the present time, as mentioned in many chapters, it is clear that productivity and farming intensity must be increased to near potential levels to feed the growing world population. This must be done while conserving the resource base and overall sustainability.

50.3 Profitability and Sustainability

As discussed in Chap. 1, profitability and sustainability are key goals of rainfed farming systems—as they are with any other enterprise or business. Sustainability has many facets: biological, physical, economic, environmental and social.

Sustainability may be achieved at any level of productivity. A farming system may be sustainable biologically and environmentally, but not profitable or productive enough to satisfy farmer or society needs. This calls for changes in inputs, management or wider factors. Conversely, a farming system may have high levels of productivity, intensity and profitability but lack sustainability if, for instance, the soil resource is allowed to be over-exploited and degraded, or a noxious weed is allowed to spread or costs tend to exceed returns. Sustainability of a system may be lost (at least temporarily) if changes occur within the system, or are imposed from outside (as with climate change, new economic policy, war, increased population pressure). Sustainability may be regained through modification of the structure, inputs, operation or management of the system. For instance, a change in intensity may be required to make the system more economically or environmentally sustainable. If that cannot be achieved, a new system may have to be substituted for the old (as may occur with serious climate change).

50.4 Some Key Concepts

Throughout this book, the diversity of farming system structure becomes apparent in the system elements—components, outside influences, inputs, and outputs and the relationships among them. Such diversity stems initially from differences in climate and soil, and then from a vast array of other factors. It is the relationships in the system that often determine the ‘success’ of system structure, operation and management. For instance, not only must farmers correct *limiting factors* such as plant nutrients deficiencies and problems of weeds, pests and diseases, but they must ensure that a wide range of system components work together at the right combination and timing to achieve success. This can be seen in Chap. 31 where the author explains how, on the Canadian prairies, he uses an appropriate combination of herbicides, herbicide-resistant crops and other crops to reduce costs, achieve weed control and avoid herbicide resistance in weeds. In addition, his system provides *flexibility* to modify the combinations in order to manage changes in economic conditions. Correct management of the right combination of key factors and their interactions brings positive effects and overall success.

Another example of *effective or positive interactions* is shown in Chap. 46 for a mixed crop–livestock farm in north-central Victoria, Australia. Here, the farm system is continually evolving to meet the challenges set by changes in climate, soil condition and commodity prices. Problems have been overcome to a considerable extent by introducing the perennial legume lucerne into the pasture phase, using no-till farming with stubble retention, diversifying crop production and changing sheep production from wool only to wool and meat. This type of system is a form of *Conservation Farming*. These and other interactions, skilfully managed, were necessary in order to make this new system profitable and sustainable.

Long-term agronomic research conducted in Mexico (Chap. 33) also showed how time trends in interactions must be understood in order to choose the best combination of elements and management in a system. With water non-limiting, wheat production without stubble retention became markedly lower than with stubble retained—but only after 5 years. The authors' conclusions are important: 'Future strategic research will have to concentrate on production system × genotype interactions (especially tillage/residue management × genotype interactions) and (also) the physiological basis of yield potential in different management systems'. They quote from Cook (2006) in saying that much more must be done to maximise the *synergies* between plant breeders and agronomists. This is a warning that a single 'breakthrough' such as a high-producing crop variety or a new type of machine such as a no-till planter, is only part of the solution to a problem; to achieve optimum effect, it is always important to think and operate with a systems perspective and with all the important factors included.

This type of effective interaction, on a larger scale, is seen as responsible for wheat grain yields in Western Australia increasing continuously by an average of 42 kg/ha/year over the 1980s and 1990s (despite lower rainfall)—an increase in Precipitation Use Efficiency (Chap. 28). The interaction is a genotype × environment × management interaction in which effective plant breeding of wheat for specific environments has been accompanied by improvements in crop and overall farm management. This effective use of interactions has clear consequences for the improvements in production and sustainability of farming systems that are needed world-wide.

The interactions between crops and livestock within and amongst rainfed farming systems are also of global importance, as explained in Chap. 11, and discussed in several other chapters, including Chaps. 20, 26, 30, 32, 42 and 46. The author of Chap. 11 gives examples of positive and negative synergies (interactions) on mixed crop–livestock farms and also on separate crop and livestock farms which may be integrated through the combined use of their outputs and inputs. Although positive synergies are common in crop–livestock systems (mixed or integrated) and such systems may also provide system *stability*, they do not always lead to the highest profitability, as when climate, soil and economic conditions favour continuous crop production (see chapters in Parts II and V). Neither do they always fit the personal goals of farmers. Synergies and a range of other factors are carefully evaluated by farmers when deciding on the structure of their rainfed farming systems, such as continuous cropping, mixed farming (with or without short-term feeding of grains for fattening), or integration of separate cropping and livestock systems. These are complex questions that have social and personal implications for farmers, especially in times of drought, as indicated in Chap. 30.

Many inter-relationships of the elements of farming systems are important for achieving outcomes such as profitability and sustainability. Apart from interactions, *feedback mechanisms* are often critical in farm system performance. The feedback effect of moisture utilisation, through crop growth, on soil moisture availability can be regulated by varying the input of crop-available N and by varying crop density or geometry. The regulation of available N (managed or natural) is discussed in many chapters, including Chaps. 4 and 6, and the chapters of Part II. The regulation of crop plant density and geometry in order to regulate the use of a limited supply of stored soil water for crop production is discussed in Chaps. 7 and 25.

Another feedback process with consequences for all farming systems is the modification of soil health (the *source*), and thus crop and pasture performance, by raising (or lowering) the soil carbon content (the *effect*). This is achieved through *processes*, such as no-tillage (or tillage) and retention of crop residues (or their depletion). These situations are mentioned in Chaps. 1, 6, 14 and 40 and in many of the chapters of Part II. Other outcomes or consequences of the processes of no-till farming and residue retention are reduction of soil erosion and increase in water infiltration with reduced water runoff (for example, in Chaps. 16, 19, 20, 23, 26, 33, 39 and 40). These show that there are usually *multiple consequences* of a course of action in a farming system.

Another important feedback operating in farming systems is that between researchers and farmers, with advisers and consultants often in between. This is discussed, in terms of both principle and practice, in Chaps. 35–37. In the past, the relationship was more a one-way process, with information largely passing from researchers to advisers and then to farmers. Present day aims are to make the process a two-way one, the source starting with either the farmer or the researcher. Starting with the researcher as source, the 'effect' would be an improvement in the farming system. This should provide information feedback which reflects or embodies this improvement, and has a positive effect on the researchers and their work, not as advice but as useful knowledge about the farm system and the farmer. This should be translated into more useful information to the system, from theoretical and practical research. Positive interactions between farmers, researchers, advisers, agribusinesses and policy makers would result in positive feedback that promotes mutual understanding and improvement in their respective operations.

Such positive relationships do exist, as many chapters of Parts II and V imply. Other positive interactions occur amongst farmers themselves, both informally and formally in group activities (see Chaps. 37, 42 and 45). The purpose of these activities is often to exchange relevant information that will assist in improving farm system *efficiency*, productivity, profitability and sustainability.

Where interactions and feedbacks occur between farmers and other agriculturists, the *boundary* of the system has been expanded beyond the farm to include all participants as components of the enlarged farm system—for their mutual betterment (see Chaps. 12, 13, 36 and 37). Chapter 13 proposes that interactions and feedback mechanisms will operate increasingly between farm families and the communities of which they are a part, and that such relationships will influence the design of future farming systems.

50.5 System Analysis, Sub-systems and Limiting Factors

The understanding of interactions and feedback mechanisms in farm or farming systems is part of a broader analysis of these systems. This is beneficial not only for an understanding of relationships of system elements but also for the detection of individual *Limiting Factors*. Section 1.2 shows how an analysis may be organised using the Circular Diagrams of Spedding. These diagrams can also be used to define sub-systems, with their often multiple, related components, and their relation to key outputs. A range of other diagrams may be used to analyse farm systems, such as the Problem–Cause diagram (Sect. 1.3) which may be used to define an approach to particular problems, and the Emergy flow diagrams of Chap. 21.

System Analysis is often done through a process of *monitoring* (Chap. 27), using *key indicators* to detect, through continuous monitoring of the system, limitations to production and sustainability. The authors of Chap. 27 use the concept of ‘adaptive management’ (flexibility and learning from past management decisions). Continual monitoring and evaluation of the farm system—‘keeping track of changes, trends, farm inputs and outputs, and assessing success or failure of past actions/ decisions’—lead to the concept of ‘continuous improvement’ of all elements of the system as a whole.

Chapter 27 also emphasises the need to improve and maintain sustainability—biological, productive, economic, environmental and social. It explains the use of key indicators of system health, productivity and sustainability which can apply both within the farm itself and also at the scale of whole catchments. An important suggestion is that key indicators for farmers should be in the form of management goals and actions, as well as simply profitability and efficiency.

Often more formal approaches are needed. These include a variety of Quality Assurance systems (many agricultural industries and markets have their own versions) and Environmental Management Systems (EMS). EMS are formalised, structured approaches to help farmers assess, document, improve and monitor their environmental performance. Farmers may also co-operate to monitor and achieve sustainable management at the catchment level (*Integrated Catchment Management*), and this is of great value for regional-scale improvements in agricultural productivity and sustainability. Within this framework, there is scope for farm and regional *action targets*, especially if government incentives are available.

50.5.1 Limiting Factors

In rainfed agricultural production, the major limiting factors are those related to climate, soil chemical and physical conditions, plant and animal diseases, insect pests, weeds and socio-economic-political constraints. All these factors are dealt with from a systems perspective in various chapters, particularly in Part I.

50.5.1.1 Climate and Climate Change

As discussed in Chaps. 2 and 3, much of the structure, operation and management of rainfed farming systems is determined by climate. In practice, it is climate variability, climate risk and climate change which are of particular importance to these systems. Chapter 3 deals with the management of climate risk from a systems point of view, illustrated by two case studies. These show the value of using seasonal weather forecasts based on measurements of the El Niño-Southern Oscillation (ENSO). The authors of Chap. 3 argue that the current information on the variable and changing climate will be more relevant to farmers and their production systems if they can discuss it, interact with it, and adapt to it in a systems framework employing three types of systems thinking:

- Natural Science, covering concepts discussed in Chap. 1, including feedbacks, resilience and stability
- Systems Engineering and applications such as Operations Research which provide tools for assessing and managing climate risk in the operation of rainfed farming systems
- Soft Systems methodology which deals with the complexity and also the benefits of characterising and managing climate risk in a farming system when different human perspectives and backgrounds are included.

The first case study compared two methods of managing climate risk for cropping on the summer-winter rainfall environment of the Liverpool Plains in northern New South Wales, Australia. These methods were: (1) fallowing the land until the soil profile was full of water before deciding to plant a summer or winter crop and (2) planting a winter crop whenever the likelihood of success was high enough, as indicated by the combination of some soil moisture storage and measurements indicating a rising Southern Oscillation Index in May. Grain prices were also taken into account. Though there was greater risk in following the second (opportunity cropping) method, it provided the greater profit, overall and prevented lost opportunities and excess drainage of water.

The second case study concerns planting of hybrid corn in the Philippines, where rainfall is greatly influenced by the El Niño-Southern Oscillation. Seasonal climate forecasting has a potential benefit for risk assessment and decision making for both corn and rice, where rainfall is commonly adequate for two or three crops a year. As hybrid corn seed and the required fertiliser are expensive, farmers need to have an assessment of the risk involved in planting it at the three possible times of the year. Their decisions to plant are based on their attitude to risk, to the missed opportunities for production by being too conservative in trying to avoid low rainfall, and also the current price for the grain they will produce.

The long-term benefits of taking account of seasonal weather forecasts appear to be worthwhile and the accuracy of such forecasts should increase with further research.

Climate change brings in an additional form of climate risk that affects a wider range of factors than weather and climate variability. It is necessary to consider the counter impacts such as the release of CO_2 from the burning of vegetation and agricultural residues and from soil tillage, and the release of methane by ruminants. These effects can be reduced by the technology of no-till and stubble retention but, as explained in Chap. 14, the potential of a farming soil to sequester carbon (in the long term) is limited by the soil clay content and by the input of carbon from crops and residues—which is determined largely by rainfall. Thus there is a much higher potential for plant carbon production and sequestration in humid or sub-humid regions than in semi-arid ones.

Just as every effort is being made to harness science and technology to manage climate constraints, so too this is being done with soil constraints of water and nutrients and with pest management.

50.5.1.2 Water

For rainfed farming systems, water is a universal limiting factor. While the amount, timing and seasonal distribution of rainfall are taken as beyond control, much can be done to optimise water availability and *Water Use Efficiency* (WUE) (see Chaps. 1–4, 19, 20, 22, 23, 25, 26, 28, 33, 40 and other chapters including Case Studies). WUE is one of the most important indicators of system 'condition' and functioning. It has become a valuable indicator since the introduction of the French–Schultz (1984) model (and its later development by other agriculturists) provided a means of measuring maximum values of WUE for various crops and hence values for *Potential Yield*. Crops that produce less than Potential Yield, with below-maximum WUE, are regarded as having grown under limitations of some sort; this then encourages farmers to seek and correct such limiting factors. This is discussed in Chap. 1 and in other chapters including Chaps. 4, 20, 23, 28 and 37). As also discussed in Chap. 1, the French–Schultz model allows separate estimates of Transpiration Efficiency and soil evaporation, and these have been tested by many agronomists (see Chap. 37).

Efficient water management is essential in rainfed farming systems. It has been improved using no-till, and by covering the soil surface with cover crop material and crop and pasture residues. This improves water infiltration and reduces runoff and evaporation. Many rainfed farming areas receive variable, intermittent and sometimes high-intensity rain. Excess water from rain (during both fallow and crop growth) can be stored in soils which have a high plant available water-holding capacity (PAWC) to accumulate water for the next crop and reduce the limitations of low rainfall (see Chaps. 4, 25, 35 and 45). As discussed in Chap. 4, in many developing countries, runoff water is highly valued and is directed and concentrated onto fields from external sources such as non-arable areas, or larger catchments ('ex-field' water harvesting) as in Ethiopia, Kenya and Zimbabwe. Such water can be stored in the soil or in dams or tanks until required. Smaller scale, 'in-field' water harvesting is also practiced, especially in African countries such as South Africa, Zimbabwe and Kenya, to reduce the risk of crop failure in small farm holdings. Ways used to concentrate water inputs to prevent crop failure include collection of runoff from unplanted land strips into basins constructed between crop rows; and also construction of planting pits and stone bunds. In Canada (Chap. 19), small but useful amounts of snow are trapped in crop stubble to assist in crop establishment. Small holdings in China also collect runoff water to apply to part of their land (Chap. 23). All the above methods are valuable means of reducing water runoff and evaporation and directing it to production and, in dry areas, prevention of crop failure.

Considerable progress has been made in the theory and practice of achieving high levels of water use efficiency (WUE) or precipitation use efficiency (PUE) and attaining yield potential for the particular rainfall regime and varieties used. This is explained in Chaps. 1 and 28, among others, and has been an important part of research and its application in many countries (see for example in Chaps. 19, 20 and 23). The efficiency of water use in rainfed farming systems can be improved by: (1) elimination of other limiting factors (besides rainfall) affecting crop yield (e.g. nutrient deficiencies, weeds, diseases and pests). Early weed control to conserve soil moisture is regarded as very important in low-production systems such as in Zimbabwe (Chap. 4); (2) lowering of soil evaporation through a dense soil surface cover of residues, and by efficient storage of moisture in deep soils. This maximises water use for plant transpiration and yield production; (3) reducing plant and canopy densities to ensure enough soil water is available for grain filling (Chap. 25); (4) defining and correcting subsoil impediments to crop water uptake (Chap. 4) and (5) plant breeding for improved transpiration efficiency (Chap. 28).

50.5.1.3 Soil Chemical and Physical Constraints

As stated from the beginning of the book, there are many forms of soil chemical and physical degradation world-wide, and the purpose of much research is to correct these limitations. Chapter 5 gives some examples of methods of detecting nutrient deficiencies and toxicities through soil and plant tissue tests, and of mapping them. One outcome of this is that automatic sampling and rapid analysis have become part of Precision Agriculture (Chaps. 34 and 39), and this now enables farmers with appropriate equipment to map the variability of their fields—in yield and also soil properties—and to provide relevant amelioration.

Behind these possibilities is the need for continued research into soil chemical and physical constraints. With the growth in Precision Agriculture and production modelling, there is increasing interest in measuring soil available water-holding capacity (Chaps. 4 and 37) as this can limit the potential for crop yields in low-rainfall situations. When Precision Agriculture is combined with Conservation Agriculture, as indicated in Chaps. 34 and 39, the opportunity is also present to raise soil health and fertility (and WUE) to levels where advantage can be taken of the many benefits (known and unknown) of soil microflora and fauna (Chap. 6) and of high soil C content (Chap. 14).

50.5.1.4 Pests

Further limiting factors may be *pests*, the general term for weeds (Chap. 8), diseases (Chap. 9) and insect pests (Chap. 10). As these also interact with each other and with their physical and biological environment, a 'systems' approach is needed for their management.

The standard ways of controlling pests all have limitations, with their effectiveness breaking down over time. *Integrated Pest Management* (IPM) is used widely as a strategy to avoid the excessive use of one particular control measure and the development of resistance in the pest while allowing the controller's methods to become integrated with the weather. Opportunities for ecological means of control exist whereby knowledge of the biology of both crops and pests and an understanding of their inter-relationships is combined with features of system structure, operation and management such as crop and crop–pasture rotations, crop geometry, pasture management and soil management. At the same time, regular monitoring provides the information needed to work with the appropriate pest–crop relationship and to determine thresholds of pest activity for action. Monitoring and control processes can now be assisted with new technologies that allow early identification and precise location of insect attack, disease and weeds and precise spraying for control (Chaps. 4, 7, 27 and 34).

50.6 Rainfed Farming Systems Around the World

Part II chapters discuss examples of rainfed farming systems around the world in terms of structure, operation, productivity and farming intensity, as well as response to external and internal change. They are usefully complemented by Case Studies in Parts I, II and V, which show both the development of farm systems over time, and the management of the system elements, inputs, and relationships for productivity, profitability, stability, flexibility and sustainability. While these examples comprise only a small part of global systems, they illustrate a good deal of the global variation in the above characteristics.

Many of the world's older farming systems evolved over time to be sustainable, in terms of both production and of preservation of the resource base. In recent times, however, with wars, increased population pressure and other social upheavals, they have become degraded, unproductive and unsustainable (see Chaps. 15, 18, 23, 24 (Fig. 31.7) 33, 38, and 40) while often increasing in intensity of exploitation. Farming systems of the nineteenth and twentieth centuries tended to be exploitative, leading to soil erosion, nutrient depletion, salination, breakdown of soil structure and reduced organic matter content. These adverse trends may be reversed by the application of science, technology and management. Innovations such as Conservation Farming and Integrated Pest Management have led to a marked reduction in the severity of these problems in developed agriculture. It is possible to achieve not only high levels of productivity and farming intensity but also economic, social and environmental sustainability (see, for example Chaps. 19, 20, 25 and 26). However, at all levels of productivity, progress in attaining efficiency, profitability and sustainability is variable, both within and between farms.

50.6.1 West Asian and African Systems

In less developed economies, large problems remain to be overcome in order to raise productivity and farming intensity to near potential levels and to achieve sustainability. Even the small number of examples of African Farming Systems in this book shows the wide range of agricultural development.

Thus in **South Africa** (Chaps. 16 and 17), the range stretches from Communal Farming Systems (with a high degree of subsistence farming) to highly developed, commercial Cropping and Crop–Livestock Systems. In between, there are the ‘Emerging Farmers’, in the process of moving from subsistence to commercial farming. All South African farming systems have some serious limits imposed on them in their attempts to increase their levels of productivity and farming intensity. For instance, commercial farmers often have to deal with low rainfall and poor soils (though not as adverse as those experienced by communal farmers living in the former ‘homelands’ defined under Apartheid). Commercial farmers are also restricted (more than they are in wealthier countries) in the development of industries that could support primary production and in the levels of agricultural research and technology development. However, they have access to much better infrastructure, including transport and marketing, than Communal farmers and even Emerging farmers.

In **Eritrea** (Chaps. 11 and 18), and **Tanzania** (Chap. 38), there are similar restrictions on increasing crop production and farming intensity. In addition, the authors of Chaps. 11, 16, 17, 18 and 38 explain how cultural and social factors, tradition and simply human nature restrict the change in farming practice needed to increase production. This occurs with both livestock and crop production despite demonstrations to farmers of improved production methods. Yet there are many worthwhile features of communal agriculture (such as mutual co-operation) and various authors (e.g. Chaps. 17 and 18) suggest that local farmers be included in the planning of improvements and that attitudes of stewardship of the land be promoted as part of the plan for sustainable resource management.

In **Zimbabwe**, once the 'bread basket' of Africa, internal upheavals have degraded farming systems, as indicated in Chap. 4. Thus comprehensive rehabilitation will be required to restore high levels of productivity and sustainability.

In **West Asia and North Africa** (WANA, Chaps. 5 and 15; also Chap. 40), there are again problems of low levels of both productivity and sustainability. Recent methods of farming (heavy cultivation, depletion of plant nutrients, year-long fallow and grazing to bare ground of self-regenerating plants and crop residues) have resulted in soil erosion, deficiencies of plant nutrients and degradation of soil carbon and soil structure. Research and extension efforts by the international research centre ICARDA, national research organisations and other international aid programs have created a strong move to greater productivity (through use of fertilisers and herbicide sprays) and intensity of farming (through marked reduction in use of fallow). The resulting system, even using traditional crop varieties and livestock breeds, could be sustainable if the removal of crop residues by grazing sheep and goats did not leave the soil exposed to water evaporation, runoff and erosion. Widespread research has prepared the way for more productive, intensive and sustainable farming systems in the WANA region. Of particular importance has been research into no-till farming (Chap. 40), water and fertiliser use efficiency and the production of pasture/fodder legumes in a farming systems framework (Chap. 15) However, achievement of success will require substantial changes to traditional methods of integrating crops and livestock and the provision of appropriate infrastructure, varying from equipment for no-till farming to improved marketing arrangements.

50.6.2 South Asian Systems

A comprehensive overview of South Asian Rainfed Farming Systems is given in Chap. 22. Rainfed farming in South Asia uses some 60% of agricultural land in a continuum of options, from totally rainfed, through degrees of supplemental irrigation to full irrigation. Over such a large area, there is a huge variation in rainfall (from low to flooding), soil type and crops, and progress in moving from low to high levels of productivity and farming intensity. Farming intensity varies from one crop in 2 years (fallow between crops) to double cropping, depending on rainfall. There is also variation in the adoption of the more productive crop cultivars of the 'Green Revolution' (which have been used more fully in irrigated agriculture).

Variability of farming intensity is also related to availability of tractors (in place of draft animals) and other farm machinery, use of fertilisers and sprays, new roads and other infrastructure. As in most other developing countries, there has been a large increase in small-scale farm mechanisation (e.g. two-wheeled tractors), and with it, a lower proportion of fallow and of animals grazing fallow and crop residues.

Where some crop residues are used for animal feed and dried dung is used for cooking, these sources of organic matter are not returned to the soil. High-quality forages could be grown for livestock and alternative sources of fuel such as methane gas used for cooking. The acceptance and use of forages for livestock grazing may be difficult to achieve while the size of individual farms and the number of animals per farm remain small. However, growing and hand cutting of high-quality forages for small numbers of milk-producing and other valued animals could be increased, thus increasing animal production while leaving more residues on the soil.

Hand labour is still used for harvesting and processing grain and for some other farm operations. As long as manual operations are still used in the field, inter-cropping, mixed cropping and relay cropping can help distribute risk. This tends to take the place of crop rotation and to raise intensity and productivity of farming, as far as availability of inexpensive labour will permit. A characteristic of developing economies is that farm labour is being attracted to cities by higher wages, depleting labour for farm work, but speeding the change to farm machinery where this is profitable. However, the resulting reduction in manual operations which allow mixed and inter-cropping will call for alternative means of maintaining productivity and intensity of cropping.

Afghanistan is mainly arid or semi-arid, with soil degradation and delays and setbacks to modernisation of agriculture caused by many years of war. The precipitation is winter-dominant but summer crops are grown by harvesting water from melting snows—a way of increasing productivity and farming intensity. As concluded by the authors, the livestock of 80% of rural households need sources of feed (forages) other than crop residues in order to improve production and return more organic matter to the soil. There is ample scope for improving water harvesting and many other aspects of farming system management in order to raise productivity and farming intensity. Research, education and extension are all needed.

In **Pakistan**, the authors of Chap. 22 state that 'an important goal of farmers is to harvest rain efficiently'. Rainfed areas in Pakistan could be made even more productive through more efficient techniques of harvesting water from melting snows.

India has made much progress in increasing the productivity, intensity and sustainability of its very varied rainfed farming systems, occupying 21 agro-ecological zones. This has been greatly assisted by a large amount of research by organisations such as the Indian Central Research Institute for Dryland Agriculture (CRIDA) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). Progress has been made on all fronts, from new varieties of cereals, pulses and oilseeds to no-till farming, other farm mechanisation and replacement of fallow by crops. Mixed cropping and inter-cropping are widespread. Livestock remain of great value to farmers. The improvements to farming systems need to be continued as changes occur, including reductions in availability of labour, climate change, and pressure for higher food plant productivity.

Bangladesh is a vast riverine plain and also has relatively high monsoon rainfall, and so is outside the normal scope of the rainfed farming systems of this book. However, it provides an instructive comparison with other parts of South Asia. Between 40% and 65% of the area may be flooded each year and soils are mostly fertile, alluvial deposits that maintain large populations of people. This chapter shows how the various types of the dominant crop (rice) and their skilful management are adapted to different levels of rainfall and flooding. However, many techniques still depend on intensive labour. As technology advances, the authors suggest that cropping diversity will decline and fertiliser use will increase on the more profitable cereals (rice, maize and wheat) as long as legume crops continue to be severely damaged by diseases and pests. Thus sustainability may depend on continued pulse crop improvement, increasing use of farm machinery to replace labour that shifts to other jobs and the continuation of high water inputs. More frequent catastrophic setbacks from cyclones, changes in river flow and in the monsoon and from rising seas may all occur as a result of global warming.

Nepal also has a high proportion of rainfed agriculture. High rainfall, ranging from 1,000 to 2,500 mm per year, is sufficient to allow rainfed rice as the major system while three agro-ecological zones based on elevation provide for a range of other crops. High rainfall and the terracing of much sloping land to prevent soil loss provide potential for high productivity and intensity and for sustainability. Two-wheeled tractors have displaced only some of the use of animals for farm power; these animals may be replaced by dairy cows and buffalos, whose dung is used for cooking. This burning of processed organic matter slows progress in building soil health.

On higher, sloping land, lower temperatures restrict double cropping of rice and thus farming intensity; but capture of water flowing down the slopes may allow winter crops to be grown. Use of high-yielding crops and fertiliser raise productivity closer to potential. Although animals graze crop residues, manure is returned to the fields. Horticulture and forestry are also important in these upland areas, but population increase has caused loss of forest, followed by soil erosion and siltation.

Progress towards greater productivity, farming intensity and sustainability is piecemeal in South Asia, and farmers need assistance with new technologies and policies which promote market access and infrastructure. The rainfed farming systems of South Asia have evolved over time to provide sustainable food production and income for farmers, from both crops and livestock. The weakness of the traditional systems now is that they cannot provide sufficient food to meet the demands of increasing populations without some technical intervention. So far, these interventions have been in crop genetics, nutrition and mechanisation, and also in improved breeds of dairy cows, sheep and goats. There is now a need for production of better fodders for livestock, and for improvements in integrated pest management. To ensure that productivity can be increased sustainably, the authors suggest that sustainable land management (e.g. no-till and stubble retention) will be needed, along with more efficient water harvesting, marketing and continued research.

50.6.3 Chinese Systems

In the vast area of Chinese agriculture attention in this book is concentrated mainly on the **Loess Plateau** (Chap. 23)—the most important region of rainfed farming. Its deep loess soil is dissected by erosion gullies, and its sparse vegetation is mainly degraded pasture. Rain from the south-east monsoon falls in summer and early autumn, is highly variable (temporally and spatially) and is sometimes of high intensity. The deep soil holds considerable water for crop growth, with good drainage. Conventional agriculture has involved continuous cropping and intensive, deep soil cultivation, exacerbated by the pressure of overpopulation. Most farms are operated by families, are small (0.7–1.0 ha) and usually have wheat as the dominant crop, with a mixed crop–livestock structure. After feeding the family, the remaining land is used to produce goods for sale and for feeding livestock, but yields have not been high.

Rainfall is the main limiting factor for crop and pasture production, although temperatures are sub-optimal at some higher altitudes. Field experiments show that N and P are the main limiting plant nutrients and that soil carbon content is low. Research conducted by international (e.g. ACIAR) and national organisations have recommended to improve farm systems through crop diversity (both winter- and summer-growing crops) and crop rotations, plant breeding, correction of nutrient deficiencies, control of soil erosion by terracing, pest management, better integration of crops and livestock (with higher quality pastures) and replacement of labour by small farm machinery. Much attention is given to: (1) the harvesting of excess (runoff) water for supplementary irrigation; (2) application of zero tillage and mulching to improve water use efficiency by increasing water infiltration, reducing soil evaporation and reducing water runoff from heavy rains. These technologies together make up a combination of Conservation Agriculture (CA) and Rainwater Harvesting Agriculture (RHA). Their importance is stressed by the authors as an effective part of an expanding process of farming intensification, productivity growth and improvement of economic and resource sustainability. Such improvements must be adapted to the generally small farm size and the need for farm families to produce their own food, through provision of appropriate infrastructure, extension, training and government policies. This should take into account all factors from the technological and economic to the social and cultural.

In Chap. 11 also, the author raises the issue of the rapidly increasing demand for livestock products in **China**. Much of this demand will be filled by grain feeding of livestock. However, the author points out that traditional mixed crop–livestock systems still dominate amongst small landholdings, where animals contribute draft animal power, manure for crop production, and weed control, as well as human food There is scope for team efforts in livestock management and also for planting improved legume forages.

The author of Chap. 11 also investigated the impact of introducing a forage legume, hairy vetch, into the continuous (summer) cropping system in the **People's Democratic Republic of Korea**. Positive benefits of vetch for livestock and following crops were found and the investigation proposed methods to replace the fallow–crop system with a legume–crop system.

Tibet, like the Loess Plateau, has small farms (1–2 ha and decreasing) of mixed cropping and livestock. It has reliable summer rains and opportunities for irrigation to make up for moisture deficiencies. The mostly higher altitudes (3,500–3,900 m asl) and lower temperatures of agricultural areas (some 230,000 ha) confine cropping to temperate species (predominantly wheat) and provide good potential for dairying, especially as irrigation from rivers and streams is possible in most areas. The slightly alkaline soils are generally fertile, but crops need N and P fertiliser to reach potential yield.

The authors of Chap. 24 found that, despite Tibetan farmers relying on spring barley to meet their food grain needs, they traditionally used crop rotations (barley or wheat and mixed plantings of any two of spring barley, oilseed and a legume) to avoid build-up of pathogens and pests and to maintain soil fertility. This diversity has recently been replaced by cereal monocultures in the moves towards self-sufficiency in grain. Irrigation structures that once led to high grain productivity have not been fully maintained in recent times, and communal small tractors and planters are now often in disrepair. This has led to the return to hand sowing and harvesting. Traditional methods are now accompanied by some modern techniques such as application of chemical N and P fertilisers (subsidised and often compulsory), and sprays for control of weeds, pests and diseases. Production from dairy cattle is very low with the animals fed on crop residues and on harvested or grazed weeds. Vetch and lucerne would improve animal and soil nutrition.

Following a thorough analysis of the many deficiencies, limiting factors and constraints of Tibetan faming systems, the authors of Chap. 24 propose a comprehensive range of strategies for improvement. The sporadic changing of farming systems from subsistence to more commercial types is taken into account by the authors in setting priorities and strategies and ensuring sustainability. As an example, the authors suggest a strategy sequence for improving the production of dairy cows, which includes replacing crop residues and weeds as feed with legumes already used in Tibet—vetch for hay and later lucerne for green feed.

The approach to improvement also acknowledges the inter-connectedness of the whole range of system elements, which must all be present to achieve a sustainable system. Thus, as the authors claim: ‘Given that many of the factors that constrain production around the world are not physical, but a consequence of social or economic circumstances, it is worth considering what social or economic circumstances may constrain agriculture in Tibet.’ Such factors may include small farm size, increasing shortage of farm labour as family members work off farm for extra income, traditional attitudes to maximising holdings of cattle and lack of fencing to control cattle movements. These and other constraints must all be managed through farmer participation in developing increasingly efficient, productive and sustainable systems.

50.6.4 Developed Farming Systems in North and South America and Australia

North and South America and Australia generally have farming systems that have evolved over the last few hundred years (though some small-scale, subsistence farming still exists in South America). Much of the land was under virgin forest or grassland, but unfortunately the new farming systems have often degraded soils through erosion, nutrient depletion, salinisation, acidification and compaction.

This was the result of more intense farming as encouraged by larger machines and other technologies following the First and, even more so, the Second World War. Only in recent decades have there been serious attempts to farm more sustainably; at the same time, farmers have been forced to increase efficiency and productivity, by new technology and management, to counteract rising costs. How farmers have done this has varied with location in the 'New World'. These attempts are reviewed below, together with some of the instructive differences.

50.6.4.1 Systems of South America

In South America, subsistence farming has long been practiced and it still is, in the sloping lands of the Andes Mountains and the inter-mountain valleys. These subsistence systems could be sustainable, provided farmers were satisfied with low production and incomes. The authors of Chap. 21 believe, in general, that all systems 'depend on unique local resources and are characterised by differences in economic, political, and social structures and environmental fragility.' All these must be taken into account in making decisions whether, how and to what extent to increase productivity.

Agriculture in the **Pampas** of Argentina is one example in South America of large increases in farming intensity and productivity. Although there was a desire for economic sustainability, the authors claim that the move to higher intensity and productivity was largely driven by politics and short-term gain. Benefits to the community are still inequitably allocated, and there is only moderate success in achieving environmental sustainability. Since European settlement, there was in Argentina, as in other 'New World' countries, an evolution which started with low-intensity cattle grazing of native pastures. The next development was either more productive exotic pasture species or mixed crop–cattle systems on individual farms of about 1,000 ha. These systems resulted in relatively low productivity but also low environmental impact. The year-round rainfall in some places allowed both summer and winter cereals to be grown. Where climate and soils are especially favourable, an even more intensive phase followed new technologies and high market demand, from about the 1980s. This comprised both continuous cropping and double cropping of various sequences of wheat, soybean and maize. This level of intensity has been accompanied by the common problems of soil degradation, herbicide resistance of weeds, and the need for inputs of N fertilisers, with some plant nutrient imbalance. However, a positive aspect of these intensive systems is the high adoption of no-till, stubble retention and cover cropping to combat soil erosion and increase soil carbon content. Mixed farming, which tends to be more sustainable, still occurs in some areas. Livestock production may also be specialised, as in highly intensified cow–calf operations on pastures, perhaps using feedlots for fattening.

Sustainability could be harder to achieve as operations become more intensive. Further, the greater intensity and productivity have not resulted in improved living standards overall (*equitability*), a deficiency linked in part, the authors think, to government policies aimed at reducing budget deficits and not necessarily achieving sustainable land use.

In the woodland/savanna **Cerrado** region of Brazil, rainfall is high but seasonal, with a summer growing season of 6 months. This more favourable climate is offset by the poor, weathered soils, which have high levels of phosphorus fixation and high exchangeable aluminium leading to Al toxicity. Cropping requires costly inputs of soil ameliorants and also pesticides. The high level of natural plant and animal biodiversity in the region is being destroyed by the move to monocropping to satisfy export demand for grains and ethanol. Even traditional livestock grazing has been displaced by cropping, and, in turn, the ranchers have moved into Amazonia to cut down rainforest and plant pastures. In this process, they displace indigenous people and reduce biodiversity. The agricultural intensification in the Cerrado thus has negative aspects which the authors believe will not allow desirable and sustainable land use.

The **Llanos** or plains of Colombia, Venezuela and Guyana are similar to the Cerrado of Brazil in their high, warm-season rainfall and acid soils. Indigenous hunter-gatherers were displaced by European immigrants who raised cattle. Since native pasture grasses and legumes and some introduced ones grow well, while crops generally do not, semi-intensive to extensive grazing has persisted. Thus agriculture in these regions appears to be operated sustainably, while only moderately intensive and productive.

The authors are aware of the ad hoc way farming intensity has grown, especially in Argentina and Brazil, and the risk of unsustainable development. They regard it as important to have an *ecosystem approach* to agricultural operations and development with recognition of the contributions of the natural ecosystems to agriculture. They present a **case study of the 'complete cycle' production of a cow–calf enterprise** using an ecological approach, whereby all inputs, including natural inputs such as rainfall and social inputs such as information are converted to common units of solar energy. These inputs are named 'Emergy', defined as the whole available energy (in common units of solar equivalents, seJ) used directly or indirectly to obtain a product or service. It provides a combined ecological-economic evaluation which takes account of the continual interactions between nature and society, and also the feedbacks associated with 'self-organisation' within the system. It builds understanding holistically from the top down rather than analytically by pulling the whole apart.

The principles and applications in this approach are explained in detail in Chaps. 1 (Supplement) and 21. When resources are abundant, 'the advantage goes to the system (or operator) which is able to draw on them faster than others, regardless of efficiency. When resources decline, efficiency must grow in order to keep output as high as possible, and for the system to survive. One of the many differences between the emergy approach and the usual approach to productivity and sustainability is that, in the emergy approach, 'complex systems adapt to (changing) environmental conditions by optimising and not necessarily maximising efficiency', and also by self-organisation through feedbacks.

The authors claim that 'when the focus shifts to short-term monetary benefit, there is likely to be less attention to the environment or to preserving the natural resources on which long-term wealth depends.' 'Thus there must be a balance between economic developments and sustainable management of the resources.' There must also be adequate emphasis on maintaining *ecosystem services*, which would include improvement or maintenance of the chemical, physical and biological health of soils, carbon sequestration in soil and trees, maintenance of biodiversity (fauna and flora), with biological controls of diseases and insect pests. Measuring emergy flow would be expected to assist long-term decisions in management and public policies.

An important benefit of the use of a common energy unit (solar) to quantify the system is the ability to calculate a range of 'performance indices'. These allow system performance to be understood and efficiencies of various systems and management programs to be compared. It is also of value to be able to calculate the total emergy that is used to obtain a product, i.e. the 'donor value' of the product and not just how much emergy ends up in it. Because this method accounts for all renewable and non-renewable inputs and flows (including such flows as information and weather events), the authors claim that information thus gained assists in devising strategies for sustainable development and welfare.

The case study showed that steer production from the cow–calf system in the Argentine Pampas had a low Environmental Investment Ratio (low ratio of imported emergy to local renewable + non-renewable emergy) which would allow increase in productivity in a sustainable way. The Environmental Sustainability index is at the best level when the system operation depends more on local resources and renewable resources than on purchased inputs—as in grazing natural pasture in Argentina and indigenous polyculture of crops in Mexico. They also suggest that stimulating interactions within the system is another option for increasing yield sustainably.

Another important index is the Emergy Exchange Indicator, which is an indicator of fair trade. The example given is related to the payment received for Argentinean steers by a farmer, who sends 11 times more emergy away from the farm in the product than is embodied in the money received. The consequences for national trade and resource use policies are discussed. It is also seen that 60% of the emergy sent away with the above steers is due to rain. While it is well known how rainfall and its deficiency affect agricultural production, emergy accounting throws fresh light on its high value, the need to use it efficiently even when it is abundant and the need to find ways to maintain its level and the integrity of the water cycle for agricultural purposes.

The authors conclude that there is potential for long-term sustainability of most of the diverse regions of South America provided the resource base is preserved by appropriate forms of Conservation Agriculture.

50.6.4.2 Systems of United States of America

Chapter 20 deals with four major rainfed farming regions: Great Plains with wheat–sorghum–cattle; Midwestern with corn–soybean–hogs; Southern with cotton–soybean–poultry; and Coastal diversified with crops–dairy. These regions have developed specialised cropping and animal production systems under the influence of temperature and availability of water. Rainfall is mainly warm-season dominant and annual precipitation varies between 400 and 1,200 mm. The growing season is limited by low winter temperatures in the north. The most important soils for agriculture are mollisols, alfisols, entisols, inceptisols and ultisols.

The authors of Chap. 20 summarise agriculture in the USA as: highly technologically advanced; dependent on fossil fuel for operating tractors and farm equipment, for supplying energy to dry and process products and for the manufacture of N fertiliser and pesticides. The four accompanying case studies (Chap. 49) show these characteristics, though in variable ways that reflect their environment, goals, management and commitment to sustainable farming.

Farming lands in the 1930s were subjected to great loss of soil by erosion. Since the Second World War, various means have been used to reduce erosion and improve soil health, the latest and most effective being conservation tillage and no-till farming with stubble retention and cropping intensification to avoid fallow periods. The methods of Conservation Agriculture are not yet fully adopted, though they are continually increasing. The aims of achieving high productivity and intensity of farming with sustainability and conservation of the resource base have been distorted by the use of government subsidies to raise farmers' incomes.

The **Great Plains region** has summer-dominant rainfall and a low P/E ratio. Temperatures dictate that wheat is mainly grown in the north and sorghum in the south, although the high water-holding capacity of mollisols allows water to be stored for wheat produced in the cooler months in the south. Reductions in tillage and fallow and increased cropping intensity have together had the greatest impact on increasing efficiency and sustainability of rainfed farming systems. They have reduced soil erosion, improved soil carbon content and microbial activity, and increased WUE through increased water infiltration and reduced loss by evaporation. The **Great Plains case study farmer** from this region has used these methods profitably for many years, as well as crop diversification, integration of crops and livestock and use of cover crops and legume-based pastures. Chemical/fertiliser inputs have consequently been greatly reduced. Wildlife habitat has also been preserved.

Success of this farmer in achieving both farm business and environmental sustainability is not matched by all farmers in the Great Plains. A major characteristic of the region is the specialisation which separates crop and beef cattle production, in order to maximise farming intensity, productivity and profitability. On specialised cropping farms dominated by wheat, cost pressures, economies of scale and the need to manage risk have resulted in farms becoming larger, with districts becoming depopulated and losing some of their community infrastructure. Subsidies are needed to make wheat profitable. In the past, diversified farms that included wheat, sorghum and cattle could offset losses in one with gains in another. The authors believe that specialisation in subsidised wheat reduces *resilience* and thus also sustainability. Currently, diversification is again returning with the opportunities to produce biofuels from cellulosic products, although this will not bring synergies such as those from the crop–cattle combination, which have also been found to be profitable. The authors conclude that in view of the increasing cost of fossil fuel and its use for producing cropping inputs, mixed crop–livestock systems, with improved livestock husbandry and the use of legumes to help reduce chemical fertiliser inputs will be more profitable and sustainable. In addition, there is degradation of natural resources as it becomes more difficult to dispose of livestock wastes on specialised livestock farms.

The **Midwestern farming region**, where agriculture has been practiced for 150–200 years, is even more intensively farmed than the Great Plains. This is consistent with the higher, summer-dominant rainfall and productive soils. However, there has been a history of serious soil erosion. When limitations to drainage are corrected, high productivity is achieved, but with 'leakiness' of agrichemicals into water systems. When problems of soil erosion were also corrected, the diversity of farm enterprises, including livestock, which made up the farm systems up to the mid-twentieth century, should have ensured sustainability of systems. However, crop and livestock specialisation and intensification replaced diversity. The ideal climate, good soil and the development of hybrid corn and of soybean for grain encouraged farmers to specialise in these crops to gain efficiency and economy of scale. This specialised cropping system was economically sustainable while yields of both crops increased steadily in recent decades (as reported also for Western Australia in Chap. 28), due to substantial genetic and management improvements.

However, with increasing fuel and chemical costs and sometimes lower prices for grain, farmers received government subsidies to remain viable. Thus, as the authors state, "specialisation has made it increasingly impractical to move away from corn and soybean production, despite the recognised benefits of diversity for economic stability, labour distribution, ecological and environmental outcomes and the ability to respond rapidly to changing climatic and economic conditions. The associated specialisation and feedlotting of livestock has resulted in the concentration of animal wastes, creation of odours, water quality problems and excessive nutrient load on the limited land available for manure application."

Other outcomes from specialisation have been: (1) increasing farm size and reduction in wider community diversity; (2) removal of structures, previously put in place for soil conservation and wildlife conservation, in order to improve the efficiency of larger equipment; (3) loss of many farm woodlots; (4) replacement of animal manure and pasture legumes with costly chemical fertilisers; (5) leaching of excess nutrients into waterways, especially in spring and early winter.

The **Case Study** farmer in this region (**Iowa**), also constrained by government subsidies, grows corn and soybeans at high levels of productivity, but combines that with a strong, traditional land ethic. This involves monitoring and precise management while maintaining soil fertility, soil contour banks and permanent grassed waterways to control soil erosion. To achieve goals, reduce costs and avoid problems of shortage of labour, he turned to conservation tillage (strip tillage) with stubble retention, herbicide-tolerant crop varieties, and RTK precision farming.

The authors of Chap. 20 see likely benefits for the mid-west from the use of perennial biomass crops for biofuel production. These can also cover the soil year-round and so increase soil organic matter and prevent erosion; if deep-rooted, they will also restrict deep drainage of excess nutrients. They believe that farmers need to lower risk and increase profitability by diversifying their operations. A rotation of corn, soybeans and alfalfa, under no-till or chisel tillage, can be more profitable than corn–soybean. They also suggest that appropriate cover crops may help prevent erosion and deep leaching of nutrients—thereby increasing overall profitability and sustainability. They believe that sustainability of these highly productive systems can be improved with changing public opinion and government policies. For example, if attention to natural resource and land management were shifted from the individual farm to the community or watershed, a systems approach would be possible to address a wide range of issues simultaneously, with coordinated efforts and results.

The **southern cotton–peanut–poultry region** differs from the others in the USA in its subtropical temperatures and abundant (but variable), near year-round rainfall. Cotton and peanuts are suited to the temperature regime and rainfall seasonal distribution. Poultry CAFOs were developed in response to low heating costs in the year-round production systems and availability of cheap land, of labour and of transport infrastructure.

The effects of low natural pH and nutrient status of the kaolinitic soils are exacerbated by the heavy, leaching rains and the fixation of P and trace elements; these require regular amelioration. The high summer temperatures cause rapid decomposition of organic matter. Poultry litter provides organic matter and nutrients, but it requires careful management to avoid over-fertilising of land near the CAFOs and escape of nutrients to waterways. In addition, the ratio of nutrients in poultry litter is variable but usually different from that required by crops. Thus litter application rates need to be based on the requirement of the crop for P and not for N, lest P is lost to waterways. The authors also suggest combining carefully controlled manure applications with conservation tillage and winter cover cropping to help reduce leaching and runoff of nutrients and also erosion. Thus the integration of separate, specialised crop and poultry systems requires consistent, accurate management for sustainability.

The use of conservation tillage with soil surface residue retention has increased water use efficiency and soil health. Carbon sequestration has increased to more than half a tonne/ha/year. Crop yield and profitability have improved while fertiliser N requirements have decreased.

The authors emphasise that: “The warm and humid conditions of the south-eastern USA are conducive to the development of crop pests and diseases so their management is more intensive than in other regions.” By concentrated efforts, including some preventative spraying, it has been possible to eradicate the cotton boll weevil. IPM comprises crop rotations, sanitation, scouting, spraying and pest resistance but controls based on ecological relationships are sought for long term sustainability.

Weed control is also based on a wide combination of strategies and methods, including use of herbicide-resistant crop varieties, chemical sprays, smothering weeds with heavy covers of plant residues and winter cover crops, and crop rotations. These strategies provide flexibility and thus help in keeping the cropping system sustainable. Where there is perennial pasture, the subsequent high soil organic matter, resists compaction from cattle traffic.

On the **Case Study farm** near **Augusta**, **Georgia**, high levels of technology are combined, with a high level of land ethics and stewardship, in a continuous cropping system typical of the region. Though annual rainfall is high (averaging 1,200 mm/year), droughts can occur in summer due to high rates of evaporation and drainage through sandy soils. High efficiency of water use has been important. The farmer has achieved this mainly through: (1) harvesting winter rainfall runoff for supplementary irrigation, and (2) using conservation tillage (30 cm wide soil disturbance) and surface soil cover to reduce soil evaporation. Efficiency in management is achieved through regular monitoring of soils and crops and precise application of fertilisers and pesticides. Economic stability is achieved by crop diversity in rotations—cotton, peanut, soybean, corn and wheat. Conservation Tillage (with the use of winter cover crops) has also been important in managing very wet conditions, water runoff and soil erosion. This farm system therefore appears to be economically and environmentally sustainable.

The authors of Chap. 20 maintain that, in this southern region, full integration of crops, pastures and livestock would add substantially to the benefits of the above strategies through greater efficiency of utilisation of resources, economic stability, lower impacts on the environment (less pollution), benefits to soil health and greater flexibility of operation. Considerable research is now being conducted into the operation and economics of a range of crop–livestock systems throughout south-eastern USA. They conclude that the combination of all the above measures will lead to greater economic and environmental sustainability.

The **north-eastern USA** is a cool, humid region, with annual rainfall generally of 1,000–1,200 mm/year, relatively uniformly distributed. The cropping system is often determined by soils and topography, which vary considerably. Climate and markets are also diverse. Parts of this almost 1,500 km long coastal region have been farmed for 350 years, and diversity of enterprises has been a feature for centuries. The total area of land under agriculture has contracted in recent years, thus also shrinking agricultural infrastructure such as input suppliers and marketing services. This makes it difficult to maintain existing levels of operation.

Farms are smaller than in other regions (though growing in recent years), and have not shifted to specialisation. Many are integrated crop–livestock systems, which rely on their own pasture, conserved fodder and grain, although some grain is imported for dairy cows. Improvements in technology and management have brought high levels of efficiency and productivity. Milk production per cow has more than doubled since 1960, as have the yield of corn and the amount fed to dairy cows as supplements. However, costs of production are high compared to larger dairy operations.

Efficient pest management is required in this humid environment, and use of no-till and crop–pasture rotations can increase some pest problems. Costs are minimised by monitoring for timely spraying and use of genetically-modified corn and disease-resistant crops. Weeds are controlled by rotation of crops/pastures and by other integrated means.

Enterprises are integrated not only by mixed crop–livestock farming but also by inter-farm relationships. For example, manure from dairy farms is transferred to potato farms for growing forages, which are transferred back to dairy farms. This allows potato farmers to diversify their operations and improve their soils while dairy farmers can dispose of excess manure and avoid pollution of waterways.

The **case study farm, in south-eastern Pennsylvania** is based, however, on a continuous cropping system, in which the resource-efficient farmer uses new technologies, with a background of long-held (tried and tested) tradition, to achieve conservation and profitability goals. Crops grown are corn, soybeans, alfalfa, small grains, tomatoes and pumpkins. The farmer modifies machinery to deal with all types of crops. With favourable climate and soils, the main problem has been soil erosion. This is countered by applying Conservation Agriculture (long term no-tillage, stubble retention and cover crops, with crop rotation). Heavy soil surface organic matter also helps smother weeds and provides resistance to soil compaction. Cover crops are killed mechanically. Thus costs are kept down, while crop yields in this environment are high.

Rainfed Farming Systems in all four USA regions discussed have the benefit of high levels of research and technology, which are major influences in the achievement of generally high levels of intensity of farming and of productivity. However, increasing intensity and productivity are not always associated with sustainability; profitability is assisted by government subsidies while pollution of land and water by chemical inputs applied at high levels acts against environmental sustainability. This is exacerbated by the specialisation of crops and livestock.

Soil erosion is also still a problem which, however, is being increasingly controlled by conservation tillage and no-till, with stubble retention and cover crops. Another problem is the depletion of groundwater for irrigation. The authors suggest that the aim should not be maximum productivity, but optimal levels in keeping with conservation of the resource base and economic sustainability. This suggestion is similar to that made in Chap. 21 for generally high rainfall areas in South America. The adverse effects of crop and livestock specialisation can be alleviated by increasing diversity of enterprises and integrating crop and livestock production. Rainfed farming systems need to be made more water- and nutrient-efficient and ecologically sustainable.

50.6.4.3 Canadian Farming Systems

The **Canadian Prairies** (Chap. 19), like the Great Plains of the USA, have sub-optimal, variable, summer-dominant rainfall and continental temperature regimes of short, warm-to-hot summers and long, cold winters. Winter temperatures are lower than in the USA. Frosts may occur between mid-August and mid-May leaving a frost-free period of 90–120 days and reducing the growing season to around 100 days.

The colour of the soils (brown, dark brown, black and grey) is used as an indicator of annual precipitation, which varies from about 330 mm (brown) to about 470 mm (grey). Since the start of agriculture on the prairies less than 130 years ago, the soils have lost about 40% of their original nitrogen content through grain export, erosion by wind and water and leaching, primarily through use of a crop–fallow system after an initial decline in soil fertility. Soil organic matter content has also declined.

Thus both climate and soil limitations strongly influence productivity. Attempts to raise productivity and intensity of farming require high levels of efficiency of utilisation and management of resources, especially moisture and nitrogen. Conservation and improvement of soils is now widely regarded as essential for the sustainability of Canadian rainfed farming systems.

The fallow-based farming system has been replaced since the 1970s by systems of continuous cropping and integrated crops and livestock. Continuous cropping has been made possible, initially by using herbicides instead of cultivation to control weeds and then using nitrogen fertiliser to replace soil mineralisation during fallow. Greater flexibility to deal with input costs and the variability of markets and climate was achieved using a wide diversity of crop types—cereals (spring and winter sown types), pulses and oilseeds, as well as GM canola and soybean to help overcome herbicide resistance in weeds.

The replacement of fallow by continuous cropping required greater efficiency in the year-round capture and use of precipitation. This has been increasingly achieved over the last 30 years by the adoption of no-till farming with soil surface stubble retention, this largely eliminating soil evaporation losses, water runoff and erosion. In addition, the small but significant water falling as snow during winter can now be trapped in tall standing crop stubble and used for early establishment of crops, including small seeds such as canola.

The greater intensity of farming since the 1980s has made farming systems more productive and sustainable. Such achievements have been supported by extensive research, education, engineering and a wide range of commercial and government infrastructure. Since about 1970, strong farmer and government-sponsored groups and programs dedicated to the conservation and improvement of agricultural soils have led to rapid progress in the development of no-till technologies, with assistance to growers to experience and adopt these methods.

The authors quote Gilson (1989) in saying: "The challenge for Canadian agriculture is to ensure economic viability while both satisfying society's need for safe and nutritious food and conserving or enhancing the environment for future generations." They add that "In order to sustain a profitable industry, attention has to be focused on efficiency and productivity" and "Advances in crop production are directly related to how efficiently water and nitrogen are managed and how the supply of one is matched with the other". As shown in Chap. 19, considerable research has been conducted to improve the efficiency of utilisation of water (WUE) and nitrogen (NUE).

WUE (or PUE) has been found to vary with crop species, rotation, tillage practice and soil fertility, but can be improved simply by employing the best agronomic practices. PUE is also increased by using no-till with stubble retention, thus reducing water run-off and soil evaporation. Where these practices are used, productivity is increased towards the potential.

Nitrogen is the nutrient that is most limiting to crop production in Prairie rainfed systems and the one applied in greatest amounts. Nitrogen fertilisers represent

65–70% of total energy input for crop production on the Prairies. NUE is therefore important and can be maximised by minimising losses and waste of applied N. The NUE in Western Canada of 50–70% is high by world standards (about 33%), but open to further improvement as costs of fertiliser increase. Losses through volatilisation, denitrification and leaching are minimised by applying N fertiliser as close as possible to the time of maximum crop uptake in spring or, if at planting (when denitrification in wet soil can be especially severe), by delaying nitrification through the application of slow-release urea. It is realised that pasture legume residues are also a source of slow-release N, but that predictions of further N requirements during crop growth (using techniques such as crop colour sensing) are still needed in this environment of low and variable rainfall.

For crop disease control, apart from fungicide sprays, resistant crop varieties, clean seed and field hygiene, crop rotation is regarded as the most effective biological control option. This is thought to be related to the changes in soil biology under different crops. The increase in organic matter with no-till also helps improve soil health. Thus Conservation Agriculture (CA) is regarded as helping greatly in achieving high productivity and sustainability of Prairie farming systems.

Under no-till, weed management becomes entirely dependent on herbicides and crop production practices. Monitoring of this system over time has shown no major shift in weed species. This is probably due in part to the diversity of crop species and herbicides used. This CA-type system is complemented by application of Precision Agriculture (PA) for precise placement of fertiliser near the crop row but more distant from inter-row weeds. It is considered that the combination of CA, PA, herbicide-resistant canola, and the wide, temporal variability of climate on the Prairies provides the means to vary selection pressure on weeds and prevent them developing resistance to herbicides. This is reflected in the overall reduction in weed densities and weed management costs on the Prairies.

Long term economic research into Prairie farming systems was largely concentrated on comparing fallow–crop and continuous cropping systems and later, no-till and conventional cultivation. This is particularly important in the drier areas of the Prairies, where the decision to adopt continuous cropping in place of a fallow–crop system depends on the rainfall, the expected price of the crop (mainly wheat) and the degree of risk aversion of the farmer. Decisions on whether to sow a crop or put the land to fallow are assisted by knowing the spring available soil moisture. A 'flexible continuous wheat rotation' is one where fallow is substituted for a wheat crop when spring available soil moisture is less than a given amount; but it is also based on the price of wheat. Such flexibility is thus simple to apply, is based on risk assessment, and also helps to improve and stabilise income (see also Chaps. 25 and 35 for discussion of the value for planting decisions and risk assessment of knowing the amount of water stored in the deep soils in north-eastern Australia).

The inclusion of lentils in the rotation has also increased financial returns, at least in higher rainfall years. This was because N fixed by the lentils replaced some fertiliser N, but success also depends on a good price for this crop. Soil quality is also improved by lentils. Thus there is qualified support for increasing farming intensity in the drier (brown soil) zones. Fairly successful attempts have been made to combine the N fixation benefits of lentils and the water accumulation benefits of fallow by growing lentils as a green manure crop on fallow land for part of the season. This could be financially beneficial if the price of N fertiliser increases further (see Chap. 7 for a similar use of short-term cover cropping in north-eastern Australia).

Experiments with no-till showed little economic benefit over conventional cultivation and minimum tillage in the mid-nineties because of high herbicide costs and lack of crop yield increase. The continued expansion of no-till, with crop diversification and snow capture in the drier areas, indicates an improved economic situation (sustainability) as long as commodity prices are average or above average. In the higher rainfall zones (dark brown, black and grey soil zones), experiments showed economic benefit in diversified and continuous cropping systems combined with no-till practices.

Energy use efficiency is of concern both because of the monetary cost of fuel energy and the effect of its use on global warming. Agriculture accounts for about 10% of total greenhouse gas emissions in Canada. With the use of continuous cropping and no-till, fertilisers account for some 60–70% of energy use in crop production but this is reduced by including legumes in the rotation. Previously, fallow reduced the need for N fertiliser but at the expense of soil quality. The authors conclude that energy use efficiency is maximised by increasing energy in the outputs, through higher water use efficiency, improving soil through no-till and stubble retention and introducing legumes into the faming system. There is considerable interest in Canada in the production of energy from agricultural products (perennial species biomass rather than grain). While this would provide greater diversity and sustainability of farming systems, questions arise about the justification of using good cropping soils for energy production rather than for food.

While the principles and technologies followed on the Canadian Prairies support increasingly intensive, productive and sustainable farming systems, it is the management of the farm systems which must carry this through to fruition. The two **case studies** show this. The two farmers, in **Manitoba** (Chap. 31) and **Saskatchewan** (Chap. 48) inherited their farms from grandparents and parents and have increased their farm size while their farming systems also changed in response to various pressures and technological opportunities. For instance, they went from mixed crop–livestock farming (which provided good year-round cash flow) to continuous cropping. Reasons for this included lower availability of labour, changing economic conditions, personal preference and decisions to take on other career work besides farming (one as a farm consultant and the other as a designer and manufacturer of no-till planting equipment).

While their non-farm work has maintained a cash flow previously provided by farm enterprise diversification, they have also had to minimise costs and work efficiently to maintain sustainability. For this, they have also adopted Conservation Agriculture and modern technologies such as the use of herbicide-resistant canola (particularly the Manitoba farmer) and Integrated Weed Management to avoid herbicide resistance in weeds.

The non-farm work of these two farmers also successfully benefits a wider community, and also feeds back information from that community for use on their own farms. This type of exchange is an important attribute of successful farming systems. Of paramount importance however, for both farmers and the sustainability of their farms is the conservation and measured improvement of their soils. The Manitoba farm also attracts all manner of wildlife species which, with care, can exist in balance with modern farming.

Both farmers have found that no-till with stubble retention, after many years of use, is the most profitable farming system, especially when accompanied by crop diversity and low input costs. They have therefore shown that it is possible to maintain relatively small, efficient and highly productive family farm systems that conserve and even improve the soil resource base, while operating a separate, outside business. They still acknowledge the need to keep up with new technologies in order to be economically sustainable and to be able to respond effectively to external change.

50.6.4.4 Southern Australian Rainfed Farming Systems

Chapter 26 focuses on the mixed crop–livestock farming areas stretching some 3,000 km across southern Australia, south of latitude 32°. Up to the 1980s this was known as the wheat–sheep zone. Annual rainfall of 300–600 mm is winter dominant, except in the eastern parts where it is more uniformly distributed. During the last 30 years, there has been a general trend to lower rainfall which, with high rainfall variability and incidence of drought, has affected the structure and operation of the farming systems.

Wheat and sheep have been integral components of southern Australian rainfed farming systems since white settlement of these lands from the mid-1800s. There were ready markets in Britain for grain and wool. Then as the initial soil fertility of farming land declined from the late 1800s, the accidental introduction and spread of annual subterranean clover (*Trifolium subterraneum*) and *Medicago* species was opportune to supply high-protein feed for sheep and add N to the soil. The crop–pasture system replaced the crop–fallow system and helped control soil erosion. The discovery of responses to superphosphate in the late 1800s and to various trace elements some 50 years later, together with wheat and sheep breeding and inventions of farm machinery raised productivity and created a low input/low cost crop–livestock system. This system seemed stable and sustainable. However, the relative decline in the profitability of wool and the greater availability of N fertilisers in the second half of the twentieth century directed the move to continuous (more intensive) cropping and often separate livestock production. This was assisted by the introduction of no-till methods and a wide range of herbicides.

These issues have also been important in many other countries. However, the separation and intensification of crop and livestock production have been less marked in Australia because: (1) the benign climate allows animals to graze green pasture and dry crop and pasture residues year-round; (2) historically there have been markets for wool and meat; and (3) the combination of crop and livestock products has provided income stability.

However the process of change since the 1980s has been complex. The authors of Chap. 26 describe the mixed farming system in southern Australia as reversible—between continuous cropping and a mixture of crop and pasture/livestock. Thus while emphasis in research, development and extension has been on improving crop production, pasture and livestock production have not been forgotten.

As in other developed countries, crop productivity has increased markedly due to a wide range of technological improvements. Increases in both Total Factor Productivity and efficiency of utilisation of inputs—such as water, fertiliser and labour—have kept individual enterprise profitability ahead of declining terms of trade.

At the same time, there is a continuing need to address problems relevant to the level of success of farming systems, such as soil degradation, herbicide resistance in weeds, increasing costs, drought and climate change; and to package solutions for economic management. The following major lines of research and their relevance to farming systems show what is required to sustain modern, developed farming systems:

- *Genetics for improved plant and animal performance.* This includes breeding not only for disease and pest resistance and quality but also for environmental adaptation associated with climate change. Breeding programs for a large range of cereal, pulse and oilseed crops and pasture species are essential to meet the need for diversity of cropping. The genetic improvements in crop and pasture species have parallels in animal breeding, where considerable potential for improvement still exists.
- *Improvements in plant and animal nutrition.* Since the 1980s, this work has developed beyond the definition and location of nutrient deficiencies to more complex problems of nutrient use efficiencies and the interactions of plants, animals, soil properties and economics. A good example is the sequence starting with the introduction to a cereal-based rotation, on acid soil, of acid-sensitive canola as a high-valued break crop, with consequent economic additions of lime. Following the use of lime, acid soil-sensitive lucerne was introduced into annual legume pastures to raise livestock production to economic levels and so provide, with wheat and canola, a considerably more diverse, profitable and stable system. In contrast, on the alkaline soils in South Australia, where there is little summer rainfall, lime and lucerne have usually no place; canola grows well and the better adapted annual *Medicago* species can provide high protein fodder (though with lower feeding value than lucerne) and improve soil nitrogen. The legume pasture is successful as a disease break only if disease host grasses are controlled. Whether to include pasture legumes in the rotation still depends on the price received for grains and the need, cost and efficiency of use of N fertiliser. The continuing provision of new herbicides and herbicide-tolerant crops, combined with adoption of Conservation Agriculture, are effective in bringing profitability and sustainability to rainfed farming systems. However, costs must be contained and a stewardship program maintained to deal with any problems arising with the use of these technologies.

- *Conservation agriculture, zone management and precision agriculture.* This structural feature of rainfed farming systems allows continuous cropping to be sustainable. However, in mixed farming, there is the risk that excessive summer grazing will reduce crop and pasture residues (including standing stubble) and also damage soil structure. This implies light grazing to preserve standing stubble rather than selling it as horse bedding straw. Zone Management and Precision Agriculture have been shown to improve efficiency of farming systems and to be potentially profitable, as will be discussed later.
- *Annual and perennial pasture*s. The vast amount of pasture research and plant breeding in Australia has been interrupted in recent times by a trend to continuous cropping. However, the benefits of mixed farming are still widely recognised and appropriate cultivars and good pasture management will still largely determine the adoption and profitability of mixed farming.
- *Mosaic farming.* A mosaic of native vegetation with crops and pastures over the landscape provides a range of ecosystem services such as soil conservation, water flow regulation and capture, deep drainage reduction, refuges for bird and insects for pest control and zones with biodiversity value.

Although the higher profitability of cropping than livestock since the 1970s has contributed to a trend to more intensive cropping, the structure and composition of rainfed farming systems has generally remained fluid. However, farmers who invested heavily in larger seed drills, sprayers and harvesters found themselves in an irreversible, specialised cropping situation. Shortage of labour also made it difficult to have livestock in the system. On the other hand, some farmers with medium-sized farms have been unable to achieve economies of scale to enable them to make continuous cropping more economic than mixed farming.

One of the most important reasons for many farmers retaining or returning to a mixed crop–livestock system is the widespread occurrence of serious drought in recent years. This caused greater economic losses in high-input cropping, especially from more drought-sensitive pulse and oilseed break crops, than from some well-managed legume-based pastures. This has also been found in Canada. Appropriate management of pastures in a rotation also helps control weeds and avoid problems of herbicide resistance and soil-borne diseases. Management is a vital factor in the success of mixed farming systems. Yet it is now uncommon to find farmers and advisers who are able to manage both crops and livestock/pastures equally well. In Chap. 11, the author suggests that crop and livestock enterprises, though integrated for the benefits of diversity and synergies, might be managed and advised by separate, specialised people.

Recent surveys of consultants throughout southern Australia (Chap. 26) show that there is generally little variation in farm profitability across a wide range of crop and livestock enterprise mixes (50–80% cropping). Higher cropping intensity increases some problems such as input costs and herbicide resistance in weeds. A key conclusion was that there was more variation in economic performance between individual producers than between different enterprise mixes, indicating the importance of individual farmer management.

The consultants surveyed also generally agreed that, within biophysical limits, personal preferences and social factors drive decisions about the enterprise mix. This differs from the simple belief that an increase in cropping intensity has been brought about mainly by the higher profitability of crops than livestock. Personal factors which may have caused some of the trend away from mixed farming to cropping could have included the retirement of older farmers who were accustomed to managing mixed systems of crops, pastures and livestock. In contrast, younger farmers are said to prefer cropping to livestock and they may also have off-farm occupations which occupy some of their time (see also Chap. 31, Canada).

The **social dimensions of mixed farming systems** are examined in depth in Chap. 30. The authors state that most farming systems in Australia are run by farming families, whose fundamental reasons for choosing to farm are social. As they try to adapt to external and internal change, there is therefore a social element operating in their decisions.

Farmers do not simply change their system when the financial incentive is sufficiently high. To them, farming is a serious and professional business where the business owners are motivated by social drivers. In deciding on whether or not to change their enterprise mix (a complex decision), they consider a range of variables which goes far beyond simply ‘costs and returns’. They include the desire to: keep their system simple; access labour when required and use it efficiently; find time for recreation; and operate predominantly those enterprises which they most enjoy (e.g. sheep husbandry or crop production).

Decision making is made more difficult and complex in times of hardship and stress, as in the recent drought over much of Australia and in the associated rural decline. Drought eats away at farm families’ physical, financial and social/personal reserves, and dramatically increases the complexity of the decisions they have to make. In time of drought, farmers try to find ways to reduce their vulnerability to its effects. Thus as the authors say: “Just as drought is seriously challenging rainfed agriculture, it is also perhaps increasing the popularity of mixed farming”. This is reminiscent of why farmers in less developed countries usually keep some cattle. Drought also exacerbates existing issues. Thus the local economic and social structures needed to keep farming systems and their managers productive and efficient in good times are depleted by drought.

The authors found that drought increased the need for assistance and additional training in financial management and decision-making. Farmers need help in ‘drought-proofing’ their farms and traditional ‘rules of thumb’ are no longer adequate.

Extension officers and advisers can help farmers make complex decisions through providing relevant information, a listening ear and help with planning strategies and tools. Research must also balance the various needs which occur in farming systems, e.g. the need for genetic improvement of pastures and livestock, and for improvement in pasture management and livestock husbandry.

The regional overviews and case studies in Chap. 26 illustrate the principles discussed above and also show the diversity of farming systems in structure, operation and management related to environmental conditions and individual farmer decisions.

In the **northern sandplains of Western Australia**, lupins have been bred as a profitable crop for rotation with wheat on the acid, sandy soils. Continuous cropping may be favoured by those committed to no-till and stubble retention, but because of low and variable rainfall, most growers will probably maintain some livestock for income diversity and lower risk. The **two case farms in this region** receive annual rainfall of 340–385 mm, both markedly winter-dominant. They show the variety of management methods used to retain flexibility and sustainability. Although the farmers have tended to buy more land and crop continuously, livestock and pastures remain part of the multi-faceted array of structural and management components (needed to cope with financial and climatic risk and herbicide resistance), which also include a variety of cereal and non-cereal crops, no-till and stubble retention, and GM canola.

In contrast to the northern sandplains of WA, **case farms** on the **southern slopes and plains of NSW**, though still based on wheat as the major crop, are more reliant on livestock. The general trend to continuous cropping in this region is less marked than in other parts of the wheat belt. The moderately high annual rainfall (400–650 mm) distributed fairly uniformly through the year favours perennial pasture species such as lucerne.

The generally low-intensity rainfall reduces the need for control of soil erosion by stubble retention and hence contributes to the relatively slow adoption of no-till farming.

It has been found that the adoption of a package comprising wheat, canola, lucerne/annual legumes, with applied lime, tactical N fertiliser and winter removal of grass weeds from pastures is beneficial to both crop and livestock production It also results in increased soil organic matter and reduced soil-borne diseases of wheat. Such mixed farming systems are semi-intensive, productive and profitable. They seem likely to remain sustainable provided appropriate technologies and management continue, with efficient use of water and nutrients.

The case studies in Chaps. 32, 44 and 46 show how farmers in south-eastern Australia have benefited from adopting lucerne pasture as a component of their rotations and have progressively developed their current farming systems from traditional systems.

Chapter 32 shows how 10 of 13 farmers in a study in south-east Australia have substantially improved their farming systems by introducing **lucerne pastures**, while still conducting intensive and often no-till cropping. The structure of the rotations has been very variable but, on average, introducing lucerne has not reduced cropping intensity. Rather, it improved farm profitability as stocking rates were increased and emphasis was placed on prime meat production, rather than wool. This occurred even though mean annual rainfall of the group was only 300–580 mm and only about a third of this fell in the warmer months when lucerne has its greatest production potential.

The manifold advantages of lucerne in rotations described in these studies make it a key component of eastern parts of southern Australian rainfed farming systems, where a substantial component of the rain falls in the warmer months. The farmers show considerable management skill in adapting it to their particular soil conditions, strategies and cropping program. Some farmers have experienced difficulties in establishing lucerne, but others have found ways to do it both successfully and cheaply. For instance in **north-central Victoria** (see Chap. 46), lucerne is planted under a lupin crop in autumn (when grass weeds are controlled by herbicide) and intercropped with cereal in its second year. This facilitates the transition between pasture and crop phases and provides an income from the land while the lucerne is establishing. This also illustrates the farmers understanding of relationships among system components, which is important for system success: he uses an understanding of competitive relationships, starting when he establishes lucerne under weed-free lupins (not under cereals). Then when the lucerne is 1 year old (of little value for grazing), it is intercropped with a profitable cereal, by which time it can withstand competition from the cereal, even after a set back from a knock-down herbicide prior to cereal planting.

However, successful establishment of lucerne is an example of an issue which can trouble farmers to the extent that it causes them to swing to continuous cropping, especially if that is their personal preference and if they have good cropping soils.

The authors give good evidence of increased farm system profitability and flexibility due to inclusion of lucerne for grazing, hay and silage and production of sheep meat rather than wool. With lucerne in the rotation, farmers have been able to grow the more profitable crop (wheat) as the main crop, needed less supplementary feed for livestock and sometimes sold lucerne hay.

The attraction of continuous cropping still remains strong for some farmers, especially those with a preference for cropping and who have good cropping soils. This attraction is increased by the greatly improved technology and equipment now available for continuous cropping. However, all farmers are aware of the value of lucerne and livestock in times of below-average rainfall, high crop input costs and low grain prices.

A mixed farming system with enterprises similar to those of Chap. 46 (such as wheat, sheep and lucerne/annual legume pasture) is discussed in Chap. 44. However, this farm (located in **southern NSW** with mean annual rainfall of 540 mm) has been different in having to deal with many limiting factors and their interactions in order to reach the present productive and profitable condition.

The failure of no-till practices (introduced in the 1970s–1980s) to provide expected benefits started a process of defining and correcting limiting factors related to plant nutrient deficiencies, soil-borne disease, low soil pH and low wool prices. This process is essential for maintaining system productivity, profitability and sustainability. The improvements attained also led to other benefits. For instance, the high yields and cash flow from correcting limitations enabled the farmer to overcome the problem of shortage of skilled farm labour, by buying new farm equipment that increased the efficiency of farm operations. He also has a policy of 'integrated flexibility' and constant improvement of system components, enterprises and management, a concept similar to 'continuous improvement' mentioned in Chap. 27 and also essential for achieving sustainability. This policy was distorted by the decade-long run of low rainfall seasons, yet the farmer was able to provide security for his family through the skilful operation of his mixed crop–livestock system.

The run of dry seasons has been so serious that the farmer believes that some off-farm investment may be required to help the farm system to remain sustainable. Suitable government policies are also needed. An example is the Farm Management Deposit Scheme, which allows farmers a tax-effective way to deposit money after good seasons and withdraw it in low income years. Another hope is that the government will reward farmers for their contribution to landscape management, greenhouse gas abatement and the protection of biodiversity.

Some 500 km south-west of the farm in southern NSW (Chap. 44) in the **Victorian Wimmera** is the case study farm of Chap. 47. It is a winter-dominant rainfall area with a mean growing season rainfall of only 290 with 120 mm in the warmer months. Thus, a major requirement of management is to use all available moisture efficiently. Continuous cropping, using no-till with stubble retention and precision farming, and annual feedlotting of purchased prime store lambs have replaced fallow, annual pastures and wool production. Unreliable rainfall has restricted crop diversification (beyond wheat) to lentils and oats for hay. Water use efficiency and soil carbon content have been increased markedly by retaining stubble, while erosion risk in summer is greatly reduced. The farm system has the ingredients for high productivity and sustainability but the farmer will require considerable skill and confidence to operate it successfully in the increasingly complex situations caused by an uncertain climate, as well as market volatility.

Further west again, in the **mid-north region of the South Australian** rainfed farming zone, the Case farm in Chap. 42 shows another pattern for achieving profitability and sustainability in mixed farming. This area has been farmed since the 1850s and has hard-setting red-brown earth soils which declined in fertility under the original cereal–fallow rotation. What makes this area valuable for rainfed farming is its relatively reliable climate: mean annual (winter-dominant) rainfall of 460–490 mm (with 350–380 mm in the growing season), relatively mild droughts and low frost risk. However, water deficit is still the dominant limiting factor for crops and pastures.

The farmer has had consistent policies which have paid off economically and in personal terms. These included: (1) involving his family in the farm and so achieving family continuity and co-operation in its operation; (2) always seeking expert advice on financial, scientific, technical and management matters; (3) continuing to buy more land over the years to provide for increasing family needs; (4) taking care of the soil and other resources; (5) adopting new practices where they improved the profitability of the farm; (6) using good farm records and budgets; (7) setting up a Board to make important strategic decisions and (8) membership of a 'benchmarking' group of farmers.

All these have led to good outcomes including less traditional enterprises, such as the long-term development of a free-range egg producing enterprise which integrates well into his crop–sheep system. In addition, new crop and pasture varieties and technologies such as conservation farming have been adopted. The management has been systems-oriented in every way, e.g. by keeping the enterprises and components of the farm system complementary to each other. This can be seen in the diverse rotation, in the development of the poultry enterprise and in the retention of sheep enterprises for wool and prime lamb production. The sheep enterprises fit in with the cropping program—utilising residues or early weed growth and occasionally early crop growth—and do not have conflicting labour requirements, as shearing occurs after grain harvest and lambing in early spring, between sowing and hay making. Wool and prime lambs provide reliable income in most years. The sheep and grazed vetch (a replacement for subterranean clover) also return N to the soil. Over the years, the return on capital has averaged 5%, capital gain on land is a further 8% and the poultry business has a return on assets of about 20%.

This Case Study has shown that this carefully structured and well managed farm system is highly productive, profitable and sustainable and has so far achieved the goals of the farm family. They realise that many new challenges continue to appear. One of the recognised future needs is for the younger generation of managers to be more highly educated and trained than in the past, but they will do well to emulate the original owner and manager in his progressive approach to the operation and management of the farming system.

Case Studies in Chap. 41 provide comparisons of changes in the structure and **performance of three South Australian family farms** with a gradation in mean growing season rainfall of high (400 mm), medium (300–320 mm) and low (250 mm). In each case, comparisons are made of the farming systems in 1985 and in 2006. By 2006, all three farms had increased their farm size and changed to a 'conservation farming' system (no-till, stubble retention and diversified rotations) with the major component being continuous cropping. These changes to the farm system opened the way for: control of soil erosion; improvement in soil health (including soil structure and N and C contents); integrated pest management; reduced reliance on labour; higher levels of water use efficiency, productivity and profitability; and thus sustainability. Each farm achieved substantial improvements in their financial returns between 1985 and 2006. Without the changes, the 1980s system would not have remained viable. The yield and financial data (gross margins, return on capital and relative profit) were made more valuable by being estimated for poor, average and good rainfall years. Sheep have not, on the whole, been totally removed from the system or from future possibilities. Prime lambs in particular are grazed on non-arable areas or fattened in farm feedlots. Other means of raising income include buying or leasing land, leasing out shed storage space for hay and operating non-farm businesses such as rural computing and distribution of machinery parts.

This valuable chapter shows that continuous cropping with conservation farming is viable and profitable over a range of average rainfall regimes and levels of seasonal rainfall, although this may change if there is permanent climate change to more regularly low rainfall.

The case study farm in the **South Australian northern mallee** region (Chap. 43) is even drier than the lowest rainfall farm in Chap. 41, with a mean annual rainfall of 270 mm, 170 of which are in the April–October growing season. Rainfall is also more variable, while early spring hot winds and mid-spring frosts can be a problem. The soils are not fertile, are strongly alkaline below the surface, and have high levels of sub-soil boron and incipient salinity. Wind erosion is a problem for the light surface soil.

The farm, now in the hands of a third generation family member has changed over recent decades from a traditional wheat–fallow and sheep system to continuous cropping on a greatly increased farm area. To achieve maximum water use efficiency, control soil erosion and reduce costs, the owner has changed to no-till farming. The gradual purchase of new machinery adapted to no-till has increased costs in the short term, alleviated by some share farming. A full-time employee enables large areas to be cropped in a short planting time window.

The overall need for greater efficiency requires, whenever possible, planting at the time (25 April–20 May) for optimal yield potential. This is similar to the need for optimal planting time for the short, temperature-governed growing season on the Canadian prairies, but here water availability is the major limiting factor. The variable climate and markets demand flexibility of operations and close contact with consultants and bank managers. At present, no-till and other sustainability practices have helped this farm to achieve better average yields than for the district and there is less soil erosion.

The two large blocks of mallee scrub at either end of the farm have been joined by a wildlife corridor and may be increasingly valued by society for their conservation of nature and its biodiversity, and perhaps as windbreaks.

As climate change brings more uncertainty, some positive features of the mallee farming system may become more widely relevant:

- The use of Electromagnetic Induction technology to map soil properties may allow better management of salinity and sub-soil sodicity, linked to boron toxicity.
- In the northern mallee, any summer rain can be conserved in the soil until planting with the use of no-till, stubble retention and herbicides.
- The northern mallee region has long been recognised for growing excellent, high-protein wheat, in high demand by bread millers. This should be paid a premium.

The developments outlined in these southern Australian case studies show ways to economic and environmental sustainability.

50.6.4.5 North-Eastern Australian Farming Systems

The rainfed farming systems of north-east Australia (Chap. 25) are located where there are fertile, deep soils, in climatic zones with suitable rainfall. These areas occur on the slopes and plains west of the Great Dividing Range, predominantly between latitudes 21 and 32° south. Because of the year-round distribution of rainfall and the water storage possible in many soils of substantial depth (especially vertosols), both summer- and winter-growing crops are planted. The trend from south to north is for increasing temperatures and increasingly summer dominance of rainfall and therefore also increasing dominance of summer-growing crops.

Though annual rainfall is often high by southern Australian standards (600–800 mm or more), this is counterbalanced by the high evaporation rates; water stress is common, as are heat stress and frost.

Although the main cropping soils (vertosols) can store 150–300 mm rainfall, they exhibit physical problems of cracking when dry and prolonged preclusion from working when wet, due to slow drainage. They and the better-structured ferrosols used for maize and peanut production in higher rainfall areas are susceptible to water erosion during high-intensity rains. Both soil types have declined in fertility over many years and now require fertiliser additions. The evidence quoted in the chapter strongly suggests that most farms in north-eastern Australia are in net negative nutrient balance. Thus the unsustainable exploitation of these soils must come to an end, although even now, net removal of nutrients remains the norm.

Inputs of N from grain legumes such as chick peas, mung beans and faba beans are insufficient for subsequent cereal crops, and perennial tropical pasture legumes are not much used in rotations. Lucerne is grown predominantly for hay. The rainfall of the cropping regions is not reliable for annual legumes.

Crops require adequate plant available water in the soil at planting, as a contribution to total water requirement. The selection of species and varieties, planting times and planting rates also aim to avoid temperature and water stress, and to ensure satisfactory filling of crop grain.

As rainfall is highly variable and unreliable, research and its application have become concentrated on seasonal climate forecasts, climatic risk and consequent management.

The need to make complex decisions on crop production and the value of seasonal weather forecasting in this environment of variable rainfall has encouraged researchers to develop crop simulation models and decision support systems (DSS). They include seasonal weather forecasts based on the El Niño-Southern Oscillation phenomenon. The DSS are being used in this region, and now in southern Australia, to model and assess the impact of a range of decisions on crop productivity. Modelling, experimentation, and research into crop physiology and soil-crop-water relations have shown how yield can be made more reliable by regulating water supply to the crop over the whole growing season, e.g. by regulating planting rates. Although mixed crop–pasture–livestock systems like those in southern Australia are not widely adopted in the north-east region, livestock play an important role in all areas except those few with deep, relatively fertile soils eminently suited to cropping and at risk of being damaged by cattle trampling. Cattle are integrated with cropping to varying degrees, through the planting of annual forage crops such as oats, barley, sorghum and millets, and the legumes lablab, cowpeas and purple vetch. Failed cereal crops, a common occurrence, can also be grazed. Cattle also graze either native grasses or longer term exotic grass pastures planted to rejuvenate the organic C content, structure and infiltration rates of soils which have become marginal for cropping. Many large beef feedlots are located in the region because of the proximity of the grain feed sources.

Greater emphasis might be placed on grazing livestock if they become more valuable economically in relation to grain production, and if more productive and persistent perennial legume pastures, with high feeding value, become available for these areas of unreliable rainfall.

Crop production in north-eastern Australia has adapted well to a variety of resource limitations, especially variability and deficit of water supply. Use is being made of combinations of soil water storage, soil cover with crop residues, crop science, seasonal weather forecasting and DSS to develop production strategies and management.

As the authors conclude: "An ongoing capacity to adapt, through adoption of new and advanced production practices, will be essential to the continued viability of agriculture in tropical and subtropical regions with variable and suboptimal rainfall." One wonders if, due to climate change, this may be the pattern which must also be followed in the formerly more reliable rainfall regions of southern Australia.

A **Case Study** farm on the **north-west slopes and plains of New South Wales** (Chap. 45) is in the southern-most part of the north-eastern Australian farming zone, between latitudes of approximately 29–32°S. Livingstone Farm is owned by the University of Sydney and run as a profitable model farm to demonstrate the principles of scientific agriculture. Thus the manager and other university staff provide leadership to the farming community. In the quest to achieve and maintain high levels of productivity, profitability and sustainability, they have worked in association with researchers, farmers, machinery firms and agribusiness.

The summer-dominant rainfall and deep clay soils of this farm are common throughout the north-east zone. A wide range of both summer and winter crops are grown, but only with the aid of moisture stored in the soil through fallow. The amount of moisture in the soil at planting time is the main determinant of whether a summer or winter crop or no crop at all is planted in a particular field. Seed is often placed into moist soil beneath dry surface soil by deep planting into furrows.

This case study shows the beneficial results of extending the farm system wider than the farm boundary, to include interaction with other farms and agricultural organisations. An example is in the program to halt soil degradation. Although the district soils originally supported excellent, high-protein wheat crops, the decline in fertility and the serious erosion under the original wheat–fallow system needed to be stopped. Pioneering research in the region showed that no-till with herbicides and stubble retention halted soil erosion and increased water infiltration and storage. The author explains how there was a concerted response to these needs through a research, development and extension (RDE) program by state government departments—the sort of effort required and being increasingly adopted by many farming systems throughout the world.

On Livingston Farm, the change to a no-till farming system required, as on other farms, much research, trial and error and even redesign of planting equipment adapted to the local climate and soils as well as to more universal requirements.

Early in the program, the achievement of a 2.2 t/ha grain harvest in spite of no significant rain after planting created great interest in the no-till system in the surrounding district, as well as promoting further work to refine the equipment. Progress on incorporating no-till into local farming systems was rapid, even while adjustments were still being made to planters; the task of planting was being made easier by the improvements in surface soil structure and moisture due to no-till/stubble retention. This illustrates the sorts of processes that follow a decision to make changes to a farming system, when there is a community approach. The changes were also assisted by the import of methodology and equipment from North America.

Sheep are an integral component of the Livingstone farm system and part of the Integrated Weed Management program. When weeds emerge, the area is 'crash grazed' so as to eat out the weeds and remove the sheep before they can consume significant quantities of crop residue. They help avoid herbicide resistance in weeds and provide significant income when sold.

Another important feature of introducing conservation farming (CA) on Livingstone Farm and in the Moree district has been the development of 'information sharing'. This began informally as regular meetings of farmers and the author (manager), supplemented by visits from researchers. It was developed further to discussion groups comprising increasing numbers of farmers, state extension officers and agribusiness advisers. The group joined the Landcare movement and then, in 2000, it merged with similar groups in southern Queensland to become Conservation Farmers Inc. As with similar farmer-controlled groups in southern Australia, this group obtains external funds, conducts some research and provides a network of information and new ideas for farmers. This also involves interaction with researchers, extension officers and consultants (see further discussion later).

This case study also provides useful insights into what is needed to achieve a sustainable mixed farming system, with Conservation Agriculture, in this semi-arid, subtropical region. The author suggests that grazed subtropical grass pasture containing an adapted annual or perennial pasture legume may be needed to achieve a farm system which supplies all the desirable features of stable Conservation Agriculture. As is always the case, a few farmers have already successfully integrated long-term pasture phases into their farming rotation and achieved a stable system.

Over the 30 years during which farming systems have been improved in northern NSW, the authors conclude that most farms have achieved real progress in productivity and sustainability. Through the adoption of the no-till system (in reality, CA), Livingston Farm has succeeded in improving crop productivity, grain quality, soil health and production efficiency. The farm continues to be profitable, in spite of stagnant commodity prices, increasing costs and inflationary pressures.

50.7 Conservation Agriculture and Precision Agriculture in Rainfed Farming Systems

50.7.1 Conservation Agriculture (CA)

Conservation Agriculture receives strong attention throughout this book (see Sect. 50.6) and is becoming adopted world-wide in rainfed farming systems. This concept introduced by the Food and Agriculture Organization of the United Nations has three main components: no-till farming; residue retention on the soil surface; and the use of appropriate crop or crop–pasture rotations. Full and consistent adoption of all three components provides the best overall means to control soil erosion, improve soil fertility, health and water relations, reduce energy costs, help manage diseases, pests and weeds and increase crop yields.

In practice, the three components are not always fully adopted on farms; crop stubble may be grazed or harvested for sale or a rotation plan interrupted to continue producing a particular crop that is receiving a high price or a subsidy. In developing countries, herbicides are not always available to replace cultivation for weed control. While there may be good short-term (often financial) reasons for not adopting some aspect of the complete CA package, it usually brings a long-term loss in the potential of soils and crops. This is explained in Chaps. 33 and 39. (The benefits of increasing the organic carbon content of cropping soils are explained in Chap. 6.)

50.7.1.1 CA in North and South America and Australia

The adoption of no-till with stubble retention, on more than 100 million hectares, mainly in North and South America and Australia, has required large changes to planting equipment and methodology, huge efforts of research and technology, and assistance and training to farmers (as explained in Chaps. 19 and 45).

Chapter 39 sets out both principles and practices for no-till planting, seed covering, residue management and crop establishment, leading to reliable plant emergence and crop growth. The right soil opener in the presence of surface residues is critical to the success of no-till planting. However, the authors suggest that new planters may need heavier drafts and larger tractors, and this may increase soil compaction. There thus remain issues of crop establishment with stubble retention to be resolved.

50.7.1.2 CA in WANA

Much research has also gone into examining no-till farming throughout West Asia–North Africa, and defining its benefits (Chap. 40). Agriculture in the region is dominated by rainfed cereal and livestock production. Over centuries, increasing populations have resulted in intensification of agriculture, over-tillage and overstocking, leading to massive erosion and other soil degradation. The urgent challenge is to reverse this degradation, restore the soil resource and increase productivity so as to satisfy future food requirements and reduce poverty. This has to be achieved in an environment (WANA) where climate change is expected (and has already begun) to bring an overall 20–25% reduction in rainfall.

Research in many of the WANA countries has shown many benefits of no-till with stubble retention. The author has concluded that the intensification and diversification of cropping required to increase food supply in WANA is only possible if water availability and WUE are increased by the no-till/stubble retention system. Improvements have been shown in: (1) rainfall use efficiency; (2) crop yields, at least in some experiments (lack of improvement is usually thought to be due to the short time of some experiments, adverse effects of weeds and other limiting factors); (3) soil quality, through increased soil organic carbon content, soil aggregate stability (with improved permeability and erosion control), and (especially with legume residues) an increase in plant-available N, P and K. In addition, the rotation of crops and herbicides is cited extensively as an effective facilitator of weed management.

In the low-rainfall areas of Africa and Asia, sheep and goats are an integral part of agriculture. Crops and livestock enterprises are linked, even if not part of the same system, by the grazing of crop residues. This conflicts with the need to use residues to help improve rainfall infiltration, control soil erosion and reduce soil water evaporation. At present there are few alternative sources of animal fodder, so the author of Chap. 40 suggests that benefits could be achieved by increasing grain production with better crop husbandry and regulating the sharing of increased crop residues between livestock feed and soil protection. However, there is also a need to reverse the degradation of the natural grasslands and to provide a resource (perhaps for regulated, common use) of legume-based pasture for grazing and forage crops for cut-and-carry or conservation.

No-till is not yet practised extensively in WANA, most being in Sudan, Tunisia and Morocco, despite WANA farmers being regarded as able to adapt to new situations. Slow uptake of no-till seems to be due to: (1) the complexity of ensuring that a wide range of input and management factors are operating together correctly; (2) the difficulty of providing finance for new planting machinery; (3) the need for changing the traditional custom of allowing livestock to have unregulated grazing of crop residues; (4) the traditional mindset that tillage is essential; and (5) the need for training which is being provided by international agencies. Other constraints to the full adoption of CA are the lack of efficient organisation of farmers, of access to markets, and poor land tenure and access to credit. Yet the author stresses that farmers must participate in the process of system change so that relevant scientific knowledge is integrated with local knowledge. This participatory approach to system improvement is discussed in other chapters of this book, including Chaps. 35–37 and 45.

50.7.1.3 CA with CIMMYT in Mexico

The principles laid down for WANA by the author of Chap. 40 are supported in Chap. 33, with reference to research conducted into Conservation Agriculture in **Mexico**, **by CIMMYT**. In part, this research was motivated by the lack of increase in productivity of wheat by plant breeding without appropriate improvement to agronomic management (see also Chap. 28). It can be difficult to convince farmers of the need for a complete change of system in developing countries (see also Chap. 38). The authors of Chap. 33 stress that some benefits of transferring to CA (such as improvements in soil health, nutrient cycling and soil biological activity) take many years to develop, and they illustrate this with the results of two long-term experiments. The first, under rainfed conditions, showed how yield was improved by residue retention, which reduced soil evaporation. In the second experiment where water was made non-limiting by irrigation, it took 5 years for the benefits of stubble retention (compared with burning) to be measurable as yield. The results convinced the authors that residue retention is essential for the success of no-till farming.

Importantly, CIMMYT officers maintain that unless widespread, on-farm soil degradation is arrested and reversed, resources used to develop new germplasm will be largely ineffective as new crop cultivars will not be able to achieve their yield potential. Rather, there will be diminishing returns from all kinds of inputs, accompanied by increasing costs.

They also conclude from this that future strategic research should concentrate on production system × genotype interactions (especially tillage/residue management × genotype interactions). In addition, the physiological basis of yield potential in different management systems needs to be studied to maximise the synergies from plant breeders and agronomists working together. A similar conclusion arose in Chap. 28 in regard to wheat yield improvements in Western Australia. To achieve the complex system changes leading to widespread adoption of full Conservation Agriculture in developing countries, farmer experimentation and adoption must be stimulated by many co-ordinated activities conducted through collaboration between farmers, government and non-government institutions and international research centres.

This sort of collaboration has also been stressed in Chap. 40, for WANA, and is, in essence, the requirement for introducing CA and other complex programs into the agriculturally developed but difficult environments of north-east Australia (Chaps. 36 and 45).

Benefits and problems associated with the development of no-till/CA should be continually assessed, as discussed in Chap. 39 and illustrated in Chaps. 41 and 45. The benefits so far are variable—often positive in financial terms but may be difficult to quantify (as in soil health and erosion control) and occurring over the long term (as in the reductions in fertiliser and herbicide use). The authors of Chap. 39 claim that no-till systems must have a continuous, full cover of residues on the soil surface for maximum improvement of soil health and fertility, and crop yields. The sustainable stage may take 20 years to reach, but might be speeded up by using occasional green manure cover crops.

The benefits of cover crops can be achieved best where adequate, year-round rainfall allows two crops to be grown in a year, as in parts of Argentina (Chap. 39) and of north-eastern and south-eastern USA (Chap. 49). Crop sequences which include cover crops achieve higher economic returns. The benefits of cover crops were also shown in the drier, summer-winter rainfall region of north-eastern Australia when stored soil water was used to grow a millet cover crop for 2 months in summer (Chap. 7). There was still sufficient stored water by the time a winter crop was planted. Such a process is important for achieving a ground cover in semi-arid and sub-humid regions. It may not be possible with strictly seasonal rainfall, as in Mediterranean-type climates, unless a cash crop is foregone.

As discussed in Chap. 39, farmers who bale, burn or graze stubble for some good reason (usually financial) may achieve some short-term gain, but prevent the attainment of full, long-term system benefits. Similarly, occasional tillage will undo the good effects of a period of no-till.

50.7.2 Controlled Traffic Farming (CTF)

Where there is full commitment to no-till and continuous cropping, farmers often go another step to Controlled Traffic Farming (CTF), as discussed in Chaps. 34 and 39. This is a good example of farmer innovation leading the way to improved efficiency of performance in no-till farming systems. Under CT, wheels are confined to permanent lanes occupying about 15% of the field area, in contrast to 85% in a conventional tillage, grain-growing operation (Chap. 39). This reduces the area of compaction of soil by the heavy machinery now used to cover large areas quickly. The authors quote references to yield and profit improvements under CT, due largely to improved water infiltration in the absence of compaction. They also list many other advantages of CT, including reduced costs, greater accuracy of seed and fertiliser placement and greater flexibility to work after rain or at night. The complexities of using CT with no-till/stubble retention are discussed, as well as the considerable benefits of combining the two procedures. Accuracy is improved by using GPS and other features of Precision Agriculture (see also Chap. 34)

The authors of Chap. 39 conclude that the integration of Conservation Agriculture, Precision Agriculture and Controlled Traffic is important to gain maximum efficiency of operations and input use. They quote data showing that the capital costs were recovered in 2–5 years. Weed control remains a problem due to the occurrence of herbicide resistance. Success has been achieved in North America and Australia using the rotation of crops and herbicides and other aspects of integrated weed management, including GM crops and weed smothering by dense surface residues. Many farmers have broadened their weed control options, for a more holistic approach to weed management in CA, and these ideas should be captured for the benefit of all farmers.

50.7.3 Precision Agriculture

Detailed information on improving the efficiency of farming systems by using Precision Agriculture (PA) is explained in Chap. 34. Farmers have previously dealt with soil variability over the farm by fencing as closely as possible according to soil type, then applying constant inputs within the fence. Localised differences in soil could result in waste of expensive inputs or their leaching to pollute the environment. With the increasing size of many farms and fields, matching chemical and other management inputs with land capability becomes more important. This is made possible by continuous monitoring of yield and grain protein during harvest, using GPS equipment.

Electro-Magnetic Induction (EMI) and soil Electronic Conductivity (EC) techniques correlated with certain soil properties can now be measured 'on-the-go', at speeds which may cover 100 ha in a day (see also Chap. 4).

Measurements of pH and estimates of lime requirement can also be made rapidly at the same time as EC with automatic soil sampling and analysis. More types of analysis will be developed in the future.

Aerial photography can provide useful information on soil type changes, early detection of weeds, problems in crop establishment, moisture stress in a crop, effects of farm equipment (such as soil compaction), crop lodging and crop disease. They are especially useful if combined with farmers' field knowledge. New advances in remote sensing include determining the nitrogen status of the crop by using a series of different wavelengths in different ratios, to provide recommendations for N application.

Leaf Area Index is also estimated, being highly correlated with canopy status, which in turn is used to estimate plant populations, biomass and N status. This can be done using satellite imagery, aerial photography or, more accurately, with ground sensing. Measurements from sensors located on farm implements are used to adjust application of chemicals, such as for variable N fertilising, and applications of fungicides, growth regulators and plant desiccants.

Precision Agriculture generates large amounts of data that have to be interpreted so that it can improve farm management decisions; this requires considerable training, skill and experience. Many countries are moving down the path to Zonal Management. "Management zones are areas of a field which, over time, show differences which are mainly related to yield", and which can be linked to different soil properties and managed accordingly.

Accurate estimation of the phosphorus removed from the soil and optimising P replacement are also important in optimising system functioning. This can be done using the P content of the grain and the yield map. Diseases of crops may also be correlated with different management zones, and applications planned accordingly. Another benefit of management zones is that they assist the farmer to conduct farm trials where responses to input treatments or varieties depend on the particular zone.

It is predicted that, "in the future, farmers will have available simple, relatively inexpensive, easy-to-use equipment to enable them to supply the optimal amount of chemicals and nutrients to crops and to be able to measure and record the results of any application". If this technology is combined with the complete Conservation Agriculture program, farming systems will have the potential to be highly efficient, productive, profitable, stable and sustainable. Achieving this will also be dependent on management, including risk management, decision making and farmer uptake of new technology, as discussed in the next section.

50.8 Farmer Risk Management, Decision Making, Participation in RDE and Uptake of New Technology

50.8.1 Risk and Risk Management Strategies

A critical component of the operation of rainfed farming systems is risk management. Chapter 35 deals in detail with risk and risk management strategies, including the use of Decision Support tools (also covered in Chaps. 7, 25 and 37). Sources of risk in rainfed farming include climate variability and extremes, finance availability, markets, human resources and change in government policy. Risk also varies with farm size, farmer goals and input costs. Most farmers are thought to be risk-averse, and this affects their decision making.

Because of the importance of minimising the exposure of farmers to risk, researchers and advisers have devised ways to assist them to make decisions which reduce risk and so optimise the performance of their farm system. These methods include the use of Decision Support tools/systems (DSS).This chapter explores the use of risk management strategies and methods, with examples from farms in south-west Queensland.

Strategies to manage risk include: enterprise diversification; planting crop varieties with different maturity dates; marketing through managed grain pools; storing conserved fodder for livestock; financial risk sharing and use of insurance; forward selling, futures and options; keeping a cash reserve; reducing input costs; and having enterprises that together produce cash flow through the year. As the authors state, "the management task facing farmers is to choose a combination of risk management strategies that best suits the unique conditions of their particular farming system and their personal circumstances."

Seasonal climate forecasts are helpful in providing risk assessments and aiding decisions on risk management. Decision Support Systems and related models (which often include climate forecasts) help to provide answers to complex problems. This chapter and others in this book (e.g. 25 and 37) provide examples of useful DSS and related tools and models.

Even complex DSS, however, do not consider all the interacting factors (including local biophysical, economic and personal factors) which enter into farm decision making. This may be part of the reason why DSS have not been widely taken up by farmers. Some farmers also have difficulty in understanding concepts used in some of these tools and coping with their complexity. Many farmers still use simple methods of decision making based on experience and intuition, and they use farm records and information read or discussed with a range of other professional people (see case studies in this book). This ability to seek out information suggests that, for many farmers, it would be but a short step for them to be able to incorporate DSS into their decision making—if they decide it is worthwhile and if they obtain appropriate assistance (see Chaps. 36 and 37).

Chapters 35 and 37 point to a mismatch between the more intuitive decision making of some farmers and the strictly defined and formal analysis and modelling of scientists—farmers see farm management from the inside while economists (and scientists) see it from the outside. There is a mismatch also between the practical/technological experience and training of farmers and the scientific education and specialised experience of researchers and modellers. Much has been done to make DSS simpler to use but it is difficult to design them to be usable over a range of complex local situations. It therefore seems logical to involve farmers with researchers in the design of models and decision support tools, in order for each to benefit from the skills, experience and insights of the other.

The surveys and case study in Chap. 35 illustrate how discussions between farmers and researchers can be mutually beneficial. In this case, they resulted in a joint partnership leading to the design of a DSS useful to the mixed crop–livestock farmers of the Maranoa–Balonne region of southern Queensland. The project began with time consuming but necessary discussions, focus groups and surveys. These showed that while farmers faced many risks in this difficult summer-winter, low-rainfall environment, their main concern was to decide what to grow and when to plant; and timeliness was critically important in reducing risk. Weather variability was regarded as the most important source of risk. Strategies used by farmers to manage this risk included conservation of soil moisture, no-till planting, enterprise diversification (as with mixed crop–livestock enterprises), generating off-farm income and good business management. The farmers agreed that it would be useful to have a decision support tool to assist them to assess soil moisture and choose the most appropriate crop at planting time so as to use this moisture most effectively.

DSS specialists then recommended that while widespread and serious problems need to be addressed, the DSS should also be location-specific. Relevance, simplicity, effectiveness and low cost were regarded as key attributes, with close involvement of end-users.

Workshops introduced participating local farmers to risk management concepts, soil moisture management and decision-making tools, and to an understanding of seasonal weather influences and climate risk. This education was seen as a necessary part of this farmer–scientist interaction. Significantly, in view of limitations in long-range weather forecasting, they considered that the best indicator of crop performance in the coming season was the amount of soil moisture in the field at planting time. Generally, participants believed that decision support tools could not make decisions for them; however, they would like the tools to produce information, or some guidelines, that they could use as a basis for making their own decisions.

The farmers and DSS specialists were able to design a DSS to select preferred crop planting options for both summer and winter planting periods, taking into account many of the factors that were identified by farmers as influencing their decision. The tool was developed to be ‘very simple’ and ‘quick to use’ by users with low levels of computer skills and using readily available information. This enabled the DSS to be ‘location specific’.

Overall, farmers use a mixture of strategies to manage risk and do not expect to avoid risk all together. Rather, they aim to find the best combination of risk and return to cope with a wide range of outcomes. This study showed that DSS must be easy to use and relevant to particular farm systems and personal needs.

50.8.2 Participation in Farming Systems Research, Development and Extension (RDE)

Farmers need appropriate support to improve and manage the productivity, profitability and sustainability of farming systems—as discussed in the previous section for risk management. Support is also needed for the application of research, in a farming systems context, often with the help of extension officers and consultants. In recent years, this has been done through a new paradigm of systems thinking which goes further than what is said in Chap. 1, and deals with Research, Development and Extension together.

As stated in Chap. 36, systems approaches in agricultural RDE have developed over the last 50 years to better support farm management and help farmers integrate the available knowledge and technologies on their farms. Modern farming systems approaches should, and often do, involve participatory processes where scientists and farmers work together, learn from each other and develop an on-going capacity for change on farms. Cooperation may also include advisers, consultants and members of agribusiness and community organisations; all become part of the farm system.

The modern participatory approach to Farming Systems RDE is notably different from that of past decades when researchers passed on their findings to farmers, either directly or through extension agents. In this Transfer of Technology (ToT) approach, new practices were expected to be taken up by at least some farmers and then to 'diffuse' through the farming community. The ToT approach to RDE has achieved rapid use of those new technologies that have direct financial benefits, minimal complexity, acceptable risk and that are easily integrated into existing practices. However, ToT has been less successful when issues are complex, or when different parts of the chain (farmers, scientists, policy makers, governments or environmentalists) have different understandings of problems, or where it encounters certain personal and community barriers. (See also Chaps. 13 and 38.)

In recent years, the nature of RDE has been re-examined in response to the reduced importance of agriculture in the economy of developed countries and a focus on services with community benefits rather than the direct private benefits that traditional agricultural advisory services emphasised (see also Chap. 13). This tends to reduce the funds available for RDE agencies, which respond by proposing more participation by farmers and the wider community in the RDE process.

"Agricultural scientists have historically wanted to maintain precision and control in their research until a new technology was ready for farmers to verify and use. Such accurate research is also appreciated by farmers and the wider community". However, participatory RDE aims to help farmers and scientists learn together to conduct more relevant research. 'Participatory Action Research' has become relevant world-wide, as development agencies grapple with the need for both increased productivity and overall economic, environmental/ecological and social sustainability.

Participatory approaches implicitly increase the diversity in age and experience of people involved and may cover a broader field than farmers and researchers; this wider field is often referred to as 'stakeholders'. Relationships between stakeholders may be positive or negative. For example, differences may occur between what farmers see as an immediate and relevant problem and what researchers see as the best way to approach a broader, though related, issue. However, all stakeholders have distinctive and valuable abilities and insights. Participatory RDE is thus likely to achieve beneficial results provided all participants seek to learn from each other and focus on common goals. As the author says, 'the impact of a participatory farming systems approach depends on how well project members deal with their diversity ….' This requires good leadership.

Chapter 36 is illuminating in explaining what is meant by participatory RDE and how it has benefited farmers and the grains industry through a large project over the north-eastern Australian grain-growing regions. It spanned the research, extension and management disciplines. The results of the project showed 'that RDE was improved by replacing passive participation of farmers with explicit farmer consultation, to influence decision making and support participatory learning between farmers and scientists.' The project improved farmers' knowledge on key technical issues as well as the profitability and sustainability of their practices. The results showed large improvements in:

- control of soil erosion with the use of no-till and controlled traffic in central Queensland
- nitrogen fertiliser management
- ley pasture management in central Queensland using a new perennial grazing legume (*Clitoria ternatea*)
- adoption of new crops (including legumes) and rotations in farming systems of western Queensland—diversification which had long been sought by RDE agencies.

Importantly, Farming Systems approaches have evolved, over the last two to three decades, to have a broader, more socially sensitive perspective, with farmer participation in RDE and farmers and scientists learning from each other.

50.8.3 Farmer Decision-Making and Use of Decision Support Tools

Chapter 35 deals with risk management, and farmer–researcher relationships in the use of Decision Support tools for making complex decisions. Chapter 36 deals with the complexities of farming systems management and improvement, particularly through the use of farmer–researcher partnerships for mutual learning, and development of research programs, applications and management. Chapter 37 advances these ideas and also discusses other ways in which farmers gain information and make decisions, participate in research and extension and improve their farm systems.

Chapter 37 discusses how farmers have changed the way they have gained much of their information on research—from the extension services of state departments of agriculture (which have been gradually withdrawn) to services provided by the private agribusiness sector, particularly farm consultants. While farmers gain information in a number of ways, farm consultants are adopting an increasingly wide and varied role in informing and advising farmers. Since the mid 1980s, as government advisory services were declining in Australia, an unprecedented increase in the choice of inputs such as pesticides and fertilisers has increased the complexity of farm decision-making. Adding to this complexity have been the new technologies of conservation farming, the problems of herbicide resistance of weeds, and the deregulation of markets. The farm consultancy services developed rapidly to satisfy the overwhelming demand by growers for the services of advisers with research and production understanding and experience. They now assist not only with filtering and selecting relevant information for the farmer but also with helping in decision making. It is claimed that the support offered by consultants has greatly increased the likelihood of uptake and speed of adoption of new technology. Chapter 37 also lists many other helpful attributes sought and found in consultants.

Consultants have also become involved, since the mid-1990s, in the formation of Farming Systems Groups, often, for a start, as leader or ‘champion’, of the farmers who belong to their consulting group. These groups practice the principles of participatory farming systems RDE in initiating both research and extension in problems facing local farming systems. They engage with researchers and advisers to identify needs, conduct research, disseminate results and provide demonstrations and training. Chapter 37 explains the origin and operation of two important southern Australian Farming Systems groups—the Birchip Cropping Group and the Yorke Peninsula Alkaline Soils Group.

In contrast to the normal initiation of RDE programs by RDE institutions, these two local farmer groups have initiated RDE programs of relevance to the productivity, profitability and sustainability of their own regional farming systems. An important example of a service provided by both Groups is the Decision Support System, ‘Yield Prophet’. In 2003, the Birchip Group, with a local consultant, won a tender from the Agricultural Production Systems Research Unit (APSRU) to commercially deliver the Agricultural Production Systems Simulator (APSIM) to grain producers across Australia. Yield Prophet appeals to growers and advisers for its information on soil water, crop physiology and probability-based yield predictions. It integrates seasonal weather forecasting tools into reports to assist decision making. It simulates soil moisture and crop growth through the growing season and is used to: (1) optimise planting time; (2) aid variety selection; (3) manage inputs such as nitrogen; (4) estimate grain yield and protein content; and (5) assist in managing risk. Prediction of crop yield can be linked to market information or used to decide if the crop should be cut for hay instead of waiting to harvest for grain. This DSS is important in that it has had widespread use and it has been assessed in a number of ways, as is required of DSS. For example, it is claimed that Yield Prophet, given accurate input data is able to closely simulate yields from farmers' fields, within about 0.5 t/ha of measured yields. Estimates of Potential Yield and soil evaporation using Yield Prophet were also found to agree with field results of other workers in Australia and North America.

It is realised that although DSS such as Yield Prophet may have some shortcomings, they still have the potential to greatly assist farmer decision making; and farmers using Yield Prophet have demonstrated significant improvements in on-farm productivity.

However, despite the considerable investment in developing Yield Prophet, its flexibility and usability in specific circumstances, its value in aiding farm decision making, and its initial high rate of uptake, the overall number of subscribers has declined in recent years. This is in spite of recent improvements to the model and the quality of its reports.

Many possible reasons for this decline in farmer use of DSS are discussed in Chaps. 35 and 37. Other reasons may be that farmers still rely to a large extent on intuition in their decision making, or that they lack adequate scientific education to use DSS. However, as the decisions they are making are becoming more complex, with greater risk (due, for example, to climate change and the volatility of global economics), they may in future have to use relevant DSS that have reached a level of accuracy that enable such decisions to be made. This may mean that farmers will need to have a higher standard of scientific and analytical education, or that they will need to be more reliant on consultants to help them use the DSS.

50.9 Conclusion

The authors in this book have shown the diversity of farming systems around the world, in their structure, operation and management. In recent decades, there have been many changes to farming systems—some harmful and challenging and some beneficial and positive. Important challenges have arisen from the degradation of soils; climate change with the possibility of more extreme climatic events and/or less rain in many rainfed farming areas; growing populations which puts pressure on farms to be more intensive and productive; rising costs and volatility of markets. There are also many problems of management of weeds, diseases and insect pests. At the same time, there is a serious challenge to make farming systems sustainable productively, economically, environmentally, and socially. To do this, there is a need for a systems approach, with well-managed integration of operations within the farm. It also requires that those who operate farms (usually farm families) are given the means to meet the above challenges and farm successfully.

On the positive side, there have been many technological advances in all aspects of farming systems and these have helped in the raising of productivity and sustainability. Unfortunately, many of these advances have not yet reached poorer countries because of the cost and the lack of agricultural infrastructure, education and training. Yet even in poorer countries, farmers in dry areas recognise the need for efficient capture of rainfall and runoff water while still needing assistance in its efficient use.

One of the most important advances, especially in developed countries, has been the development of no-till farming which, with residue retention and appropriate rotations, forms the powerful tool of Conservation Agriculture. This has many advantages, including high efficiency of water use and the improvement of soil conservation and health.

Many chapters also show the value of combining crop and livestock production, either in traditional mixed farming or in other ways of integrating the two. The value of, and need for, highly productive and low-cost pastures is as clear now in dry areas as it has long been in the more favourably watered areas of the world. To provide this will require many changes to traditional farming systems where crop residues are used to feed livestock rather than sown pastures.

Many farming systems at various levels of intensity and productivity are not economically or environmentally sustainable. But it is clear that they could be made sustainable with good management, appropriate government policies and infrastructure, prevention of serious climate change, farmer education and training, positive relations between farmers and the wider community, and fair rewards for their work. These will all be necessary to feed the world and to sustain rainfed agriculture in all its aspects, including the conservation of its resource base.

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Chapter 51
Glossary

Compiled by Ian Cooper

Active Light Sensor An apparatus for assessing plant status remotely, allowing selective monitoring or treatment of individual plants. May also be used for measuring the reflectance characteristics of soil or of objects in general. It uses a solid state light source to illuminate a plant canopy or object under investigation and an array of spectrally sensitive photosensors detect light reflected.

Adaptability (of a System) An adaptable farming system is one that can respond to opportunities for improving production without permanent detriment to its ecological function.

Adjuvant 1. Any component which improves the characteristics of a formulation or mixture of chemical sprays. 2. Any component which improves the effect of a drug or immunological agent while having few if any direct effects when given by itself.

Agricultural Bureau (of South Australia) A non-profit voluntary organisation run by farmers for farmers for anyone associated with or interested in farming, agricultural development and education. It helps to bridge the gap between scientist and farmer and assists its members in working together on issues such as management and marketing.

Agroecology The science of applying ecological concepts and principles to the design and management of sustainable agroecosystems.

Agroecosystems (a) Ecological systems modified by human beings to produce food, fibre or other agricultural products. An agroecosystem is a complex of air, water, soil, plants, animals, micro-organisms and everything else in a bounded area that people have modified for the purposes of agricultural production. See Boundary. (b) Land used for crops, pasture, and livestock; the adjacent uncultivated land that supports other vegetation and wildlife; and the associated atmosphere, the underlying soils, groundwater, and drainage networks (US Environmental Protection Agency).

P. Tow et al. (eds.), *Rainfed Farming Systems*, DOI 10.1007/978-1-4020-9132-2_51,

Agroforestry A farming system that integrates trees or woody perennials, grown for fruits, nuts, seeds, plant extracts, timber, fodder or natural resource management, with grazing, cropping or other farm enterprises. Farm forestry is one type of agroforestry, where trees are managed in stands or woodlots for traditional wood products, but integrated into the whole-farm plan and farm business.

Air seeder A broadacre planting machine in which seed and fertiliser are distributed by air blasts to the planting points.

Allelopathy The release by one plant species of chemicals (alleotoxins) which affect other species in its vicinity, usually to their detriment.

Allelotoxin A chemical produced by one plant that is toxic to another (also termed Alleochemical).

Anamorph An asexual reproductive stage (morph) of a fungus, often mould-like.

Animal feeding operations (AFOs) Agricultural facilities that house and feed animals in a confined area for 45 days or more during any 12-month period and where structures or animal traffic prevents vegetative growth (USA EPA definition).

Anthesis A developmental stage in flowering when anthers rupture and pollen is shed.

Arbuscular Mycorrhizal Fungi A type of mycorrhiza in which the fungus penetrates the cortical cells of the roots of a vascular plant. They are characterised by the formation of unique structures such as arbuscules and vesicles by fungi of the phylum Glomeromycota (AM fungi). AM fungi help plants to capture nutrients such as phosphorus and micronutrients from the soil. It is believed that the development of the arbuscular mycorrhizal symbiosis played a crucial role in the initial colonisation of land by plants and in the evolution of the vascular plants.

Australian Wheat Grades Australian wheat is classified into six major market grades including Australian Prime Hard (APH), Australian Hard (AH), Australian Premium White (APW), Australian Standard White (ASW), Australian Soft (AS) and Australian Premium Durum (APDR). However, each year more than 50 different wheat products are exported.

Avirulence gene A gene in a pathogen that must be present for a resistance gene in the host to recognise and resist the pathogen.

Back-grounding agistment A form of agistment where payment is made on the basis of liveweight gain by the agisted animals.

Bare Tramlines Traditionally tramlines have been left bare. However, due to concerns with herbicide resistance, gaps in the crop and potential erosion, fuzzy, sown and furry tramlines have been developed. Bare tramlines provide a firm compacted zone for running machinery and no crop is damaged during post-seeding operations. Bare tramlines are very visible for in-crop guidance.

Base exchange capacity A measure of the absorptive capacity of a soil for materials with exchangeable cations, a non-acid reaction (see cation exchange capacity). A soil with a high base exchange capacity will retain more plant nutrients and is less apt to leach than one with a low exchange capacity.

Belly dumper Truck or trailer designed for fast emptying through the floor or 'belly' of the tray.

Benchmarking An enterprise or activity-based analysis that focuses on the physical/technical processes used by a farmer to enact his enterprise plan and the consequences of those processes in terms of unit revenue and costs, enterprise efficiency and enterprise profitability.

Bioactive Having an interaction with, or effect on, a living organism.

Biofertiliser Biologically active (living or temporarily inert) materials used to increase fertility of soils. For example some free-living or symbiotic bacteria and blue-green algae (*Cyanobacteria*) fix gaseous nitrogen as ammonia and release it, increasing the fertility of soil and water. Rhizobium or Bradyrhizobium producing root nodules in legumes.

Biofumigation The suppression of soil-borne pests and pathogens by biocidal compounds, principally isothiocyanates (ITCs) released when glucosinolates (GSLs) in the tissues of *Brassica* plants are hydrolysed in soil.

Biomass The total mass of living matter in a given unit area.

Biomining The use of micro-organisms to extract metals and minerals from ores in the mining process. Ores of high quality are rapidly being depleted and biomining allows environmentally friendly ways of extracting metals from low-grade ores (ores that have small amounts of valuable metals scattered throughout).

Biotrophic An organism which cannot survive or reproduce unless it is on another organism.

Bioturbation Mixing of soil by living organisms.

Blade plough Tractor implement that draws large V shaped blades below the soil surface cutting plant roots.

Block farming Organising farm so individual crops are planted together in a 'block' to minimise spray drift and better manage pests and diseases.

Bottom up approach An approach that pieces together systems to give rise to grander systems, thus making the original systems sub-systems of the emergent system. In a bottom-up approach, the individual base elements of the system are first specified in great detail. These elements are then linked together to form larger sub-systems, which then in turn are linked, sometimes in many levels, until a complete top-level system is formed (synthesis).

Boundary (of a system) Separates a system from its environment. This is decided by the observer. Where a boundary is drawn depends on the purpose of the observer.

The boundary identifies the system, and its position is critical for appropriate analysis.

Break of season The rains which mark the opening or start of a cropping season. Occurs when the amount of rainfall exceeds the demand of evaporation so creating suitable crop sowing conditions.

Brewer's grain The material that is remaining after grains have been fermented during the beer-making process. These materials can be fed to livestock either undried (wet brewers grains) or dried (dried brewers grains).

Broadacre An Australian term used to describe land suitable for farms practicing large-scale crop (agriculture) operations. ABARE uses the following key crop segments—Oilseeds, Winter and summer cereals, Pulses, Sugar cane and Rice.

Bt Crops BT = *Bacillus thuringiensis*. Proteins from this fungus have been inserted in crops by genetic modification methods to provide resistance to insect attack e.g. BT cotton.

Bund A wall or berm which surrounds a field or a tank to contain any spills or leaks.

C3 Plant A plant employing the pentose phosphate pathway of carbon dioxide assimilation during photosynthesis; often a cool-season plant.

C4 Plant A plant employing the dicarboxylic acid pathway of carbon dioxide assimilation during photosynthesis; often a warm-season plant.

Carbon farming Either the cultivation of trees, or undertaking specific farming practices, in order to sequester carbon and then to obtain tradable rights in that carbon. These rights can then be sold to emitters of CO_2 and other interested parties.

Cast An animal that has fallen or lies down and cannot get up without help.

Cation exchange capacity The number of negatively charged sites on a soil which can react with and hold cations. The cation exchange capacity is high for clays and humus, and low for sand.

Cellulosic Of, pertaining to, or derived from cellulose.

Chisel plough Ploughs used to shatter but not turn or move the soil.

Circular diagram A tool to assist in the analysis of a system. The output of central interest (e.g. crop production) is placed at the centre of the diagram and the major factors thought to influence it are grouped in a ring around it with appropriate arrows pointing inwards. There may be effects of these factors on each other and these are indicated by arrows. Factors in the ring are influenced by secondary factors and these are arranged in an outer ring with arrows indicating their influence on the inner ring and each other. Further rings may be added if necessary.

Closed Systems Are those that are self-contained and for which there is no interchange with the environment. In reality, they are difficult to achieve but may be assumed for the purposed of study, c.f. open systems.

Codex Alimentarius A collection of internationally recognised standards, codes of practice, guidelines and other recommendations relating to foods, food production and food safety.

Combine In this book, used to describe a ‘combined-harvester thresher’; also known as a header in Australia. In Australia, ‘combine’ commonly refers to a combined seed–fertiliser planter.

Complex System Methodology (CSM) A complex system has innumerable emergent properties, hard or even impossible-to-define boundaries, and relations and characteristics that are open to an infinite number of different interpretations.

Components (of a farm system) Components of a farm system may be located on, above or below the ground and may be plants, animals, micro-organisms, soil components (biological, nutrients, moisture, air), water supply, machines, fences and sheds and other ‘capital’ items. Components may be classed as resources if they contribute to system productivity.

Concentrated animal feeding operations (CAFOs) Agricultural facilities that house and feed a large number of animals in a confined area for 45 days or more during any 12-month period and where structures or animal traffic prevents vegetative growth. They differ from AFOs only is size of operation (USA EPA definition). Also termed Factory Farming and industrial farming.

Conservation agriculture The achievement of sustainable and profitable agriculture through the application of the three principles: minimal soil disturbance, permanent soil cover and crop rotations.

Conservation tillage Methods of soil tillage which leave a minimum of 30% of crop residue on the soil surface or at least 1,100 kg/ha of small-grain residue on the surface during the critical soil erosion period. This slows water movement, which reduces the amount of soil erosion; it also warms the soil, enabling the next year’s crop to be planted earlier in the spring. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. By reducing the number of times the farmer travels over the field, farmers realise significant savings in fuel and labour. Also termed Trash farming. See also No-till, Strip-Till, Mulch-Till, Ridge-Till.

Contour Banks Earthen banks constructed level or with a slight slope to remove runoff water slowly from erosion-prone slopes.

Controlled Traffic Farming Tramline or Controlled Traffic farming improves farm production and efficiency by controlling traffic and confining compaction to permanent tramlines and reducing overlap.

Conventional tillage See intensive tillage.

Copiotrophic micro-organisms These grow in carbon-rich soils and their distribution implies that abundant carbon favours their survival. c.f. oligotrophic organisms.

Cost Price Squeeze An individual farmer's 'terms of trade' is the ratio of prices received (for outputs like wool and wheat) to prices paid (for purchased inputs). Historically, this has been declining in developed economics giving rise to the so-called cost-price squeeze on agriculture. It means farmers have to increase their productivity to remain viable.

Coulter Originally a sharp knife-like blade in front the ploughshare to cut the turf. More recently refers to a knife or disc that makes the first cut in a tillage operation.

Cover crop A crop used to cover the soil surface; to decrease erosion and leaching; shade the ground and improve soil quality (especially by adding nitrogen). They may be incorporated into the soil by tillage.

Crabbing (of implements) A term which describes undesired off-centre tracking of a trailed implement caused by contrasting soil textures at opposing sides creating leverage resulting in crab like sideways movement. Also caused by trailing implement across a slope.

Crassulacean acid metabolism (CAM) plants A carbon fixation pathway found in some photosynthetic plants. CAM is usually found in plants living in arid conditions, including cacti and pineapples (also known as CAM photosynthesis).

Crop heat units (Corn heat units) A North American indexing system to assist farmers in selecting suitable hybrids and varieties for their area. This indexing system was originally developed for field corn. The crop heat unit ratings are based on the total accumulated crop heat units (CHU) for the frost-free growing season. See http://www.omafra.gov.on.ca/english/crops/facts/93-119.htm.

Crop topping The application of a grass-specific weedicide soon after the anthesis of grass weeds infesting grain legume crops.

Crossdisciplinarity The act of crossing disciplinary boundaries to explain one subject in the terms of another, foreign subject or method. See Multidisciplinary, Interdisciplinary, Transdisciplinary.

Cultural sustainability Developing, renewing and maintaining human cultures that create positive, enduring relationships with other peoples and the natural world.

Dambo A class of complex shallow wetlands in central, southern and eastern Africa. They are generally found in higher rainfall flat plateau areas, and have river-like branching forms.

DAP Diammonium phosphate. A fertiliser containing phosphorus (46%) and some nitrogen (18%).

Decile Deciles are used to give an element a ranking based on ten divisions, e.g. Rainfall Deciles (see below) give a better idea of relative rainfall than comparison with an average.

Detritusphere The part of the soil associated with decomposing residues.

Diazotrophs Bacteria that fix atmospheric nitrogen gas into a more usable form, e.g. *Azospirillum*, *Herbaspirillum*, *Azotobactor* and *Acetobactor* spp.

Differential Global Positioning System (DGPS) This system is used to correct bias errors at one location with measured bias errors at a known position. A reference receiver, or base station, computes corrections for each satellite signal for all satellites in view. Differential GPS are measured at two stations, one of which has known coordinates. Correction values can then be used to calculate the exact position of the unknown points from the roving receiver. In this way it is possible to calculate the exact position of survey control stations.

Disc ploughs and offset discs These break up undisturbed soil by inverting it to bury surface weeds and trash. Regular use of disc ploughs reduces soil aggregates to small particles and produces a compacted layer or plough pan which prevents air, water or roots penetrating the sub-soil. When it rains, soil particles on the surface may collapse together to form a crust which repels air and water and is difficult for seedlings to break through. Offset disc ploughs, which have two rows of discs running at angles to each other, serve a similar purpose. They are usually used as a second tillage implement, and for initial tillage on lighter soils.

Discounted cash flow (discounting) A method to value a project, or financial asset, using the concepts of the time value of money. All future cash flows are estimated and discounted to give them a present value. The discount rate used is generally the appropriate cost of capital, and incorporates judgments of the uncertainty (riskiness) of the future cash flows.

Disker A tillage implement that uses disks rather than tynes to penetrate the soil (see Disc ploughs).

Diversify, Diversification The production of two or more commodities for which production levels and/or prices are not closely correlated (c.f. specialisation). Advocates of diversification argue it provides greater income stability while specialised farms may benefit from economies of size.

Donor value Derived from the value of the sum of all inputs used to create a product compared with ‘receiver value’ favoured by economists—what the purchaser is willing to pay.

Double Knock technique The use of a second weed-control tactic to eliminate survivors of the first tactic. Pre-sowing, this can be an application of glyphosate, followed by paraquat or by a full-cut tillage operation. It is intended to delay the development of herbicide resistance.

DrumMuster An Australian scheme to reduce pesticide pollution by organised collection, central storage and disposal of used pesticide drums.

Dry Matter The various mineral and organic material (carbohydrate, protein, fats or oils, and vitamins) in feedstuffs. Measured by drying the material to be tested.

Drylot An enclosure of limited size usually bare of vegetation and used for fattening livestock Syn. Feedlot, Feedyard.

DSE Dry Sheep Equivalent. The ability to maintain a 45 kg Merino wether at constant body weight.

Ducks-foot A relatively broad tyne used for shallow cultivation and minimum tillage.

Ecofallow A method of farming that diminishes weeds and conserves water by rotating crops and reducing or eliminating tillage.

Economic Efficiency 1. Productive efficiency: Relates output value to cost and attempts to minimise costs for a given level of output or maximise output for a given level of costs. 2. Allocative Efficiency relates to how scarce resources are allocated among goods and services produced by an economy.What is desired is a situation where it is not possible to change the allocation for resources without making someone worse off. This is called the Pareto criterion of efficiency.

Ecoregion An ecologically and geographically defined area. Ecoregions cover relatively large areas of land or water, and contain characteristic, geographically-distinct assemblages of natural communities and species. The biodiversity of flora, fauna and ecosystems that characterise an ecoregion tends to be distinct from that of other ecoregions. Syn. Bioregion.

Ecosystem services Natural ecosystems provide a number of benefits known as ecosystem services. These include products like clean drinking water and processes such as the decomposition of wastes.

Edaphic Of or relating to the soil, resulting from or influenced by the soil rather than climate.

Efficiency The ratio of the effective or useful output to the total input in any system. See also Economic efficiency, Rainfall Use Efficiency.

El Niño The name given to warming of coastal waters off Peru around Christmas. When this warming is exceptionally strong (once every 5 years) it creates an El Niño episode, and is measured as negative values of the Southern Oscillation Index. This negative ENSO connection is associated with periods of drought over eastern Australia, Indonesia and parts of India and southern Africa, but with excess rainfall over western America. See La Niña.

Elasticity In economics, a measure of the responsiveness of the quantity demanded or supplied to changes in prices. Elasticity measures the degree to which price is effective in calling forth or holding back quantity.

Electrical Conductivity (EC) of soil Apparent soil electrical conductivity is influenced by a combination of physico-chemical properties including soluble salts, clay content and mineralogy, soil water content, bulk density, organic matter, and soil temperature; consequently, measurements of ECa have been used at field scales to map the spatial variation of several edaphic properties: soil salinity, clay content or depth to clay-rich layers, soil water content, the depth of flood-deposited sands, and organic matter. EC is measured by electromagnetic induction (EM) or by a contact electrode method.

Electro Magnetic (EM) Induction EM surveys use an instrument called an electromagnetic induction meter that induces an electromagnetic signal into the ground (without making contact) and measures how well it is conducted by the soil. The alternative contact electrode method involves devices that direct electrical current into the soil through insulated metal electrodes that penetrate the soil surface.

Elements (of a system) The combination of system components and external influences. Elements may be used to characterise or define a farm system, to pin-point essential features of management and to enable comparison with other systems.

Emergence (in relation to systems) The way complex systems and patterns arise out of a multiplicity of relatively simple interactions. The concept is central to the theory of complex systems and yet is very controversial.

Emergent properties Properties that arise out of a multiplicity of relatively simple interactions (see Emergence).

Emergy The available energy of one form (usually solar) used up directly and indirectly to make a product or a service. H.T. Odum developed the idea of evaluating Emergy as a common denominator for energy flows of different kinds, focused on the need to evaluate the quality as well as the quantity of energy flows. Emergy is measured in solar equivalent joules, abbreviated seJ.

Endophyte An organism, often a bacterium or fungus, which lives within a plant for at least part of its life without causing apparent disease.

Energetics The scientific study of energy flows and storages under transformation.

Environment (of a system) That which is outside the system's boundaries. A farm system may have physical, technological, social, political/institutional and economic aspects to its environment.

Environmental load Disturbance in ecological systems caused by humans, resulting in deviations from normal behaviour.

Equity (system) All stakeholders of a system are treated equally and justly. The evenness of distribution, both spatially and temporally, of the benefits and costs from the productivity of the system.

Ergosterol A biological precursor to Vitamin D2. It is a component of fungal cell membranes. The presence of ergosterol in fungal cell membranes coupled with its absence in animal cell membranes makes it a useful target for anti-fungal drugs.

Eutrophication The process by which a body of water becomes rich in dissolved nutrients from fertilisers or sewage, thereby encouraging the growth and decomposition of oxygen-depleting plant life and resulting in harm to other organisms.

Evapo-transpiration The total water lost or used by evaporation from the soil and transpiration through a crop or vegetation.

Evapo-transpiration Ratio kg water used/kg dry matter produced.

Exergy (available energy) The energy with the potential to perform work and which is degraded in the process.

Expected Utility Theory In economics, game theory and decision theory, the expected utility theorem or expected utility hypothesis predicts that the 'betting preferences' of people with regard to uncertain outcomes (gambles) can be described by a mathematical relation which takes into account the size of a payout (whether in money or other goods), the probability of occurrence, risk aversion, and the different utility of the same payout to people with different assets or personal preferences. It is a more sophisticated theory than simply predicting that choices will be made based on expected value (which takes into account only the size of the payout and the probability of occurrence).

External Factors or influences (on a system) Things that act on the system from outside the defined boundaries of the system. Generally there is no perceptible feedback on them from the system. For a farm system they would include climatic factors such as solar radiation, rainfall and temperature, but could also include factors such as market conditions, legal frameworks, government policies, institutional structures and other social influences, education, availability of various types of technology (as information, training, equipment etc.), availability of finance, and the appearance of new pests, diseases and weeds. Deliberately-introduced things from outside the system are termed inputs.

Externality, Externalities In economics, an externality is a cost or benefit resulting from an economic transaction that is borne or received by parties not directly involved in the transaction. The concept can be expanded to cover positive or negative effects on third parties of an action of an individual.

Faba beans *Vicia faba*, also called broad bean, fava bean, horse bean, field bean, tic bean is a species of bean (Fabaceae) native to north Africa and south-west Asia, and extensively cultivated elsewhere.

Fallow A farming system in which land is left without a crop or weed growth (by ploughing or chemical spray) for extended periods to accumulate soil moisture.

Fallow Efficiency The proportion of water entering fallow soil that is eventually captured by the following crop. Values vary with climate and soil conditions, including texture, depth and surface cover.

Farm management The process by which managers consider the information they have about the resources available in farm systems and the potential for improvements. They can then evaluate the potential costs and benefits of any change, and make a decision based on their goals.

Farm System The particular way an individual farm is organised and operated. See Farming System.

Farm Water Use Efficiency Average kg product/ha/mm rain for a farm.

Farming System A particular design of agricultural system which is well defined and distinguishable from others.

Feed budget A technique for closely matching pasture feed supply and grazing animal demand.

Feedback 1. Information about the performance of a system which can influence its operation either directly or as a result of decisions based on this information. 2. Negative feedback is a return input which reduces the quantity or quality of outputs, and positive feedback is returned input which increases subsequent outputs.

Feedback Loop The pathway by which a portion of the output of a system or process returns to become a part of its inputs.

Feeder A livestock animal that is fed an enriched diet to fatten it for market (often in a feedlot).

Feedlot A type of Confined Animal Feeding Operation (CAFO) which is used for finishing livestock, notably beef cattle, prior to slaughter. Syn. Drylot.

Field Efficiency The actual accomplishment rate for a field implement as a percent of the theoretical accomplishment rate if no time were lost due to overlapping, turning, and adjusting the machine.

Flexibility (of a system) The ability of a system to adapt to a new environment or recover from a shock or disturbance.

Foot-and-mouth disease A highly contagious and sometimes fatal viral disease of cloven-hoofed animals, including domestic animals such as cattle, water buffalo, sheep, goats and pigs, as well as antelope, bison and other wild bovids, and deer. It is caused by foot-and-mouth disease virus (Aphtae epizooticae).

Forward Selling A forward contract is an agreement between two parties to buy or sell an asset (such as a tonne of wheat) at a pre-agreed future point in time at an agreed price. No money changes hands until delivery. A farmer may do this to lock into high prices but runs the risk of not being able to deliver (and therefore having to buy grain) if the crop fails.

Function (of a system) See System function.

Functional Foods Foods or dietary components that may provide a health benefit beyond basic nutrition.

Furry (chaff) tramlines Chaff from harvesters is diverted onto bare tramlines to provide a mulch.

Futures Market In many lines of trade, buyers and sellers find it advantageous to enter into contracts—termed futures contracts calling for delivery of a commodity at a future date at a specified price. Nowadays, people trade in futures in grains and other agricultural commodities.

Fuzzy tramlines These are made by rolling topdressed seed into the tramline with one of the following wheels of the seeder. See Tramline.

Gallery forests Evergreen forests that form as corridors along rivers or wetlands and project into landscapes that are otherwise only sparsely treed such as savannas, grasslands or deserts.

Georeference To define something's existence in physical space. That is, establishing a relation between raster or vector images to map projections or coordinate systems.

GMO A genetically modified organism, using recombinant DNA technology. See Transgenic.

Goal A desired state of affairs of a person or of a system. For businesses the primary 'goal' is to derive profits by making goods or services available to the end user (customer) at the best possible cost. See Objective.

Goyder's Line A line across South Australia at an approximate rainfall boundary indicating the edge of the area suitable for agriculture. North of Goyder's Line, the rainfall is not reliable enough, and the land is only suitable for grazing on a long-term sustainable basis. The line traces a distinct change in vegetation between the scrub bushes known as mallee to the south and the arid salt bush to the north. This change forms a line across the state. Goyder's line almost exactly represents the demarcation of a long-term average of 254 mm (10 in.) of rain per year.

Grass cleaned Grass removal from an area with grass-specific herbicides.

Green Revolution A significant increase in agricultural productivity resulting from the introduction of high-yield varieties of grains, the use of pesticides, fertilisers and improved management techniques.

Greenchop Chopped forage plants that may be fed direct to animals (as is or wilted) or ensiled.

Gross Domestic Product (GDP) Is the final value of goods and services, at current market prices, produced by the economy in a year. All intermediate products are excluded and only goods used for final consumption or investment goods are included. Imported goods consumed are excluded, while goods for export are included.

Gross Margin Of an enterprise (or of an activity within an enterprise) is the gross receipts less the variable expenses (e.g. fertiliser, fuel, seed). Specific gross margins may be expressed on a 'per hectare', 'per labour-month', 'per $ invested', etc. May be calculated on a historic basis from records or budgeted and can also be calculated for the whole farm. In mixed farms (crop and livestock), the cumulative gross margin of a rotation is preferable to looking at individual enterprises as they may receive benefits from each other (crops benefiting from nitrogen produced by pasture legumes, livestock grazing stubbles).

Ground truthing A term used in cartography, meteorology, analysis of aerial photographs, satellite imagery and a range of other remote sensing techniques in which data are gathered at a distance. Ground truth refers to information that is collected 'on location' i.e. what is there in reality. In remote sensing, this is especially important in order to relate image data to real features and materials on the ground.

The collection of ground-truth data enables calibration of remote-sensing data, and aids in the interpretation and analysis of what is being sensed.

Hair-pinning A situation when planting where stubble is not cut but is pushed into the seeding slot, and compromises soil–seed contact. Crop losses increase further when soil applied herbicides are used.

Hard System Methodology (HSM) A system where it is assumed that the system is well-defined and that a scientific or technical approach will solve problems. Typically, there is a desired objective that the system is designed to work towards.

Harvest index The ratio of grain weight to total plant weight.

Harvester trail The trail of straw and chaff left behind a combine harvester.

Haylage Forage that is baled at a higher moisture content than dry hay and then stored in a sealed plastic wrap. Because of the high moisture level and air-tight environment, the forage ferments and is preserved by acid production during fermentation. Also termed 'round bale silage'.

Hedging A strategy designed to minimise exposure to an unwanted business risk, while still allowing the business to profit from an investment activity.

Hemicellulose A heteropolymer (matrix polysaccharide) present in almost all plant cell walls along with cellulose. While cellulose is crystalline, strong, and resistant to hydrolysis, hemicellulose has a random, amorphous structure with little strength and more easily hydrolysed.

Hierarchy (of systems) A system is part of a hierarchy, i.e. it has component subsystems and can be viewed as a sub-system of some higher-level system.

Hog General term usually used to describe young pigs. May be used for castrates or barrows but not specific (American).

Holistic Emphasising the organic or functional relation between parts and whole.

Hybrid The offspring of parents of different species, varieties or breeds of plants or animals. They may be fertile or sterile. The greater the difference between the genotypes of the parents, the more likely is sterility. An example is the crossing of a horse and a donkey; the resulting mule is sterile.

Hybrid Vigour Qualities in a hybrid not present in either parent. Examples are increase hardiness, improved growth rate.

Hyperspectral imaging analysis The analysis of images using a large number of channels (corresponding to spectrum intervals). The distinction between hyperspectral and multispectral is not defined by a set number of spectral bands. It is best defined by the manner in which the data is collected. Hyperspectral data is a set of contiguous bands (usually by one sensor). Multispectral is a set of optimally-chosen spectral bands that are typically not contiguous (usually by multiple sensors). Capturing the same object on many bands of the spectrum to generate a data cube can reveal objects and information that more limited scanners cannot pick up.

Identity-retained marketing Marketing of produce emphasising that it meets locally grown, naturally produced, organic, or certified standards.

Imi herbicide Imidazolinone (Group 2) herbicide.

Income elasticity of demand A measure of the responsiveness of the quantity demanded to changes in prices. Elasticity measures the degree to which price is effective in calling forth or holding back quantity.

Industrial farming This term lacks clear definition. In general, it refers to treating farming in a similar way to large industry. There are technical, scientific, economic and political aspects to this view. These include innovation in agricultural machinery and farming methods, genetic technology, techniques for achieving economies of scale in production, the creation of new markets for consumption, the application of patent protection to genetic information, and global trade. Particularly in animal industries, there is a trend toward consolidation, simplification, and specialisation. Production is often by highly leveraged farm factories where the animals are owned by, or under contract to, by multinational companies from the time they are born or hatched right through their arrival at the processing plant and from there to market, i.e. a high degree of vertical integration.

Influence diagram (ID) A compact graphical and mathematical representation of a decision situation (also called a decision network).

Input(s) (a) A resource used in the production of an output. (b) Something which goes into a system.

Input use efficiency Output per unit input, e.g. tonnes of grain per kg of applied nitrogen.

Integrated farming system Where crop production and livestock production are conducted as separate businesses which are integrated, intra- or inter-regionally, to achieve certain benefits, e.g. where one or more cropping farms supply grain to a cattle feedlot or a piggery and manure from the intensive operation is spread on broadacre farms, c.f. Mixed farming.

Intensity of Farming Is usually gauged by the pressure placed on the resources by the farming system. An increase in the number of crop cycles per year and/or the number of years of cultivation or a decrease in the number of years of fallow or pasture ley results in an increase in intensity, as would an increase in the number of livestock per unit area. Increased intensity usually requires increased inputs and management.

Intensive tillage A tillage system that leaves less than 15% crop residue cover or less than 560 kg/ha of small-grain residue. These types of tillage systems are often referred to as conventional tillage systems but, as reduced and conservation tillage systems have been more widely adopted, it is often not appropriate to refer to this type of system as conventional. These systems involve often multiple operations with implements such as a mouldboard plough, disk, and/or chisel plough. After ploughing, further workings with discs or harrows are often used to break clods, kill weeds and prepare a ‘seed bed’.

Interaction A phenomenon whereby the effect of one factor varies with the level or strength of another factor.

Intercropping Cultivating two or more crops in the same space at the same time.

Interdisciplinary In an interdisciplinary approach, people from multiple disciplines and professions are engaged in creating and applying new knowledge as they work together as equal stakeholders in addressing a common challenge. See Multidisciplinary, Transdisciplinary, Crossdisciplinarity.

Inter-relationship A situation where one part of a system will have an influence on another; however, without the direct effect, it would be classed as an interaction.

Isothiocyanates Sulphur-containing phytochemicals with the general formula R-NCS.

Kraal An Afrikaans and South African English word for an enclosure for cattle or other livestock, located within an African homestead or village surrounded by a palisade, mud wall, or other fencing, roughly circular in form.

Kriging A group of geostatistical techniques to interpolate the value of a random field (e.g. the elevation of the landscape as a function of the geographic location) at an unobserved location from observations of its value at nearby locations.

La Niña The opposite of EI Niño, when the waters in the eastern equatorial Pacific are abnormally cold. La Niña episodes (positive phases of the Southern Oscillation) are characterised by more frequent and heavier rain periods, occasionally with severe flooding in Australia but drier periods in the western Americas.

Labile Readily undergoing change or breakdown.

Land Equivalent Ratio The ratio of the area needed under sole cropping to the area under inter- or mixed-cropping to give equal amounts of yield at the same management level.

Landcare A community-based movement working to care for the land. It began as a movement in the 1980's and has developed to involve more than 3,000 Landcare groups around Australia. Supported by the Federal Government, to help improve the environment in both rural and urban areas. The groups usually work together in a particular locality to tackle land and water management issues.

Law of the Optimum See Liebscher's Law.

Ley farming A generic term that in Australia is commonly applied to the short and long forms of the crop–pasture rotation. There is a recent trend towards the use of 'ley' to denote a 1-year self-regenerating pasture between crops and 'phase' to denote several consecutive years of re-sown pasture after a sequence of crops.

Liebig's Law of the Minimum Suggests that the growth of a plant is dependent on the amount of foodstuff which is presented to it in minimum quantities. Yields of crops are often limited not so much by nutrients needed in large quantities but by elements which need to be present in the soil in only trace amounts.

Liebscher's Law (of the Optimum) Predicts an increase in the use efficiency of nutrients by a plant as other nutrients are brought closer to the optimum. Liebscher's Law was originally described as of a modification of Liebig's law of the Minimum.

Life cycle assessment (LCA) The investigation and valuation of the environmental impacts of a given product or service caused or necessitated by its existence (also known as life cycle analysis, ecobalance, and cradle-to-grave analysis).

Lignocellulosic Describing any of several closely-related substances constituting the essential part of woody cell walls of plants and consisting of cellulose intimately associated with lignin.

Livelihood systems A concept that accounts for the effects of off-farm income on the operation, management and income stability of a farm system.

Livestock Unit Animal (e.g. steer) with a weight of 450 kg. See also DSE.

Loess A fine-grained unstratified accumulation of clay and silt deposited by wind.

Macrofauna Organisms such as earthworms and termites (found in soil).

Madden-Julian Oscillation An equatorial band of anomalous rainfall that travels across the Indian and western Pacific Oceans at approximately 6 week intervals.

Mallee (a) Small eucalypt trees (or large shrubs) which produce several stems from large underground lignotubers; (b) a region in South Australia lying between the Mount Lofty ranges and the Victorian border; and (c) a region in the north-western portion of Victoria.

Marketing margin The difference between the price of a product (or an input) on the farm and the price in the market where it is sold. This difference is associated with real marketing costs such as transportation, storage, foregone interest on capital, and spoilage.

Meadow A field or pasture; a piece of land covered or cultivated with grass, usually intended to be mown for hay; an area of low lying vegetation, especially near a river.

Mean weight diameter (Soil) An index of soil aggregate stability which is equal to the sum of products of the mean diameter of each size fraction and the proportion of the total sample weight occurring in the corresponding size fraction.

Mesofauna Organisms such as microarthropods and mites (found in soil).

Microbacteria *Microbacteria* spp.

Microfauna Small organisms such as bacteria and fungi (microorganisms), protozoa and nematodes.

Microflora The part of the plant population consisting of individuals that are too small to be clearly distinguished without the use of a microscope. It includes algae, bacteria, and fungi.

Mixed Farm The use of a single farm for multiple purposes, such as the growing of cash crops and the raising of livestock. Opposite of monoculture.

Monocropping, Monoculture The practice of producing or growing one single crop over a wide area. Sometimes used where the same crop is grown repeatedly on the same land. Opposite of mixed cropping.

Monocyclic diseases Diseases in which the pathogens complete only one generation, or part of a generation, in a given year and thus reinfection due to a new generation of pathogen does not occur during a single year. Corn smut caused by *Ustilago maydis*, for example, produces its teliospores at the end of the season. These spores over-winter in or on soil, germinate producing basidia and basidiospores which infect the host. It takes a full year for completion of the disease cycle.

Mosaic farming The arrangement of vegetation types in relation to landscape or soil characteristics to maximise long-term economic and environmental goals.

Mouldboard plough A plough shaped to cut and turn over soil to bury surface residue. It is rarely used in Australia's shallow topsoils as it brings up less fertile subsoil. However, it has been used successfully where hard setting or crusting occurs to bring up swelling or shrinking clay subsoil to improve topsoil structure.

Mulch-till A system of conservation tillage in which the soil is disturbed anytime after harvesting and before planting using chisels, field cultivators, disks, sweeps or blades. Weed control is accomplished with herbicides and/or cultivation. Mulch-till is a category that may be used to include all conservation tillage practices other than no-till and ridge-till.

Mulesing The removal of skin from around the anus of sheep to prevent the growth of wool. This is a practice which successfully controls blowfly strike.

Multidisciplinary A multidisciplinary approach is the joining together two or more disciplines without integration. See Interdisciplinary, Transdisciplinary, Crossdisciplinarity.

Multifunctionality An assertion that agriculture is inextricably linked to social and environmental benefits that cannot otherwise be produced by society and so should be provided with support to continue to provide such benefits.

Multispectral image analysis Uses a set of optimally chosen spectral bands that are typically not contiguous (usually by multiple sensors).See Hyperspectral imaging analysis.

Mycotoxin A poisonous substance produced by a fungus.

Natural capital An extension of the economic notion of capital (manufactured means of production) to environmental goods and services. It is the stock of natural ecosystems that yields a flow of valuable ecosystem goods or services into the future. For example, a stock of trees or fish provides a flow of new trees or fish, a flow which can be sustainable indefinitely. See Ecosystem services.

Natural sequence farming A farming system devised in Australia by Peter Andrews based on restoring natural hydrological features in the landscape that existed before European settlement.

Necrotrophic Utilising dead plant or animal tissues as a source of nutrients.

Net Present Value (NPV) The present value (at a given interest rate) of the net cash flows that will result from an investment, minus the amount of the original investment.

Nitrogenase An enzyme used by some organisms to fix atmospheric nitrogen gas.

Normalized Difference Vegetation Index NDVI is a simple numerical indicator that can be used to analyse remote sensing measurements, typically, but not necessarily, from a space platform, and to assess whether the target being observed contains live green vegetation.

No-till A form of conservation tillage also called zero tillage and previously termed chemical farming. The crop is planted (drilled) into the undisturbed soil using equipment designed to handle previous crop or pasture residues. Chemical sprays are generally used to kill weeds or other plants prior to planting.

Nutraceuticals A term derived from the words ‘nutrition’ and ‘pharmaceutical’ which refers to foods claimed to have a medicinal effect on human health. Such foods are also called functional foods. It can also refer to individual chemicals present in common foods.

Objective The means of achieving a goal. They state what is to be achieved and when but not necessarily how. Objectives should be SMART, i.e. Specific, Measurable, Attainable, Realistic, and Time-based. Some add ER (SMARTER) i.e. Enjoyable and Rewarding.

Oligotrophic organism These organisms have ability to multiply and maintain activity in low-carbon soils.

On-the-go sensors Sensors that function while machinery is operating giving real time information.

Oomycetes (Water moulds) A group of filamentous, unicellular Heterokonts, physically resembling fungi. They are microscopic, absorptive organisms that reproduce both sexually and asexually and are composed of mycelia, or a tube-like vegetative body (all of an organism’s mycelia are called its thallus).

Open Systems Are those that have flow of matter, energy and/or information between the system and its environment, c.f. closed systems.

Operation (of a system) See System operation.

Orthocorrected or orthorectified A GIS term that means the distortions associated with terrain and image collection have been removed so that accurate measurements can be made directly from the imagery.

Osmoregulation The active regulation of the osmotic pressure of fluids in plant and animal cells to regulate water content—that is keeping the cell’s fluids from becoming too dilute or too concentrated. In plants, it can refer to the active accumulation of solutes as water deficits develop.

Osmotic adjustment See Osmoregulation.

Output (a) An amount produced over a given time. The result or yield from a production process, such as raising crops and livestock; and (b) a product of a system.

Para plough A primary tillage implement used for deep ploughing without inversion. It reduces the bulk density and increases the hydraulic conductivity of the soil.

Parasitoid An insect (e.g. an ichneumon wasp) that lays its eggs inside the living body of another animal or insect. The hatching larvae live as parasites which eventually kill their hosts.

Path-dependent Path dependence explains how the set of decisions one faces for any given circumstance is limited by the decisions one has made in the past, even though past circumstances may no longer be relevant.

Penman equation Calculates evaporation (E) from an open water surface, and was developed by Howard Penman in 1948. Penman's equation to predict E requires daily mean temperature, wind speed, relative humidity and solar radiation.

Perennate, perennation, perenniality Of plants; to survive from season to season, i.e. a perennial plant.

Phase farming Alternating a series of crops with a few years of perennial species such as lucerne or pastures.

Phenological development. The natural development of a plant or animal through the various stages of its life cycle. Environmental factors may influence this development.

Phenotypic plasticity The ability of an organism with a given genotype to change its phenotype in response to changes in the environment.

Pigs Also called hogs or swine.

Planting Sowing, Seeding. To place seed in or on the ground by hand or machine for future growth.

Plastic mulch Plastic sheeting used, in a similar fashion to mulch, to suppress weeds and conserve water.

Plough pan A hard layer (pan) which develops at plough depth and which prevents root penetration and water infiltration.

Polyculture Agriculture using multiple crops in the same space, in imitation of the diversity of natural ecosystems, and avoiding large stands of single crops, or monoculture. It includes crop rotation, multi-cropping, intercropping, companion planting, beneficial weeds, and alley cropping.

Polycyclic diseases Diseases where secondary cycles of reinfection occur during the season. They can spread rapidly within fields and to other fields in a single season. Control options are aimed at reducing spread by decreasing the number of secondary cycles that occur. An example is the stem, black or cereal rusts caused by the fungus *Puccinia graminis*.

Pop-up fertiliser Small amounts of fertiliser placed directly with seed. Syn. Starter fertiliser.

Potential Yield See Production Potential.

Prairie A term used in North America for an area of land of low topographic relief that historically supported grasses and herbs, with few trees, and having generally a moderate or temperate climate. The term encompasses much of the area referred to as the Great Plains of the United States and Canada. Other similar temperate grasslands regions include the Pampas of Argentina, and the steppes of Russia, Ukraine and Western Germany.

Precipitation Condensation from the atmosphere, falling as rainfall, dew, snow, hail or sleet.

Precipitation-Use Efficiency See Rainfall Use Efficiency.

Precision Agriculture A system that seeks to exert more control over a production system by recognising variation and managing different areas of land differently, according to a range of economic and environmental goals. Various tools used to collect large amounts of data on crop performance and the attributes of individual production areas at a high spatial resolution. A number of enabling technologies are critical, including the global positioning system (GPS), geographical information systems (GIS), soil sensors and yield monitors which, with GPS, enable georeferenced records of yield to be collected 'on-the-go' during harvest.

Present Value Calculated by multiplying a sum in the future by a discount factor. It is, in effect, the sum of money that could be invested now at the specified compound interest rate that would grow to the desired future value.

Press Wheels Are small wheels behind a sowing implement to compact the soil around the newly-sown seed to improve seed–soil moisture relations.

Problem Cause diagram or tree A particular problem is identified, and the possible causes are drawn up and linked to the problem.

Problem map A diagram where each node is a problem, and each link shows the relationship between problems.

Production Potential The calculation of Potential yield Y = m W/P, where m is a constant for a particular crop and soil conditions, including the proportion of moisture lost by evaporation from the soil; W = Total seasonal water use and P = mean growing season (from sowing to maturity) Class A Pan Evaporation. French and Schultz estimated values of m for various crops and soil evaporation situations.

Productivity Economics: The amount of output created (in terms of goods produced or services rendered) per unit input used. More generally the amount of production for a given set of resources. See Water Productivity.

Products (of a system) Desired outputs of a system.

Profit (a) The opposite of loss; (b) the reward for employing capital; (c) the excess of total revenue over total expenses over a specified period; and (d) an increase in equity resulting from the operation of a business.

Propagules Any part of an organism, produced sexually or asexually, that is capable of giving rise to a new individual.

Quadruple bottom line A business planning approach that tries to achieve a balance between goals—profit, environment, people and culture.

Rainfall (mm) This is measured by volume and expressed as height per unit area. To maintain mass balance, it is assumed that 1 g of water occupies 1 cm^3.

Rainfall Deciles All rainfalls received (for a year or the growing season months or a particular month) are ranked in order from lowest to highest. The lowest 10% are delineated by the decile 1 value, and belong to decile range 1. The next 10% are in decile range 2, and so on, the highest 10% being in decile range 10. The median is equivalent to the decile 5 value. Decile ranges shown in tables and in maps give a better indication of how dry or wet the month or year has been than does the departure from the 'mean' or 'average'.

Rainfall Use Efficiency The mass (kg) of dry matter (DM) produced/unit area/mm precipitation (rainfall, snow and dew) received. Runoff and deep drainage may be included as components of the rainfall, subtracted from it if they can be estimated, or regarded as negligible in strongly water-limited environments.

Real Time Kinematic Global Positioning System A technique based on the use of carrier phase measurements of the GPS. A single reference station provides the real-time corrections as close as 1 cm level of accuracy. The system is also commonly referred to as Carrier-Phase Enhancement, CPGPS.

Red gut in sheep An acute haemorrhagic enterocolitis occurring in sheep grazing some lucerne or clover pastures, or other fresh, young green feed. Some cases show severe abdominal distension, with rapid death. Syn. Intestinal volvulus, torsion of mesentery, colonic bloat, intestinal venous infarction.

Reduced tillage Tillage systems that leave between 15% and 30% residue cover on the soil or 560–1,100 kg/ha of small-grain residue during the critical erosion period. This may involve the use of a chisel plough, field cultivators, or other implements.

Relay Cropping A form of multiple cropping where a second crop is started amidst the first crop before the latter has been harvested.

Remote Sensing The acquisition of information of an object or phenomenon by the use of either recording or real-time sensing device(s) that is not in physical or intimate contact with the object (such as by way of aircraft, spacecraft, satellite, buoy, or ship).

Renewability (percentage) Renewable energy divided by total energy used expressed as a percentage of total energy.

Resilience The ability of a system to withstand severe, usually unpredictable, disturbing forces. It involves both resistance to the disturbance and the rate and degree of recovery from the disturbance.

Resistance The ability of the plant to reduce the activity and reproduction of the pathogen. The opposite of resistance is susceptibility.

Resource base Resources available to a farmer—especially soil.

Resources Total means available for further development including plant, labour, and raw material; assets.

Return on capital The ratio of net profit to total capital invested, expressed as a percentage.

Rhizodeposition Transfer of material from roots to soil.

Rhizoplane The part of a plant's root that lies at the surface of the soil, and where many microorganisms adhere to it.

Rhizosphere The narrow region of soil that is directly influenced by root secretions and associated soil microorganisms.

Ridge-till A system of conservation tillage in which the soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width. Planting is completed on the ridge and usually involves the removal of the top of the ridge. Planting is completed with sweeps, disk openers, coulters, or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished by sprays and/or cultivation. Ridges are rebuilt during row cultivation.

Rod weeder Tractor-drawn implement that has a rod that rotates below the surface of the soil and which pulls and uproots weeds, depositing them on the surface fully exposed to sun and wind.

Root mean square error (RMSE) A measure of the differences between values predicted by a model or an estimator and the values actually observed from the thing being modelled or estimated.

Runoff The portion of precipitation on land that ultimately reaches streams—often with dissolved or suspended material.

Sahelian zone A semi-arid tropical savanna and steppe ecoregion in Africa, which forms the transition between the Sahara to the north and the slightly less arid savanna belt to the south, known as the Sudan (not to be confused with the country of the same name).

Screenings Undersized or pinched grain screened out during harvesting.

Seeder, Seed drill Machine that places seed in or on the ground for future growth.

Seeding Sowing, Planting. To place seed in or on the ground by hand or machine for future growth.

Self-mulching A soil in which the surface layer becomes so well aggregated that it does not crust and seal under the impact of rain but, instead, serves as a surface mulch upon drying.

Sink A body or process that acts to absorb or remove energy or a particular component from a system; the opposite of source: a heat sink the oceans can act as a sink for CO^2.

Sink limited A process is termed 'sink limited' if there is nothing to absorb or remove a particular component of a system.

Site Specific Agriculture A management strategy that uses information technologies to bring spatial data from numerous sources, which can influence decisions associated with crop production.

Slickensides Polished, grooved surfaces that occur along shear planes within the soil which result from the shrink-swell action of clays that accompanies cycles of wetting and drying.

Sod That stratum of the surface of the soil which is filled with the roots of grass, or any portion of that surface; turf; sward.

Sod-based rotations A north American term for rotations that alternate sod-forming grasses and legumes with row crops and cereal grains. The grass and/or legumes should break up the row crop cycle for more than 1 year. Termed pasture ley in Australia.

Sodbusting North American term for breaking up native pasture with implements.

Soft System Methodology (SSM) A system where the overall ends may be known but the actual outcomes and means to achieve them are not easily quantified. Frequently there is an attempt to improve the situation rather than find the 'best' solution.

Soil Health The ability of a soil to: (a) sustain plant and animal productivity and diversity; (b) Maintain or enhance water and air quality; and (c) support human health and habitation. It includes appropriate levels of minerals, nutrients, and microbial activity, pH, and structure that is not degraded or degrading but providing a full range of functions (especially nutrient, carbon and water cycling) in such a way that it maintains its capacity into the future.

Soil quality The capacity of a specific kind of soil to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation.

Soldier-settler block Soldier settlement refers to the occupation and settlement of land throughout parts of Australia by returning discharged soldiers under schemes administered by state governments after World Wars I and II. A parcel of land sold or leased to a returning soldier was termed a 'soldier settler block' (often in fractions of a square mile (640 acres).

Sorptivity A measure of the capacity of the medium to absorb or desorb liquid by capillarity action.

Southern Oscillation Index (SOI) A measure of differences in equatorial sea surface temperatures between the Indonesian region and the eastern Pacific regions, and calculated from atmospheric pressures in Tahiti and Darwin. A strongly negative index is associated with El Niño episodes, a strongly positive SOI with La Niña episodes. See El Niño and La Niña.

Sowing Planting, Seeding. To place seed in or on the ground by hand or machine for future growth.

Sown tramlines Tramlines are sown with shallow points or disc openers to retain as much firmness as possible in the tramline and assist traction while providing cover to reduce erosion.

Specific leaf area The area per unit mass or weight of leaf and is a measure of leaf thickness: thin leaves have a higher specific leaf area.

Spray or Pasture Topping A technique for reducing grass seed set in a pasture in the years before cropping. For good results, paddocks need to be grazed heavily in winter and left free in early spring to ensure that all grasses come to head at the same time. Low rates of knockdown herbicides (such as Roundup®) are then applied to bum off the seed heads before viable seed is set.

Stability A situation where there is minimal fluctuation over time. In farming systems, a constancy of productivity in the face of small, usually cyclical, disturbing forces.

Stacked hybrids Bioengineered hybrid plants with two or more beneficial traits.

Stocker 1. A young bovine kept until fattened or matured and suitable for a breeding establishment. 2. (US) A young steer or heifer that is fed chiefly pasture or other roughage prior to more intensive feeding, c.f. Feeder.

Stover Consists of the leaves and stalks of corn (maize), sorghum or soybean plants that are left in a field after harvest. It can be directly grazed by cattle or dried for use as fodder (forage). It is similar to straw, the residue left after any cereal grain or grass has been harvested at maturity for its seed.

Strip cropping A system that alternates strips of grass or closely sown crops such as hay, wheat, or other small grains with strips of row crops, such as corn, soybeans, cotton, or sugar beets. These are sown on the contour to reduce erosion. Syn. Strip farming.

Strip-Till A tillage method that retains most of the crop residue left from the previous year's harvest. Only a narrow strip of residue is removed in which the seed is planted. Mounds may be created in this narrow strip during fertiliser application, aiming to produce a warmer, drier seedbed.

Structure (of a system) How the system is organised. Closely related to the function of the system. It includes the components and their patterns of use; the flow of materials, energy, information, labour, management and capital into, out of and within the system; and the annual calendar of activities.

Subsoiler A tractor-mounted implement used to loosen and break up soil at depths below the level of traditional cultivating implements. Syn. Deep rippers.

Subsystem A system that, for the purposes of the investigation, is part of a larger system.

Succession Planning Deliberate planning by the current farm holding generation to hand over the farm assets to the next generation while providing for their own retirement and for those of the next generation not remaining in the farm business.

Supply chain The system of organisations, people, technology, activities, information and resources involved in moving a product or service from supplier to customer.

Sustainability In agriculture, sustainable practices are those which are, and will continue to be, profitable for farmers; that will conserve soil and water resources and protect the environment; and that will assure adequate and safe food supplies.

Sustainable Agriculture A set of goals or objectives for agricultural systems. It is about managing the land with a healthy ecological balance, a sensitivity to the land's capabilities, using technologies and practices which have minimal impact while maintaining production and economic viability.

Sustainable Development Development that meets the needs of the present without compromising the ability of future generations to meet their needs.

Sustainable Society A society which, through population control, land care and control of pollutants, is capable of permanent quality of life, c.f. conservation, stewardship role.

Swath grazing A grazing system used in cold climates where annual cereals are planted in summer and swathed (cut) in autumn to provide feed for animals in winter.

Swine See Pigs.

Symbiosis An obligate relationship between two organisms of different species living together in close association for their mutual benefit. e.g. legume–rhizobium symbiosis for nitrogen fixation.

System A group of interacting components, capable of reacting as a whole to external stimuli applied to one or more components and having a specified boundary based on the inclusion of all significant feedbacks. See Hard, Soft system and Subsystem.

System function How a system operates or works.

System Operation Includes production and management and the flow of materials, energy, information, labour, machinery, and capital into, out of and within the system; and the annual calendar of activities.

System Structure See Structure (of a system).

Systemic Generally distributed throughout an organism.

Systems Analysis An integrated, step-by-step approach for helping a decision maker choose a course of action by investigating the full problem, searching out objectives and alternatives, and comparing them in the light of their consequences, using an appropriate framework (in so far as possible analytic and quantitative) to bring expert judgment and intuition to bear on the problem.

Systems Approach The systems approach is a methodology for dealing objectively and, as often as practicable, scientifically, with the complexity of systems. Systems thinking is a way to broaden the analysis in the direction of holism, cf. holistic.

Systems Boundary See Boundary.

Systems theory An interdisciplinary field of science and the study of the nature of complex systems in nature, society, and science. More specifically, it is a framework by which one can analyse and/or describe any group of objects that work in concert to produce some result.

Taff, Teff *Eragrostis tef*—A small-seeded cereal that is staple in Eritrea and other parts of North Africa.

Take-all decline Take-all (*Gaeumannomyces graminis*) is a disease of cereal roots common in temperate climates. Experiments performed at Rothamsted Experimental Station have shown that take-all build-up occurs in successive crops to reach a peak in the 3rd to 5th cropping year, after which the disease declines, ultimately restoring yields to 80–90% of 1st and 2nd year levels. The decline cycle is destroyed by the introduction of a crop other than wheat or barley.

Tame pasture Cultivated fields planted with introduced (non-native) grass and legume species or cultivars. Syn. Sown or improved pasture.

Teleomorph The sexual reproductive stage (morph), typically a fruiting body of a fungus.

Terms of trade The purchasing power of a bundle of exports in terms of imports or the level of export prices as compared with import prices. The terms of trade are said to become more favourable if export prices are rising more rapidly or falling less rapidly than import prices. In either case, a larger quantity of imports can be obtained for a given quantity of exports. On the other hand, if export prices are rising less rapidly or falling more rapidly than import prices, the terms of trade are unfavourable. May also be applied to a sector within an economy such as farming. See also Cost Price Squeeze.

Tillage See Intensive tillage, Reduced tillage, Conservation tillage.

Tillering A stage in the growth of crop plants such as wheat. The tillers (shoots) form at the base of the plant in the axil of the first-formed leaves of the main stem and of the coleoptile.

Tolerance (disease) The ability of a plant to grow and yield well despite being infected with the disease. The opposite of tolerance is sensitivity.

Top-down approach The breaking down a system to gain insight into its compositional sub-systems (analysis or decomposition).

Toposequence A sequence of related soils that differ, one from the other, primarily because of topography as a soil-formation factor.

Trade-off An exchange that occurs as a compromise.

Tramline Farming Tramline or Controlled Traffic farming improves farm production and efficiency by controlling traffic and confining compaction to permanent tramlines and reducing overlap. Tramlines may be bare, fuzzy, sown or furry.

Transdisciplinary A transdisciplinary approach dissolves boundaries between disciplines while respecting disciplinary expertise. See Multidisciplinary, Interdisciplinary, Crossdisciplinarity.

Transformity The ratio of the total emergy that contributes to generate an output to the available energy of the output (seJ/J). In other words it is the emergy of one type required to make a unit of energy of another type.

Transgenic Transgenic organisms possess a gene or genes that have been transferred from a different species. See GMO.

Transpiration Efficiency Dry matter production per unit of water transpired.

Two-wheel tractor Rubber-tyred or iron-rimmed two-wheeled, self-propelled machines that may be equipped with a range of attachments such as rotovators, ploughs, cultivators, seeders, transplanters, and planters or attached to a cart for transport. Used in small-scale agriculture in Asia and Europe.

Vlei Southern African term for a shallow body of typically seasonal fresh water. Vlei soils are generally poorly drained.

Volumetric soil water content The amount of water in the soil defined in volumetric terms. That is, the mass of water per unit of volume of soil (w/v). This is easily measured and should not be confused with the often inappropriate units of volume of water per unit volume of soil (v/v). This alternative unit for volumetric water content, based on the volume of water rather than its mass, is a valid measurement, but it can be inappropriate for studies that require mass balance where wide temperature changes alters its volume but not mass.

Water Balance Equation $W2 - W1 = P - R - D - (Es + T)$, where $W2 - W1$ = the change in soil water content from Time 1 to Time 2, P = precipitation (which may be rain, snow or dew), R = runoff, D = drainage below potential root zone, Es = soil evaporation, loss of water by evaporation from the soil, and T = transpiration: water travelling through the plant and out through the leaves.

Water depletion Water rendered unavailable for further use in the present hydrological cycle. In rainfed agriculture, this occurs by transpiration, evaporation, runoff and deep drainage. It may also occur when water stored in a subsoil becomes unavailable to plants because of the presence of toxic levels of certain minerals.

Water Productivity Agricultural output per unit of water depleted.

Water Use Efficiency (WUE) Technical: The quantity of product (e.g. grain) produced per increment of water supplied (e.g. mm rainfall). Economic: The value of product produced per increment of water supplied. See also Transpiration Efficiency, Rainfall Use Efficiency, Farm Water Use Efficiency.

Whitehead A bleached cereal ear containing little or no grain. Usually a result of attack by stem base or root pathogens, particularly *Gaeumannomyces graminis* (take-all).

Whole Farm Planning A process of planning and property design management based on ecological, social and economic factors.

Wideline farm implements Term used in Australia for very wide cultivators or seeders (e.g. 20 m wide).

Worldview A comprehensive, esp. personal, philosophy or conception of the world and of human life.

Yield Prophet® An on-line crop production model designed to provide grain growers with real-time information about the crop during growth. It uses the computer simulation model APSIM together with paddock specific soil, crop and climate data to generate information about the likely outcomes of farming decisions.

Zai Or 'water pocket' is a planting pit developed in the Yatenga province, northwestern part of Burkina Faso, West Africa, where average rainfall is about 600 mm, with recurrent droughts and where soils are heavily encrusted (zipele).

Zero-till See No-till.

Zipele West African term for bare, crusted, compact, and infertile soils.

Zonal Management Managing operations and applying inputs according to the specific needs of different areas within the same field.

Zone tillage The indirect loosening of an area of soil between two coulter blades which are stagger mounted on either side of a planter row.

Abbreviations

AFO	Animal feeding operations
ALS	Active Light Sensor
AMF	Arbuscular Mycorrhizal Fungi
APW	Australian Premium White—a classification of Australian Bread Wheat
ASBVs	Australian Sheep Breeding Values
asl	Above sea level
BD	Bulk density
BLM	Border Leicester × Merino ewes
BPR	Buried Plant Residues
BSE	Bovine Spongiform Encephalopathy
BT	*Bacillus thuringiensis*. Proteins from this fungus have been inserted in crops by genetic modification methods to provide resistance to insect attack e.g. BT cotton.
CA	Conservation Agriculture
CAFO	Concentrated animal feeding operations
CAM	Crassulacean acid metabolism
CBP	Critical Breaking Point
CCN	Cereal Cyst Nematode
CEC	Cation exchange capacity
CHU	Crop heat units (Corn heat units)
CSM	Complex system methodology
CT	Conventional Tillage
CTF	Controlled Traffic Farming
DAP	Diammonium Phosphate (fertiliser)
DBS	Deep Blade System
DGPS	Differential Global Positioning System
DMI	Demethylation inhibitor
DPTA	Diethylenetriaminepentaacetic acid
DRB	Deleterious rhizobacteria
DSE	Dry Sheep Equivalent. The ability to maintain a 45 kg Merino wether at constant body weight
DSS	Decision support systems
DWR	Deepwater, rainfed lands
E	Evaporation
EAR	Emergy Appropriation Ratio
EBVs	Estimated Breeding Values
EC	Electrical conductivity
ECa	Apparent electrical conductivity
EER	Emergy Exchange Ratio. The ratio of the emergy exported with the product or service to the emergy of the money or the product received for it

EFP	Environmental Farm Plan
EIA	Environmental Impact Assessment
Eo	Potential evaporation from a free water surface
Eg	Net energy gains
ELISA	Enzyme linked immunosorbent assay
ELR	Environmental Loading Ratio
EM	Electromagnetic (induction or survey)
EMA	Emergy Analysis
EMS	Environmental Management Systems
ENSO	El Niño–Southern Oscillation
Er	Energy Efficiency Ratio
ER	Evapo-transpiration Ratio
Es	Soil evaporation
ESI	Emergy Sustainability Index
ET, ETP	Evapo-transpiration
EUREPGAP	European Good Agricultural Practice
EYR	Emergy Yield Ratio
F	Imported flows or outside resources in emergy calculations
FSR	Farming Systems Research
$G \times E \times M$	Interaction of genotype, environment and management
GAP	Good Agricultural Practice
GDP	Gross Domestic Product
Ggt fungus	*Gaeumanomyces graminis* var. *tritici* (Take-all)
GHG	Greenhouse gas
GIS	Geographical Information System
GM	Genetically modified
GMO	Genetically modified organism
GSR	Growing season rainfall
HACCP	Hazard Analysis and Critical Control Point
HEIA	High external input agriculture
HEL	Highly erodible land
HSM	Hard-systems methodology
HUM	Humus
ICM	Integrated Catchment Management
IGR	Insect Growth Regulator
IPM	Integrated pest management
ITC	Isothiocyanates
IWM	Integrated weed management
K	Potassium
LCA	Life Cycle Analysis
LEAF	Linking Environment And Farming
LED	Light-emitting diode
LEIA	Low external input agriculture
LER	Land Equivalent Ratio

LL	Lower limit
LL	Liberty Link
LRAD	Land Redistribution for Agricultural Development (South Africa)
LSU	Livestock Unit: Animal (e.g. steer) with a weight of 450 kg.
masl	Metres above sea level
MAT	Management Action Target
MBC	Microbial biomass carbon
Mg	Magnesium
MIGI	Median seasonally-integrated growth index
MIR	Mid infrared technology
MWD	Mean weight diameter (Soil)
N	Nitrogen
NDVI	Normalized Difference Vegetation Index
NGO	Non-Government Organisations
NIR	Near Infrared
NR	Non-renewable resources
NSNF	Non-symbiotic nitrogen fixation
NT	No-till
NUE	Nitrogen use efficiency
OA	Organic Agriculture
OM	Organic matter
OH&S	Occupational Health and Safety
P	Phosphorus
P	Precipitation
PA	Precision Agriculture
PAR	Participatory Action Research
PAR	Photosynetically Active Radiation
PAW	Plant available soil water
PAWC	Plant available soil water storage capacity
PC	Personal computer
PDA	Personal digital assistant or hand-held computer
PET	Potential evaporation from soil plus transpiration by plants
PGPR	Plant growth and root growth promoting Rhizobacteria
PMP	Property Management Planning
POC	Particulate Organic Carbon
PSNT	Pre-sidedress soil N test
PUE	Precipitation Use Efficiency
QA	Quality Assurance
R	Renewable resources
R&D	Research and Development
RCT	Resource Condition Target
RDE	Research, development and extension
Ren	Renewability
RHA	Rainwater harvesting agriculture

RMSE	Root Mean Square Error
ROC	Resistant Organic Carbon
RR	RoundUp Ready®
RTK GPS	Real Time Kinematic Global Positioning System
RUE	Radiation use efficiency
SCF	Seasonal climate forecasts
SE	Standard Error, Soil Evaporation
seJ	Solar equivalent joules
SFA	Substance flow analysis
SLAG	Settlement Land Acquisition Grant (South Africa)
SMME	Small, micro and medium enterprises
SMN	Soil mineral nitrogen
SNF	Symbiotic nitrogen fixation
SOC	Soil organic carbon
SoE	State of the Environment
SOI	Southern Oscillation Index
SOM	Soil organic matter
SOS	Save our Soils (Canada)
SpHLRMS	Soil pH and Lime Requirement Measurement System
SPR	Surface Plant Residues
SQF	Safe Quality Food
SSM	Soft-systems methodology
SST	Sea surface temperature
SU	Sulfonylurea (A Group B herbicide)
T	Transpiration
TE	Transpiration Efficiency(yield/T)
TFP	Total Factor Productivity
ToT	Transfer-of-technology
TT	Triazine (Atrazine) tolerant
U	Total emergy. The sum of all emergy inputs (independent of each other) that have contributed to the system
UAN	Urea Ammonium Nitrate
VESPER	Variogram Estimation and Spatial Prediction plus Error
VPD	Vapour pressure deficit
VR	Variable rate
WANA	West Asia and North Africa
WEM	Wast energy and materials
WFS	Western Farming Systems (Queensland, Australia)
WHC	Water-holding capacity
WUE	Water Use Efficiency

Acronyms (Areas, Organisations and Models)

AAAID	Arab Authority for Agricultural Investment and Development
ACIAR	Australian Centre for International Agricultural Research
ACPA	Australian Centre for Precision Agriculture
AFD	French Agency for Development, Agence Française de Développement
AICRPDA	All-India Coordinated Research Project for Dryland Agriculture
ANC	African National Congress
ANZECC	Australian and New Zealand Environment Conservation Council
APSIM	Agricultural Production Systems sIMulator. A modeling framework with the ability to integrate models derived in fragmented research efforts.
APSRU	Agricultural Production Systems Research Unit (Australia)
BCG	Birchip Cropping Group
CERES	Crop Environment Resource Synthesis. A predictive, deterministic model designed to simulate a specific crop's growth, soil, water and temperature and soil nitrogen dynamics at a field scale for one growing season
CGIAR	Consultative Group on International Agricultural Research
CIAT	Centro Internacional de Agricultura Tropical (International Center for Tropical Agriculture
CIMMYT	International Centre for Maize and Wheat Improvement
CIRAD	International Centre for Research and Development (France), Centre International de la Recherche Agronomique pour le Développement
CRIDA	Central Research Institute for Dryland Agricuture (India)
CRS	Catholic Relief Services
CSIRO	Australian Commonwealth Scientific & Industrial Research Organisation
DPRK	Democratic People's Republic of Korea
EADS	European Aeronautic Defence And Space Company
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária(Brasil)
EU, EC, EEC	European Union (formerly European Community)
EUREP	European Retailers Group
FAO	Food and Agriculture Organization of the United Nations
FAST	Farming and Sustainable Technology
GATS	General Agreement on Trade and Services
GRASSGRO	A decision support tool developed by CSIRO Plant Industry (Australia) to examine variability in pasture and animal production and assist decision-making in sheep and beef enterprises.

GRDC	Australian Grains Research & Development Corporation
GTZ	Deutsche Gesellschaft für Technische Zusammenarbei
ICA	Instituto Colombiano Agropecuario (Columbia)
ICARDA	International Centre for Agricultural Research in Dry Areas
ICRISAT	International Centre for Agricultural Research in the Semi-Arid Tropic
INTA	Instituto Nacional de Tecnología Agropecuaria (Argentina)
IPCC	Intergovernmental Panel on Climate Change
KARI	Kenya Agricultural Research Institute
NARI	National Agricultural Research Institute (Eritrea)
NERPO	National Emerging Red Meat Producers Organisation (South Africa)
NRCS	USDA-Natural Resource Conservation Service
OECD	Organisation for Economic Cooperation and Development
OSCIA	Ontario Soil and Crop Improvement Association
OSGMB	Ontario Soybean Growers Marketing Board
PIRSA	Department of Primary Industries and Resources of South Australia
QDPI&F	Queensland Department of Primary Industries and Fisheries
SANTFA	South Australian No-Till Farmers Association
SPAA	Southern Precision Agriculture Association (Australia)
TAR	Tibet Autonomous Region of China
USDA	United States Department of Agriculture
WANA	West Asia and North Africa
WHEATMAN	A computer program that estimates the likelihood of good, average or poor yield for winter crops, based on soil moisture and historical weather records; this provides the basis for nitrogen decisions. Wheatman also helps decide the best fertiliser rate for existing seasonal conditions

Botanical names of plants

Common names	Genus and species
Afgan mellon	*Citrullus lanatus*
Alfalfa, Lucerne	*Medicago sativa*
Amaranth, Pigweed	*Amaranthus* spp.
Annual ryegrass	*Lolium rigidum*
Apple	*Malus domestica*
Arracacha	*Arracacia xanthorriza*
Awnless barnyard grass	*Echinochloa colona*
Bahiagrass, Dallis grasses, Paspalum	*Paspalum* spp.
Ball clover	*Trifolium glomeratum*
Ball mustard	*Neslia paniculata*
Bambara groundnut	*Vigna subterranea*
Banana	*Musa* spp.
Barley	*Hordeum vulgare*
Barley grass	*Hordeum leporinum*
Barnyard grass	*Echinochloa crusgalli*
Bean, Navy, Common White, Pea, Haricot, Pinto	*Phaseolus vulgaris*
Birdsfoot trefoil	*Lotus corniculatus*
Black gram, urdbean	*Vigna mungo*
Blackberry	*Rubus fruiticosa*, *Rubus* spp.
Blowaway grass	*Panicum* spp.
Blue grama grass	*Bouteloua gracilis*
Bluestem grass	*Andropogon* spp.
Broad bean	*Vicia faba*
Bromegrass	*Bromus inermis*
Buckwheat	*Fagopyrum esculentum*
Buffel grass	*Cenchrus ciliaris*
Burgundy bean	*Macroptilium bracteatum*
Butterfly pea	*Clitoria ternatea*
Caltrop	*Tribulus terrestris*
Camelina or false flax	*Camelina sativa*
Canada thistle, Creeping Thistle	*Cirsium arvense*
Canary seed	*Phalaris canariensis*
Canola	*Brassica napus*
Capeweed, cape dandelion, or cape marigold	*Arctotheca calendula*
Caragana	*Caragana arborescens*
Cardamom	*Elettaria cardamomum*
Carpetgrass	*Axonopus affinis*
Cassava	*Manihot esculenta*
Castor	*Ricinus communis*
Cheatgrass	*Bromus tectorum*
Chicory	*Cichorium intybus*
Chickpea (garbanzo bean, Indian pea, ceci bean, bengal gram, chana, kadale kaalu, sanaga pappu, shimbra)	*Cicer arietinum*
Chickweed	*Stellaria media*
Chilli	*Capsicum annuum*
Cicer milkvetch	*Astragalus cicer*
Cleavers	*Galium aparine*

(continued)

Botanical names of plants (continued)

Common names	Genus and species
Clover	*Trifolium* spp.
Cocksfoot, Cocksfoot grass, Orchardgrass	*Dactylis glomerata*
Coriander	*Coriandrum sativum*
Corn	*Zea mays*
Cotton	*Gossypium* sp.
Cowpea	*Vigna unguiculata*
Crested wheat grass	*Agropyron desertorum*
Crinkleawn grass	*Trachypogon* spp.
Crown vetch	*Securigera varia*
Cumin	*Cuminum sativum*
Custard apple	*Annona reticulata*
Dallis grasses, Bahiagrass, Paspalum	*Paspalum* spp.
Dandelion	*Taraxacum* spp., *Taraxacum officinale*
Dolichos lablab, Hyacinth Bean, Indian Bean, Egyptian Bean	*Lablab purpureus*
Dropseed grass	*Sporobolus* spp.
Durum wheat	*Triticum durum*
Faba bean, fava bean, horse bean, field bean, tic bean	*Vicia faba*
False Flax	*Camelina sativa*
Fat-hen; white goosefoot, lamb's quarters, pigweed or dungweed	*Chenopodium album*
Fenugreek	*Trigonella foenum-graecum*
Field pea	*Pisum sativum*
Field pennycress	*Thlaspsi arvens*
Finger millet, African millet or Ragi	*Eleusine coracana*
Flax, Linseed	*Linum usitatissimum*
Flaxleaf fleabane	*Conyza bonariensis*
Foxtail barley	*Hordeum jubatum*
Foxtail millet, German millet	*Setaria italica*
Giant foxtail	*Setaria faberi*
Goatgrass	*Aegilops* spp.
Grape	*Vitis* spp.
Grasspea (blue sweet pea, chickling vetch, Indian pea, Indian vetch, white vetch, almorta or alverjón (Spain), cicerchia (Italy), guaya (Ethiopia), and khesari (India))	*Lathyrus sativus*
Green foxtail, Green bristlegrass	*Setaria viridis*
Green gram	*Vigna radiata*
Green needlegrass	*Stipa viridula*
Groundnut or Peanut	*Arachis hypogaea*
Hairy Fleabane	*Conyza bonariensis*
Hairy vetch	*Vicia villosa*
Heliotrope	*Heliotropium europaeum*
Hempnettle	*Galeopsis tetrahit*
Hirsutum cotton (Upland Cotton or Mexican Cotton)	*Gossypium hirsutum*
Hoary cress	*Cardaria draba*

(continued)

Botanical names of plants (continued)

Common names	Genus and species
Horseweed	*Conyza canadensis*
Hyacinth bean (Lablab, Indian Bean, Egyptian Bean)	*Lablab purpureus* (syn. *Dolichos lablab* L., *Dolichos purpureus* L., *Lablab niger Medikus*, *Lablab lablab* (L.) *Lyons*, *Vigna aristata Piper*, and *Lablab vulgaris*, L.)
Indian pea	*Lathyrus sativus*
Italian ryegrass	*Lolium multiflorum*
Johnston Grass	*Sorghum halipense*
Kenaf	*Hibiscus* spp.
Kiwi fruit, Chinese Gooseberry	*Actinidia deliciosa*
Kochia	*Kochia scoparia*
Lablab (Hyacinth bean, Indian Bean, Egyptian Bean)	*Lablab purpureus* (syn. *Dolichos lablab*, *Dolichos purpureus*, *Lablab niger Medikus*, *Lablab lablab*, *Vigna aristata*, and *Lablab vulgaris*)
Lambs Tounge, fat-hen, white goosefoot, lamb's quarters, pigweed or dungweed	*Chenopodium album*
Lantana	*Lantana camara*
Lentil	*Lens culinaris*
Linseed, Common flax	*Linum usitatissimum*
Litchi, Lychee	*Litchi chinensis*
Lucerne, Alfalfa	*Medicago sativa*
Lupin	*Lupinus angustifolius*
Maize, Corn	*Zea mays*
Mallee	*Eucalyptus* spp.
Mango	*Mangifera* spp.
Marrowfat peas	*Pisum sativum*
Medics	*Medicago* spp.
Millet	Includes species in several genera, mostly in the subfamily *Panicoideae*
Mitchell Grass	*Astrebla* spp.
Mulberry	*Morus* spp.
Mung bean (moong, mash bean, munggo or monggo, green gram, golden gram, and green soy)	*Vigna radiate*, *Vigna mungo*
Musk heron's bill	*Erodium moschatum*
Mustard	*Brassica campestris*, *Brassica juncea* and *Sinapsis alba*
Narrow-leaf lupins	*Lupinus angustifolius*
Navy bean, Common Bean, White bean, Pea bean, Haricot bean, Pinto bean	*Phaseolus vulgaris*
Needle-and-thread grass	*Hesperostipa comata*
Neem tree	*Azadirachta indica*
Niger, nyjer, niger seed; noog; ramtil or ramtilla; inga seed; blackseed.	*Guizotia abyssinica*
Noogoora burr	*Xanthium pungens*, *Xanthium occidentale*
Oat	*Avena sativa*
Oca, New Zealand yam	*Oxalis tuberosa*
Oil palm	*Elaeis guineensis*, *Elaeis oleifera*
Oilseed radish	*Raphanus sativus*
Olive	*Olea europaea*

(continued)

Botanical names of plants (continued)

Common names	Genus and species
Onion weed	*Asphodelus fistulosus*
Orange	*Citrus sinensis* syn. *Citrus aurantium*
Orchardgrass, Cocksfoot, Cocksfoot grass	*Dactylis glomerata*
Paddymelon	*Cucumis myriocarpus*
Palmer Amaranth	*Amaranthus palmeri*
Papaya	*Carica papaya*
Paspalum, Dallis grasses, Bahiagrass	*Paspalum* spp.
Pea	*Pisum sativum*
Peach, Nectarine	*Prunus persica*
Peanut or Groundnut	*Arachis hypogaea*
Pearl millet	*Pennisetum glaucum*
Perennial ryegrass	*Lolium perenne*
Perennial sowthistle	*Sonchus arvensis*
Persian darnel	*Lolium persicum*
Phalaris	*Phalaris aquatica*
Pigeonpea	*Cajanus cajan*
Pineapple	*Ananas comosus*
Pink serradella	*Ornithopus sativus*
Pinto Bean	*Phaseolus vulgaris*
Plantain	*Musa* spp.
Pomegranate	*Punica granatum*
Potato	*Solanum tuberosum*
Prairie junegrass	*Koeleria macrantha*
Prickly pear	*Opuntia stricta*
Quackgrass	*Agropyron repens*
Quinoa	*Chenopodium quinoa*
Radish	*Raphanus sativus*
Ragweed, bitterweed, bloodweed	*Ambrosia* spp.
Rape, rapeseed	*Brassica napus*
Red clover	*Trifolium pratense*
Red grass	*Bothriochloa macra*
Red root pigweed	*Amaranthus retroflexus*
Rose clover	*Trifolium hirtum*
Rice	*Oryza sativa*
Ripgut brome	*Bromus diandru*
Rubber	*Hevea brasiliensis*
Russian thistle	*Salsola iberica*
Rye, Ryecorn	*Secale cereale*
Ryegrass	*Lolium rigidum*
Safflower	*Carthamus tinctorius*
Saia oats	*Avena strigosa*
Sainfoin	*Onobrychis viciaefolia*
Serradella	*Ornithopus compressus*
Sesame	*Sesamum indicum*
Sisal hemp	*Agave sisalana*
Skeleton weed	*Chondrilla juncea*
Snake melon	*Cucumis melo*
Sorghum	*Sorghum* spp. especially *Sorghum bicolor*
Soursob	*Oxalis pes-caprae*

(continued)

Botanical names of plants (continued)

Common names	Genus and species
Sowthistle	*Sonchus oleraceus*
Soybean	*Glycine max*
Spear grass	*Stipa* spp.
Spring wheat	*Triticum aestivum*
Spiny emex	*Emex australis*
Squash	*Cucurbita* spp.
Stylosanthes	*Stylosanthes* spp.
Subterranean clover	*Trifolium subterraneum*
Sudan grass	*Sorghum vulgare* var. *sudanense*
Sudex	*A sorghum-sudan grass hybrid*
Sugar beans	*Phaseolus lunatus*
Sugar beet	*Beta vulgaris*
Sugarcane	*Saccharum* spp.
Sulla	*Hedysarum coronarium*
Sun hemp	*Crotalaria juncea*
Sunflower	*Helianthus annuus*
Sweet clover	*Melilotus* spp.
Sweet potato	*Ipomoea batatas*
Switchgrass	*Panicum virgatum*
Tall fescue	*Festuca arundinacea*
Tangerine	*Citrus reticulata*
Tepary bean	*Phaseolus acutifolius*
Threeawn grass	*Aristida* spp.
Tick trefoil	*Desmodium* spp.
Timothy grass	*Phleum pratense*
Tobacco	*Nicotiana* spp.
Tomato	*Solanum lycopersicum*, syn. *Lycopersicon lycopersicum* and *Lycopersicon esculentum*
Trigonella	*Trigonella foenum-graecum*
Triticale	*Triticosecale X*—a hybrid of wheat (*Triticum*) and rye (*Secale*)
Ulluco, melloco, oca quina, rubas (Ecuador), olloco, ulluca, ulluma (Argentina), papa lisas, lisas (Bolivia), olluco, papalisa (Peru), rubas, camarones de tierra, ruhuas (Colombia), micuche, miguri, ruba, tinquino (Venezuela)	*Ullucus tuberosus*
Velvetleaf	*Abutilon theophrast*
Vetch	*Vicia* spp.
Wallaby grass	*Austrodanthonia* spp.
Watermelon	*Citrullus vulgaris*
Western Australian blue lupin	*Lupinus cosentinii*
Western Wheatgrass	*Pascopyrum smithii*
Wheat	*Triticum* spp.
White clover	*Trifolium repens*
White lupins	*Lupinus albus*
White Vetch	*Vicia sativa*
Wild melon (Afgan melon, Paddymelon)	*Citrullus lanatus*, *Cucumis myriocarpus*
Wild Mustard	*Sinapis arvensis*, *Brassica kaber* var. *pinnatifida*

(continued)

Botanical names of plants (continued)

Common names	Genus and species
Wild oats	*Avena* spp.
Wild Radish (raminas, runch)	*Raphanus raphanistrum*
Winter wheat	*Triticum aestivum*
Wire weed	*Polygonum aviculare*
Woolly clover	*Trifolium tomentosum*
Witchweed	*Striga asiatica*
Yellow lupin	*Lupinus luteus*
Yellow pea, yellow vetch	*Lathyrus aphaca*
Yellow serradella	*Ornithopus compressus*
Yuca (Cassava)	*Manihot esculenta*

Scientific names of insects

Common name	Genus and species
African bollworm	*Helicoverpa armigera*
Alfalfa snout beetle	*Otiorhynchus ligustici*
Alfalfa weevil	*Hypera postica*
Armyworm, Fall armyworm (Corn)	*Spodoptera frugiperda*
Assassin bug,	*Pristhesancus plagipennis*
Bean leaf beetle	*Cerotoma trifurcata*
Big-eyed bugs	*Geocoris* spp.
Black maize beetle	*Heteronychus arator*
Boll Weevil	*Anthonomus grandis*
Bollworm	Numerous moth larvae including *Diaparopsis*, *Earias*, *Helicoverpa* and *Pectinophora* spp.
Brown wheat mite	*Petrobia latens*
Bruchids	*Callosobruchus* spp. *Callosobruchus chinensis*, *C. maculatus*
Cereal bug	*Aelia rostrata*
Chilo	*Chilo suppressalis*
Common armyworm	*Leucania convecta*
Corn earworm	*Helicoverpa zea*, *Helicoverpa armigera*
Corn rootworm	*Diabrotica* spp.
Cotton bollworm/legume pod borer	*Helicoverpa armigera*
Curl mite	*Aceria tosichella*
Cutworms	*Agrotis* spp.
Diamondback moth	*Plutella xylostella*
Dusty surface beetle	*Gonocephalum simplex*
Earworm (Corn)	*Helicoverpa zea*, *Helicoverpa armigera*
English grain aphid	*Sitobion avenae*
European corn borer	*Ostrinia nubilalis*
Fall armyworm	*Spodoptera frugiperda*
False wireworm	*Gonocephalum* spp.
Fire ants	*Solenopsis invicta*
Greenbug	*Schizaphis graminum*
Head bug, Sorghum	*Calocoris angustatus*
Heliocoverpa	*H. armigera* and *H. punctigera*
Heliothis	*Heliothis spp*

(continued)

Scientific names of insects (continued)

Common name	Genus and species
Hessian fly	*Mayetiola destructor*
Leaf miner	*Liriomyza cicerina*
Leafhoppers (maize streak disease)	*Cicadulina* spp.
Lesser grain borer	*Rhyzopertha dominica*
Maize beetles	*Sitophilus* spp.
Maize stalk borer	*Busseola fusca*
Minute pirate bugs	*Orius* spp.
Native budworm	*Helicoverpa punctigera*
Oat aphid	*Rhopalosiphum padi*
Oriental armyworm	*Mythimna separata*
Pea weevil	*Bruchus pisorum*, *B. dentipes*
Pod borer	*Helicoverpa armigera*
Potato leafhopper	*Empoasca fabae*
Red hairy caterpillar	*Amsacta albistriga*, *Amsacta moorei*
Redheaded pasture cockchafer	*Adoryphorus couloni*
Redlegged earth mite	*Halotydeus destructor*
Rose grain aphid	*Metopolophium dirhodum*
Russian wheat aphid	*Diuraphis noxia*
Rust red flour beetle	*Tribolium castaneum*
Seedcorn maggot	*Delia platura*
Shoot fly	*Atherigona soccata*
Sitona weevil	*Sitona discoideus*, *Sitona crinitus*, *Sitona lineatus*
Sorghum Head bug	*Calocoris angustatus*
Sorghum midge	*Stenodiplosis sorghicola*
Sorghum shoot fly	*Atherigona soccata*
Soybean aphid	*Aphis glycines*
Spotted alfalfa aphid	*Therioaphis trifolii*
Stalk and stemborers	*Chilo partellus*, *Sesamia inferens*
Stem borer, Corn/maize	*Chilo partellus*
Stinkbug	*Nezara viridula*
Termites	*Odontotermes obesus*, *Microtermes* sp.
Webworm	*Hednota spp*
Wheat aphid	*Macrosiphon avenae*
Wireworm (False)	*Tenebrionidae*; *numerous species*
Wireworm (True)	*Elateridae*; numerous species: *Agriotes lineatus*, *Ctenicerca destructor*

Diseases

Common name	Causal genus and species	Other names
Anthracnose	*Colletotrichum gloeosporiodes*	
Ascochyta blight	*Ascochyta* sp.	
Asian Soybean Rust	*Phakopsora pachyrhizi*	
Barley stripe	*Pyrenophora graminea*	
Blackleg	*Leptosphaeria maculans*	
Cereal (stem or black) rust	*Puccinia graminis*	
Cereal cyst nematode	*Heterodera avenae*	CCN

(continued)

Scientific names of insects (continued)

Common name	Causal genus and species	Other names
Common root rot (wheat)	Caused by one or more fungi e.g. *Cochliobolus sativus* (*Bipolaris sorokiniana* (*anamorph*)), *Fusarium culmorum* and *F. gramine*	
Common rust (maize)	*Puccinia sorghi*	
Corn stalk rots	*Gibberella zeae*; *Stenocarpella maydis*; *Colletotrichum graminicola*; *Macrophomina phaseolina*; *Fusarium moniliforme*	
Crown rot of wheat	*Fusarium pseudograminearum*	Fusarium crown rot
Cylindrocladium black rot	*Cylindrocladium crotalariae*, *Calonectria crotalariae* [*teleomorph*]	
Damping off of seedlings	Caused by several soil and water-borne fungi (particularly those in the genera *Pythium*, *Phytophthora* and *Rhizoctonia*	
Diplodia ear rot	*Diplodia maydis*	
Early leaf spot	*Cercospora arachidicola*, *Mycosphaerella arachidis* [*teleomorph*]	
Ergot	*Claviceps* spp. including *C. purpurea* (grasses and cereal*s*), *C. fusiformis* (pearl millet, buffel grass), and *C. africana* (sorghum)	
Fusarium ear rot	*Fusarium* spp.	
Fusarium wilt	*Fusarium oxysporum*	Panama disease or Agent Green
Gibberella ear rot	*Gibberella zeae*, also known as *Fusarium graminearum*	
Gray leaf spot (Corn)	*Cercospora zeae-maydis*	
Head moulds	Caused by many fungi. *Fusarium* spp. (e.g. *F. moniliforme*), *Curvularia* spp., *Colletotrichum* spp., *Alternaria* spp. and *Helminthosporium* spp	
Karnal bunt	*Tilletia* sp.	
Leaf rust (wheat)	*Puccinia triticina*, *Puccinnia graminis*	
Net Blotch (barley)	*Pyrenophora teres*	
Northern corn leaf blight	*Exserohilum turcicum*	
Onion white rot	*Sclerotium cepivorum*	
Pyrenophora diseases	See Barley Stripe	
Rhizoctonia Root Rot	*Rhizoctonia* spp. *Rhizoctonia solani*	
Rust (cereal)	*Puccinia graminis*	
Sclerotinia	*Sclerotinia* spp.	
Sclerotinia blight	*Sclerotinia minor*, *Sclerotinia sclerotiorum*	
Septoria nodorun blotch	*Phaeosphaeria nodorum*	
Septoria tritici blotch	*Septoria tritici* (perfect state *Mycospharella graminicola*)	
Sorghum ergot	*Claviceps africana*	
Soybean cyst nematode	*Heterodera glycines*	
Stem rust (wheat)	*Puccinia graminis* f.sp. *tritici*	

(continued)

Diseases (continued)

Common name	Causal genus and species	Other names
Stripe or yellow rust (wheat)	*Puccinia striiformis* f.sp. *tritici*	
Take-all	*Gaeumannomyces graminis*	
Turcicum leaf blight of maize	*Exserohilum turcicum*	Northern leaf blight
Web blotch, Net blotch	*Phoma arachidicola = Ascochyta adzamethica*, *Didymosphaeria arachidicola = Mycosphaerella arachidicola*	
White rust (sunflower)	*Albugo tragopogonis*	
Yellow leaf spot	*Pyrenophora tritici-repentis*	
Yellow rust (wheat)	*Puccinia striiformis* f.sp. *tritici*	Stripe rust

Chemicals

General name	Chemical	Trade/other names
2,4-D	2,4-Dichloro-phenoxy-acetic acid	
Aldicarb	2-Methyl-2-(methylthio)propionaldehyde O-methylcarbamoyloxime	
Chlorsulfuron	2-Chloro-N-[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) aminocarbonyl]-benzenesulfonamide	Glean
Chlorothalonil	2,4,5,6-Tetrachloro-1, 3-benzenedicarbonitrile	Bravo, Daconil, tetrachloroisophthalonitrile
Ciallate	S-(2,3-dichoroallyl) diisopropylthiocarbamate	
Diquat	6,7-Dihydrodipyrido[1,2-a:2¢,1¢-c] pyrazinediium	
Fenamiphos	(Ethyl 3-methyl-4-(methylthio) phenyl (1-methylethyl) phosphoramidate)	
Flusilazole	Bis(4-fluorophenyl)(methyl)(1H-1,2,4-triazol-1-ylmethyl)silane	
Glufosinate	2-Amino-4-(hydroxy-methyl-phosphoryl) butanoic acid	Basta, Rely, Finale, Challenge, Liberty
Glyphosate	N-(phosphonomethyl) glycine	Roundup
Imazamox	2-[4,5-Dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl)-3-pyridinecarboxylic acid	
Imazethapyr	2-[4.5-Dihydro-4-methyl-4-(1-methylethyl)-5-oxo-lH-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid	
Mancozeb	Manganese ethylenebis(dithicarbamate) polymeric complex with zinc salt	
MCPA	4-Chloro-2-methyl phenoxy acetic acid	
Paraquat	1,1¢-Dimethyl-4,4¢-bipyridinium dichloride	

(continued)

Chemicals (continued)

General name	Chemical	Trade/other names
Prochloraz	N-propyl-N-[2-(2,4,6-trichlorophenoxy) ethyl]imiazole-1-carboxamide	
Propiconazole	1-[2-(2,4-Dichlorophenyl)-4-propyl-1,3-dioxolan-2-ylmethyl]-1H-1,2,4-triazole	
Simazine	2-Chloro-4,6- bis(ethylamino)-s-triazine	
Thiram	Tetramethylthiuram disulfide	
Triallate	S-(2,3,3-trichloroallyl diisopropylthiocarbamate	
Triadimenol	(1RS,2RS;1RS,2SR)-1-(4-chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazol-1-yl) butan-2-ol	
Zineb	Zinc ethylenebis (dithiocarbamate)	

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