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No-till Farming Systems for Sustainable Agriculture

Challenges and Opportunities

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Foreword

The expected increase in global population to 9.7 billion by 2050 years represents a significant threat to global food security, particularly in developing countries. This expectation highlights an urgency to boost food production in a world where the opportunity to expand the area for agriculture is limited and existing agricultural land is threatened by land degradation, water resource scarcity and increases in climate variability. Thus, to meet the world's need for greater food demand, agricultural systems will be required to evolve to increase production with greater sustainability.

The No-Till (NT) farming system is about reducing cultivation, retaining plant cover and diversification of crop rotations. This is one approach that has the potential to help global agriculture achieve the sustainable intensification required to meet the world food demand. The NT system allows for greater soil water storage, improved soil quality and decreased erosion, most often resulting in greater yield and net farm income. It has the potential to help ensure future food production and buffer agricultural productivity against the extreme climate events such as drought and heat waves, which are predicted to increase in frequency.

Despite its obvious advantages, the widespread implementation of NT systems remains a challenge in many world regions. It requires a different approach that needs to be well adapted to local conditions in order to operate successfully. Even in situations where the knowledge exists on how to make the NT system function agronomically, often social and economic barriers prevent its successful implementation at a farmer level. Thus, a comprehensive understanding of how to make the NT system function within social, economic and agronomic constraints is required to promote its wide spread adaptation and boost global food production sustainably.

This book provides a comprehensive compendium of global research on No-Till Farming Systems with contributors from around the globe, providing insight into its benefits as well as challenges from both agronomic, social and economic perspectives. Importantly, it also contains a series of chapters detailing the characteristics and future requirements of NT systems across different geographical and climatic location, authored by expert NT practitioners from these regions.

There is no doubt how we farm in the future will need to change. I firmly believe that this book is a remarkable compilation of expert opinions from around the world which will prove to be a great resource in the promotion and expansion of the NT farming system worldwide. It will work as an invaluable reference to help practitioners who are grappling with the challenges of food production in a world increasingly impacted by climate change.

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Preface

The no-till (NT) farming system is a holistic approach that incorporates minimum soil disturbance, stubble retention and appropriate crop rotations to enhance the quality of our natural resources, including soil, water and air, and energy to ensure that future generations will have food security. No-till farming systems have demonstrated advantages in economic, social, environmental and soil health aspects over conventional tillage. Global agriculture is faced with new challenges and opportunities. Key among these are global food security and climate change. The world population is projected to reach 9.7 billion by 2050, which will require sustained increases in food production. However, at the same time, crop yields are predicted to fall by 5% with each degree increase in temperature. Climate change may impact all four dimensions of food security: availability, access, utilisation and system stability. Developing a resilient food system requires a holistic, long-term perspective with other co-benefits. No-till farming systems have been demonstrated to improve food production and have the potential to preserve soil carbon to improve soil health and productivity. No-tillage is thus a critically important management practice in our complex agricultural production system.

Extensive research, development and extension (R, D & E) activities to refine and promote NT systems have led to an exponential increase in the rate of adoption over the past three decades. However, there are still significant agronomic, economic and/or social challenges that limit large-scale worldwide adoption. The principles of NT systems are universal, but the solutions are local and revolve around carbon cycling using a systems approach. Efforts are required to develop site-specific management practices to alleviate biophysical and socio-economic barriers. The principles of NT systems should ideally be integrated and applied continuously for improved carbon management and long-term sustainability. This means avoiding tillage whenever possible, although some soils may have 'natural resilience' that allows an occasional tillage event with minimum impact on soil, agronomy and the environment.

There are voluminous publications that cover R, D & E into NT farming systems and these continue to emerge. This is particularly important in terms of NT as a land management practice, and is important for the sustainable use of agricultural land

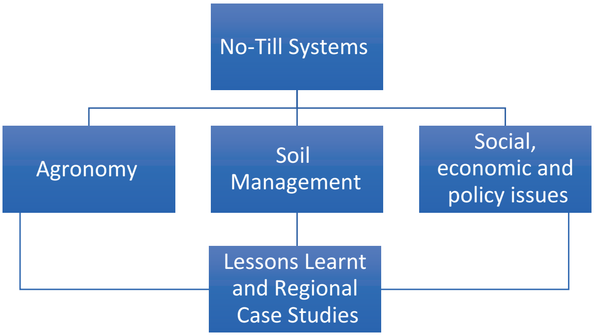

Fig. 1 Outline showing the four major book sections: Agronomy; Soil Management; Social, economic, and policy issues; and Lessons learnt and regional case studies

whilst ensuring food security with increasing adoption of this practice. Although global adoption of NT systems is increasing, they still only cover 12.5% of croplands. In order to promote the continued uptake of NT, innovative and environmental approaches are required. As a result, we have collated global information on the latest developments on NT farming systems in this book. The content of this book is divided into 4 sections (Fig. 1) and 35 chapters.

The chapters in this book examine in detail the agronomic and soil management issues that need to be resolved to ensure the successful implementation of NT systems and the challenges and opportunities associated with their use. In addition, the economic, environmental, social and policy considerations that are important for the successful development and implementation of NT are discussed. Finally, a series of case studies showcasing the development and implementation of NT systems in different world regions are presented to highlight the challenges and opportunities for NT introduction and how these vary depending on climate and geopolitical location. This book provides a comprehensive summary of our knowledge of NT systems and outlines the future research needs and opportunities in order to increase the uptake of NT farming systems worldwide.

We would like to thank Springer Nature team, Ms Marleen Moore, Ms Melania Ruiz, Ms Takeesha Moreland-Torpey and Ms Malini Arumugam, for their invaluable support in developing and finalising this project.

It was a long journey, which seemed very challenging at times; however, a very generous support of our volunteer contributors to this book has made this possible. We would like to thank all the contributors for their time and valuable scientific input during this journey.

Finally, and importantly, we acknowledge the most diligent and consistent support of Dr Kathryn Page, who worked on the project tirelessly and meticulously.

Once again, we appreciate all the support and collaboration to deliver this book.

St Lucia, QLD, Australia

Yash P. Dang
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Part I

Agronomy

Chapter 1
No-till Farming Systems for Sustainable Agriculture: An Overview

Yash P. Dang, Kathryn L. Page, Ram C. Dalal, and Neal W. Menzies

Abstract No-till (NT) farming systems have revolutionized agriculture by improving erosion control, soil water storage, soil quality and, in many instances, yield and net farm income. The adoption of NT systems has increased at an exponential rate since the 1990s and they are now used on 12.5% of global croplands. However, while the development of NT systems has seen much success, there can be significant agronomic, economic and/or social challenges associated with their use that limit large scale worldwide adoption. In addition, where NT is not implemented as part of an integrated system that incorporates stubble retention and appropriate crop rotations to help manage weeds, diseases, pests and soil fertility, decreases in yield can be observed. A combination of research, education and good policy development to remove economic/institutional and social barriers to uptake are required to ensure the continued success of NT. In particular, the tailoring of NT farming systems according to individual locations and the introduction of some flexibility in approach to tillage management can provide an opportunity to manage some of the challenges of NT farming systems.

Keywords Adoption opportunities · No till challenges · System performance · Strategic tillage

1.1 Introduction

No-till (NT) has revolutionized agricultural systems by allowing farmers to manage greater areas of land with reduced energy and machinery inputs (Triplett and Dick 2008). It has also been responsible for improving erosion control, soil water storage, soil quality and, in many instances, yield and net farm income (FAO 2019). These

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benefits have led to the identification of NT farming systems as an important tool to help ensure future food security and help buffer agricultural productivity against extreme climate events, such as drought and heat waves, which are likely to increase in frequency under climate change (FAO 2019). However, despite its potential benefits, the long-term sustainability of NT farming systems has been questioned due to an increasing number of biotic and abiotic agronomic challenges, as many farmers are increasingly devoting additional time and economic resources to deal with herbicide-resistant weeds, increasing disease or pest pressure, and soil compaction (Dang et al. 2015a). Various economic and social barriers may also limit the uptake of NT systems, particularly in resource poor regions.

To deal with some of the challenges of NT, many growers are shifting towards a flexible approach to tillage management that includes some soil disturbance (Kirkegaard et al. 2014). However, the impact of such a flexible approach is likely to vary with soil type, climate and soil/crop management (Dang et al. 2015a, 2018; Conyers et al. 2019), and our understanding of its effects are currently incomplete. This chapter will provide an overview of the characteristics of NT farming systems, the history of their development and the various agronomic, economic and social barriers that exist to prevent their uptake. Opportunities and strategies to increase adoption and adaptation of NT farming and improve these systems into the future will also be discussed. This broad discussion will form the basis for a detailed exploration of the characteristics, challenges and opportunities for NT farming systems throughout the remainder of the book.

1.2 Characteristics of No-till v Conventional-till Systems

In traditional agricultural systems, the soil is tilled several times during the fallow period to control weeds and prepare a seedbed suitable for sowing. In addition, residues from the previous crop are typically removed, either by burning, baling or grazing, to make tillage and sowing easier and assist establishment of the next crop. Tillage operations (number and intensity) may vary from region to region, but worldwide one of the most common techniques involves ploughing with a mouldboard plough, which inverts the soil and helps burry weeds, followed by several passes with a disc harrow, which helps to further break up the soil, bury weed seeds and prepare the seedbed for planting (Zarea 2010). In regions with lighter, or more fragile soil, many growers also use non-inversion tillage based on tine and disc implements (Dang et al. 2015b). In these situations, tines lift and shatter the soil, removing any shallow compacted layers, and discs cut and mix the stubble and any soil clods to leave a fine tilth for sowing.

However, since the 1960s and 1970s, concerns regarding the fuel costs and soil degradation associated with tillage operations have prompted farmers worldwide to begin switching from traditional forms of tillage to NT. Globally, NT farming

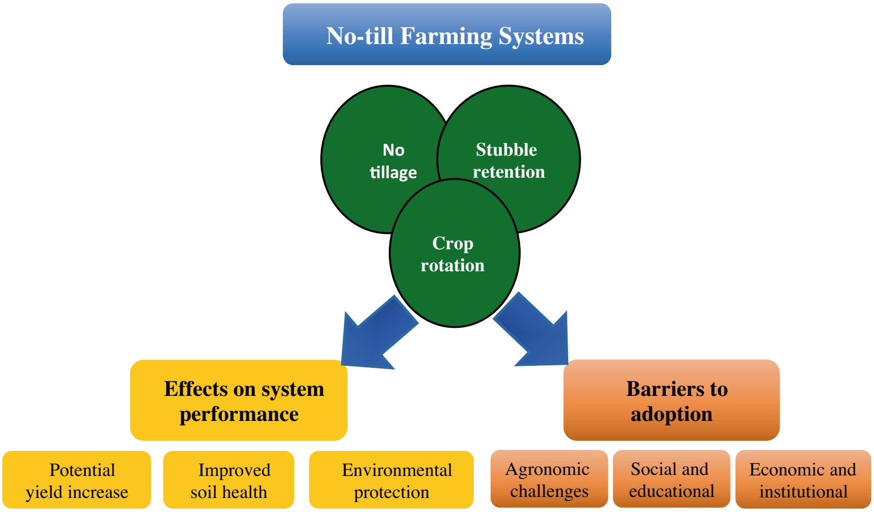


Fig. 1.1 No-till farming systems, their characteristics, effects on systems performance and barriers to adoption

systems have been defined in several ways and have included systems with various degree of soil disturbance (e.g. both strict NT and reduced tillage), crop residue management (retained and removed) and cropping systems (e.g. monocultures with extended periods of fallow and systems with complex crop rotations and cover crops). This variation in definition has sometimes been responsible for inconsistent and contradictory conclusions regarding the impacts and effects of NT systems on crop production and environmental outcomes (Derpsch et al. 2014). For the purposes of this review we will consider NT systems to be those that do not undertake any tillage operations and conduct seeding into untilled soil where the previous crop residues have been retained on the surface. Weed management is conducted using herbicides or by hand, and crop rotations, which include at least one legume crop, are also in place to increase soil fertility, help manage weeds, pests and diseases and to improve soil health (Fig. 1.1). Such practices are similar to those used under conservation agriculture (CA), although conservation agriculture may also encompass systems that incorporate minimal tillage (FAO 2019).

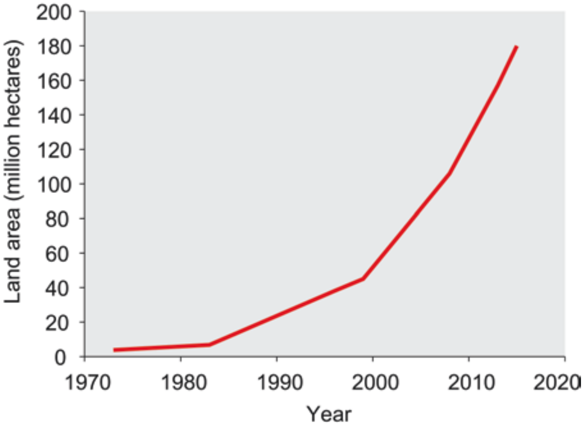
No-till systems have several benefits compared to CT systems and have the potential to increase yield, improve soil health and increase environmental protection (Fig. 1.1). However, NT systems can also present challenges that act as barriers to their adoption. These can include agronomic challenges, problems around the social and educational needs of farmers and economic and institutional barriers (Fig. 1.1). These will be discussed in detail below.

1.3 The History of NT Systems

The principles of NT first began to develop in the US in response to severe droughts and erosion events in the 1930s (Awada et al. 2014; Idol 2015). This initially started with the development of machinery capable of reducing the level of soil disturbance during tillage operations in order to increase residue cover and help reduce erosion (Idol 2015). However, few farmers initially made the shift to this new way of tilling, partly due to the poor economic conditions at the time and their inability to invest in the technology required to change farming practices (Awada et al. 2014). Weed control without tillage was also problematic and machinery that could successful conduct seeding for optimum plant establishment in fields with high crop residue loads was unavailable. From 1950 to 1970 the development of herbicides that allowed weed control without tillage, and the development and refinement of low disturbance direct seeding equipment helped NT practice to develop (Triplett and Dick 2008; Awada et al. 2014). However, the high cost of these early herbicides, their lack of effectiveness against some broadleaf weeds, and continuing issues with seeding, meant that NT was still not widespread (Awada et al. 2014). It wasn’t until the 1970–1980s and the development of the broad-spectrum herbicide glyphosate, further refinement of seeding equipment, and demonstration by some early adopters that NT could be profitable, that NT systems started to gain popularity (Awada et al. 2014).

Since the 1990s decreases in herbicide costs, increases in fuel prices and a growing awareness of the benefits of NT have acted to drive farmer uptake worldwide (Awada et al. 2014). Indeed, adoption of CA, which is similar to NT, has increased by 400% in the previous two decades and it is now practiced on 180 M ha worldwide, representing 12.5% of global cropland (Fig. 1.2) (Kassam et al. 2019). The USA, Brazil, Argentina, Canada and Australia are the top five adopters (Kassam et al. 2019), while there have been lower rates of uptake in the Middle East, Europe,

Fig. 1.2 Area of cropping land worldwide under conservation agriculture. (Drawn from data reported by Kassam et al. 2019)



Asia and Africa (Bhan and Behera 2014; Carvalho and Lourenco 2014; Bashour et al. 2016; Ding 2018; Kassam et al. 2019).

Instrumental to these increasing rates of adoption have been the proliferation of activities in the research, development and extension of NT farming systems. Indeed, long-term research experiments to test and refine NT systems have now been in operation for nearly 60 years in many countries throughout the world, including the USA (since 1962 in Ohio), Australia (since 1968 in Queensland), Switzerland (since 1969 in Changins), Argentina (since 1975 in Córboda) and Africa (since 1988 in Zimbabwe). Initially the focus of this research (and associated extension activities) was on the use of NT to reduce erosion and the development/demonstration of machinery and agronomic practices adapted for NT conditions. However, as NT systems have evolved over time, research has had an increasing focus on the identification of crop rotations to maximize productivity and economic gain and best cope with the long-term challenges of NT systems (e.g. pests, diseases, weeds).

1.4 Benefits of NT Systems

No-till systems have several advantages over traditional tillage. In particular, their ability to help control erosion (and its associated environmental impacts), reduce fuel use, conserve soil moisture, promote greater soil health and increase yields is highly valued (Lyon et al. 2004; Triplett and Dick 2008; Verhulst et al. 2010; Zarea 2010) (Fig. 1.1).

The reduction in soil disturbance and greater retention of crop residues characteristic of NT systems often lead to increased concentrations of soil organic carbon (SOC), particularly at the surface of the profile (Franzluebbers 2010; Aguilera et al. 2013; Conceição et al. 2013; Francaviglia et al. 2017). This increase in SOC can lead to greater soil structural stability (Chan et al. 2002; Li et al. 2007; Somasundaram et al. 2017), greater soil nutrient stores (Chan et al. 1992; Redel et al. 2007; González-Chávez et al. 2010), and increased biological diversity (González-Chávez et al. 2010; Wang et al. 2010). In the absence of soil tillage the number and/or continuity of soil macropores also often increases (Moreno et al. 1997; McGarry et al. 2000; Verhulst et al. 2010). Both increases in aggregate stability and macroporosity combined with the increases in surface cover help to increase soil water infiltration, slow runoff and consequently decrease rates of erosion and increase moisture storage in the soil profile (Lyon et al. 1998; Page et al. 2013).

Reductions in the rate of erosion can help preserve soil nutrients and protect waterways from sediment associated pollution (Holland 2004; Verhulst et al. 2010). Increases in soil water storage are also highly valued, particularly in rainfed semi-arid areas where soil water is typically the major limitation to crop growth, and the increases in water availability under NT systems can be associated with increased yield, particularly in dry years (Corbeels et al. 2014; Pittelkow et al. 2015b). Indeed, in drier regions, this increase in production combined with decreased costs associated with fuel usage are often associated with greater profitability in NT systems (Carvalho and Lourenco 2014; Ares et al. 2015; Abdulai 2016; Dhar et al. 2018; Page et al. 2019).

1.5 Challenges of NT Systems

While the development of NT has seen much success and there are many advantages associated with this system, significant challenges also exist and act as a barrier to the widespread uptake (Fig. 1.1). These challenges can be agronomic, environmental economic and/or social in nature.

1.5.1 Agronomic

A number of agronomic issues have been associated with NT systems, including:

- Problems in the control of weed and pest populations. In particular, grassy weeds are difficult to control in wheat without tillage (Kettler et al. 2000; Chauhan et al. 2012), and many weed species now have resistance to common herbicides such as glyphosate (Heap 2019). Soil insect pests with belowground pupal stages may also be difficult to control without tillage (Mensah et al. 2013; Wilson et al. 2013);
- The persistence of soil and stubble borne diseases. The increased retention of residues in NT systems can provide some pathogens with a refuge in which to survive between harvest and planting (Roper and Gupta 1995; Bockus and Shroyer 1998);
- Stratification of nutrients in the surface of the profile, Vertical stratification of immobile nutrients, particularly phosphorus and potassium, is commonly observed in NT systems and can lead to problems for crop nutrient availability during dry periods when plant roots cannot extract nutrients from the surface of the profile (Pierce et al. 1994; Garcia et al. 2007);
- Decreased N availability due to decreased rates of mineralization, and/or greater N immobilization, leaching and/or denitrification (Thompson 1992; O'Leary and Connor 1997);
- The restriction of soil warming during the establishment of early spring crops due to higher soil water contents and shading of the soil surface by crop residues (Hatfield et al. 2001; Wang et al. 2007); and
- The development of soil structural issues, such as compaction (Brouder and Gomez-Macpherson 2014; Dang et al. 2015b; Dhar et al. 2018).

In addition, in areas where low yields are the norm (e.g. sub-Saharan Africa) it can be difficult to maintain sufficient residue cover to prevent erosion, soil compaction and suppress weeds in NT systems, which can undermine system effectiveness (Andersson and D'Souza 2014).

Strategic tillage (ST), which is the practice of occasionally cultivating NT soils, has been proposed as a mechanism to deal with some of the challenges associated with weed, pest and disease management and compaction in continuous long-term NT systems (Kirkegaard et al. 2014; Dang et al. 2015b, 2018). Weed, pest and disease management and some nutrient stratification in the surface soil issues, can also be controlled via crop rotations that disrupt weed and disease cycles and improve soil fertility (e.g. inclusion of legumes) (Verhulst et al. 2010). However, further research is still required to develop effective and locally adapted crop rotations in many locations (Bellotti and Rochecouste 2014). In addition, research into whether occasional ST will undo some, or all, of the benefits of long-term NT is in its infancy and our understanding of the pros and cons of this type of approach is incomplete. Dang et al. (2015a) identified the generalized impacts of a one-time strategic tillage event for long-term continuous NT in north-eastern Australia (Fig. 1.3). However, these impacts require further testing in a range of soils and agro-climatic regions. Further, it is unclear if it is possible to use ST to fully manage constraints, or whether a return to a system with a higher frequency of tillage will be required.

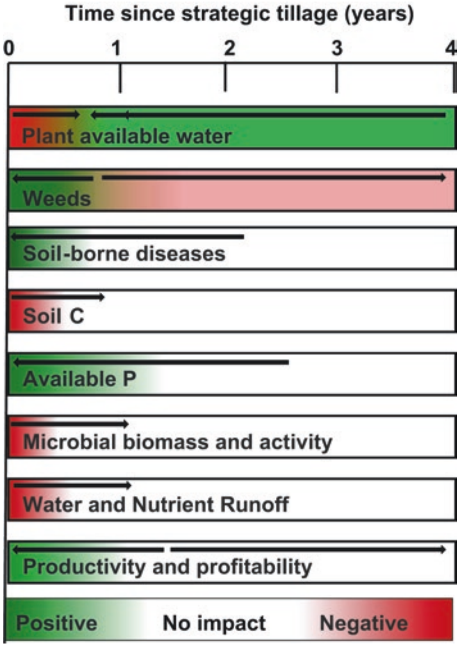


Fig. 1.3 Implications of occasional strategic tillage in otherwise no-till farming systems. Direction of arrows indicate positive or negative impacts and the length of arrows indicates time since introduction of strategic tillage. Red color indicates negative impact; green color indicates positive impact and white color indicate no impact. (Adapted from Dang et al. 2015a)

1.5.2 Environmental

While NT systems are commonly observed to have many environmental benefits due to reductions in runoff and erosion and increases in SOC (Verhulst et al. 2010; Palm et al. 2014), some environmental problems can also occur. For example, the increases in infiltration that commonly lead to greater soil water storage in NT systems, can also lead to increased rates of leaching (Turpin et al. 1998; McGarry et al. 2000). This can potentially lead to the increased movement of water, salt, nutrients and pesticides out of soil profiles and into groundwater (Turpin et al. 1998; McGarry et al. 2000; Alletto et al. 2010). In addition, while nutrient and sediment movement to surface water is most commonly found to be lower under NT (Palm et al. 2014), losses of pesticides can be more variable, with both reductions and increases observed depending on the pesticide in question and site characteristics (Alletto et al. 2010; Palm et al. 2014; Elias et al. 2018).

Indeed, there is often a general perception that chemical use is higher under NT and general community concern exists regarding the potential detrimental effects of this for both the environment and human health (Friedrich and Kassam 2012). Greater chemical use can be the case under NT, particularly where it is implemented without integration into a 'NT system' that incorporates diversification of crop rotations and the use of integrated strategies (alteration of sowing times, planting densities, row spacings etc.) to help control weeds, pests and diseases (Fuglie 1999; Friedrich and Kassam 2012; Malone and Foster 2019). However, chemical use has also been observed to be no different or even decline under NT (Day et al. 1999; Fuglie 1999; Friedrich and Kassam 2012; Adeux et al. 2019), particularly where NT systems are successfully combined with integrated weed, pest and disease management (Friedrich and Kassam 2012).

In addition to chemical use, NT can also significantly impact greenhouse gas (GHG) emissions from soil. NT can result in clear reductions in GHG emissions due to reductions in fuel use (Kern and Johnson 1993), and in some regions, due to increases in SOC sequestration (Alvarez 2005; Mangalassery et al. 2015). However, where NT is used on fine textured and poorly drained soils in wetter regions, increases in N_2O production can also be observed (Gregorich et al. 2005; Steinbach and Alvarez 2006; Rochette 2008). In some regions, this can negate the positive effects of increased carbon sequestration and decreased fuel use and may even lead to net increases in global warming potential (Gregorich et al. 2005; Steinbach and Alvarez 2006).

1.5.3 Economic/Social

Many studies report that there are net increases in production and significant economic benefits associated with the use of NT (Carvalho and Lourenco 2014; Ares et al. 2015; Abdulai 2016; Dhar et al. 2018; Page et al. 2019). However, in some instances there can also be significant economic costs. For example, in mixed crop-livestock systems there can be significant opportunity cost involved in the introduction of NT due to the inability to use residues as stock feed, or bale residues for sale to other producers (Andersson and D'Souza 2014; Ares et al. 2015; Beuchelt et al. 2015). Input costs also tend to be higher in NT as new tools (e.g. planting equipment), additional fertilizers, and herbicides are required in many instances (Andersson and D'Souza 2014; Dhar et al. 2018). This combined with delays before the production and economic benefits of NT systems materialize can lead to initial net decreases in farm income and present a barrier to uptake for farmers with low levels of liquidity (Beuchelt et al. 2015; Ding 2018; Harper et al. 2018).

In small holder operations, it can also often be difficult for farmers to afford herbicides to control weeds, which can increase labor requirements, particularly for women, due to the need for hand weeding (Andersson and D'Souza 2014). Lack of access to seed, suitable markets, transportation facilities and/or suitable storage facilities can also limit some farmers (in both developed and developing regions) from using certain crop rotations, which can be an important part of the success of NT systems (Andersson and D'Souza 2014; Ares et al. 2015; Carlisle 2016; Brown et al. 2017; Dhar et al. 2018).

In many farming communities, the principles of NT systems may also run counter to many established land management traditions that have worked for generations and which have often created cultural values and rural traditions (Gonzalez-Sanchez et al. 2016; Tekle 2016). Those farmers who initially go against social norms and adopt NT systems can risk mockery and exclusion from their community (Tekle 2016). Overcoming the mindset in farming communities that tillage is required for successful agricultural production is, therefore, also a challenge in many regions (Awada et al. 2014; Bhan and Behera 2014; Gonzalez-Sanchez et al. 2016; Tekle 2016).

1.6 Overall NT System Performance

From the discussion above it is clear that NT systems clearly have the potential to improve many aspects of soil health and environmental quality compared to CT systems (Fig. 1.4). Increases in aggregate stability, soil water storage, SOC and biological diversity are all commonly observed under NT management and lead to improvements in soil health. Similarly decreases in erosion have a significant impact on environmental quality by reducing sediment pollution in waterways and reducing soil erosion and degradation relative to CT systems (Fig. 1.4). However, while significant benefits exist, problems associated with plant nutrient management, diseases, weeds, and soil structure, may limit plant growth and prevent improvements in soil quality translating into improvements in crop production and yield. In some instances, strategic tillage may be an effective tool to help manage some of these problems and increase yield without major losses of soil health or increases in environmental degradation (Fig. 1.4). While in other instances, improvements in the use

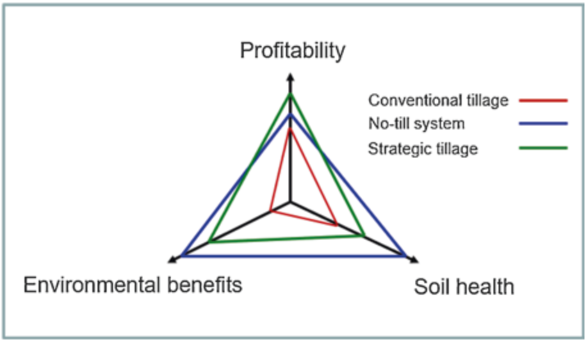


Fig. 1.4 Example of the relative difference in profitability, soil health and environmental benefits observed between conventional, no-till and strategic tillage systems. Note that while the relative environmental and soil health benefits are similar in many systems worldwide, the relative difference in profitability can vary from region to region and depending on climate and the skill with which NT is implemented. The relative difference shown in this figure is typical of that observed in semi-arid farming regions where NT is implemented in combination with stubble retention and locally appropriate crop rotations to manage soil fertility and weeds, pests and diseases

of crop rotations and strategies such as integrated weed and pest management are required to overcome the challenges associated with NT.

Overall, yield is the ultimate indicator of cropping system performance. In many instances where NT is used as part of an integrated system that incorporates stubble retention, the diversification of crop rotations, and effective nutrient management, yield in NT systems is either observed to be very similar to CT, or to increase, particularly in semi-arid areas where water availability limits crop yield (Pittelkow et al. 2015a, b) (Fig. 1.4). However, the yield benefits associated with NT systems may take a number of years to emerge due to the time taken for positive impacts on soil quality and water balance to develop, and yield declines may even be observed in the early years of adoption (Derpsch 2008; Pittelkow et al. 2015a, b; Thierfelder et al. 2015; Büchi et al. 2017). For example, the build-up of SOC and associated improvements in nutrient cycling and soil structure may take several years to emerge, and up to 25–30 years may be required before a new equilibrium is reached (Alvarez 2005; Derpsch 2008; Perego et al. 2019). In some instances, delays in yield improvement can also be due to an initial learning curve on how best to manage NT systems and deal with any challenges they present (e.g. changes to disease, weeds, nutrient management) (Derpsch et al. 2014; Perego et al. 2019). Similarly, in regions with variable rainfall, the positive impacts of NT may only become apparent in drier years (Brouder and Gomez-Macpherson 2014; Corbeels et al. 2014).

Where NT systems are not effectively implemented, significant declines in yield are likely (Pittelkow et al. 2015a, b). For example, where NT is implemented in isolation without stubble retention to increase SOC or effective practices are not in place to help manage diseases, weeds and nutrients, significant declines in yield can be observed (Lundy et al. 2015; Pittelkow et al. 2015b). In a worldwide meta-analysis it was observed that average yield declines of 9.9% were observed under

NT where this was the case, with the decline in yield being greater in humid compared to dry regions (Pittelkow et al. 2015a, b). Similarly, yields would not be expected to increase where NT is implemented on already degraded land without first rectifying any existing soil constraints, such as compacted layers, low nutrient availability or soil acidity (Derpsch et al. 2014). For resource poor farmers, this can present a major barrier for successful NT implementation. In addition, the complex nature of NT farming means that systems that are adapted to local conditions are required before gains in productivity can be expected to occur. As will be discussed below, this requires significant research, farmer and community education, and the identification and implementation of appropriate policy tools.

1.7 Opportunities to Increase No-till Adoption

In order to overcome the agronomic, economic and social barriers associated with the uptake of NT systems a combination of research, education and the removal of economic/institutional barriers to uptake are required.

1.7.1 Research

Due to the heterogeneity of farmers and farming communities worldwide, NT systems cannot be implemented with a 'one size fits all' approach and require adaptation to local areas (Dauphin 2003; Bhan and Behera 2014; Ares et al. 2015; Carlisle 2016). This is particularly important to ensure the identification of locally appropriate crops and crop rotations to help manage many of the challenges of NT systems, such as pest, weed and disease problems. The identification of locally appropriate seeding and harvesting equipment is also essential, particularly in areas where currently available technology is not appropriate (e.g. the use of equipment developed for broadscale agriculture is not possible in small holder operations). Indeed, site specific and applied research that involves partnerships between farmers, researchers and the private sector (e.g. seed companies, machinery suppliers) to refine NT systems and demonstrate their benefits has been successful in driving adoption in many areas (Dauphin 2003; Bellotti and Rochecouste 2014; Bhan and Behera 2014; de Freitas and Landers 2014; Ares et al. 2015).

In recent years, it has also become apparent that a degree of flexibility in approach to NT systems is likely to meet with the greatest success (Tekle 2016). For example, allowing occasional tillage to help deal with some of the negative impacts of NT systems, rather than dogmatically adhering to complete NT, may be beneficial in some instances (Dang et al. 2018). However, good quality, local research is required to identify how best to modify NT systems (Scopel et al. 2013; Tekle 2016). For example, the frequency, type and timing of tillage most appropriate to manage some of the constraints of NT on a range of soils and in different agro-climatic regions is currently poorly understood. However, greater understanding in this area is essential in order to avoid undoing any of the improvements in soil quality gained from NT implementation.

Greater study to identify the specific constraints preventing farmers from adopting NT in their particular region are also essential to increase adoption. This will involve not only identifying technical barriers, but also the economic, social and institutional constraints present. In particular, the economic, social and institutional barriers to NT adoption have been under researched and are key to understanding why some farmers choose not to adopt NT, even in situations where its production and benefits may be clear. It is only once these constraints have been successfully identified that appropriate and targeted strategies can be developed to help maximize farmer uptake.

1.7.2 Education

Educational institutions can also play an important role in both the development and promotion of NT technology, and strong linkages between research, education and extension organizations are essential to successfully develop and promote NT systems (Farooq and Siddique 2015; Harper et al. 2018). Studies have observed that farmer knowledge of, and commitment to, the treatment of land degradation issues (e.g. erosion) and access to information regarding the benefits and use of NT are important precursors for adoption (Llewellyn et al. 2012; Abdulai 2016; Carlisle 2016). Effective extension services are thus vital in facilitating this knowledge dissemination and are often positively correlated with NT uptake (Arslan et al. 2014; Abdulai 2016; Carlisle 2016). Extension efforts that are tailored to individual audiences (e.g. small v large farmers, gender specific communication, adopters v non-adopters), and that provide continuing support over time to help manage the challenges of NT systems are also more likely to meet with success (Carlisle 2016; Chinse et al. 2019). Indeed, the complexity of NT systems and the need for a high degree of understanding of appropriate agronomic techniques to manage weed/pest/diseases and ensure sufficient crop nutrient availability mean that the implementation of NT without sufficient education around the management of its challenges is unlikely to result in long-term uptake. In some instances community perceptions surrounding management practices can play a significant role in either helping or hindering NT system uptake (Dauphin 2003; Carlisle 2016; D'Souza and Mishra 2018; Chinse et al. 2019), and education campaigns with a broader community focus that concentrate on demonstrating NT systems technology and shifting social norms in farming communities can also be important (Tekle 2016).

1.7.3 Policy Tools to Remove Economic and Institutional Barriers

Farmers who have liquidity constraints are less likely to adopt NT due to the initial investment required around establishment (Abdulai 2016; Brown et al. 2017; Ding 2018; Harper et al. 2018). In developing countries in particular, the greater input costs of NT operations relative to CT is likely to reduce uptake (Abdulai 2016; Tekle 2016; Ding 2018), and/or lead to dis-adoption in the longer term (Brown et al. 2017). Consequently, policy initiatives to subsidize or incentivize NT, for example by increasing access to credit and the farm machinery required for NT operations (e.g. rental schemes, custom hire) can increase adoption (Bhan and Behera 2014; Abdulai 2016; Carlisle 2016). This is particularly important in the early stages of adoption when yield increases are slow to develop and the farmer is learning the best way to practice NT for their particular circumstance.

However, policy measures that help farmers adopt NT but do not also address the presence of other community or institutional constraints are unlikely to be successful in the long term (Andersson and D'Souza 2014; Brown et al. 2017; Chinse et al. 2019). Such constraints can include lack of access to markets for produce, insecure land tenure (including the presence of communal grazing rights), inability to obtain the inputs required for NT (e.g. seed, fertiliser, herbicide, locally appropriate machinery), and insufficient information on how to successfully overcome some of the challenges associated with NT systems (Corbeels et al. 2014; Carlisle 2016; Tekle 2016; Brown et al. 2017). The implementation of policies aimed to address these constraints are thus also essential to increase and maintain NT uptake in the long-term. The presence of policies that hinder uptake should also be considered. For example, protectionist mechanisms, such as subsidies for the production of certain commodities, tend to limit the adoption of NT as they do not encourage the reduction of production costs (Carvalho and Lourenco 2014; Tekle 2016).

1.8 Conclusion

Overall, despite the substantial advantages associated with NT systems, significant work is still required to refine these systems for a wider variety of locations and overcome some of the agronomic, economic and social barriers to NT systems uptake. This book will examine in detail the agronomic and soil management issues that need to be resolved to ensure the successful implementation of NT systems and the challenges and opportunities associated with their use. In addition, the economic, social and policy considerations that are also important for the successful development and implementation of NT will be discussed. Finally, a series of case studies showcasing the development and implementation of NT systems in different world regions will be presented to highlight the challenges and opportunities for NT introduction and how these vary depending on climate and geopolitical location.

This material will provide a comprehensive summary of our knowledge of NT systems and an outline the future research needs and opportunities in order to increase the uptake of NT systems farming worldwide.

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Chapter 2
Managing Crop Rotations in No-till Farming Systems

Leonard Rusinamhodzi

Abstract Crop rotation is an important pillar of no-till (NT) cropping systems for soil fertility management, and pests and disease control. In this chapter, the potential benefits of crop rotations under NT systems are discussed and challenges highlighted, including possible solutions where it was practical to do so. Cereal-grain legume rotations are the most ideal for small farms, especially the dual-purpose legumes, which play a significant role in nutritional diversity at the farm level. This is because the legume will produce edible leaves and grains – and sometimes mature earlier than the main crop covering critical food deficit periods before the main crop is harvested. However, limited landholdings prevent widespread adoption of cereal-legume rotations. Large scale farmers have many crop rotations options, and they are able to make a profit due to fuel and labor savings with NT in combination with cultivating cash legumes on a large scale, which have multiple uses as food or feed. In the future, the design of crop rotations has to address a range of issues, especially for small scale farmers, including: (a) small land sizes; (b) multiple uses of legumes crops, including leaves; (c) crop-livestock integration and use of crop residues as livestock feed; (d) poorly developed markets for legumes; (e) differences in planting techniques between legumes and non-legumes; and (f) farmers perception of risk. It is concluded that crop rotation is an integral component of good agricultural practice and is much more critical in NT systems where pests and diseases outbreak is high, and additional N from nitrogen fixation needed.

Keywords Crop productivity · Soil fertility · Pests and diseases · Weed control

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2.1 Introduction

Crop rotation is the strategic practice of growing different types of crops in a preplanned sequence on the same field. Crop rotation along with NT and mulch cover constitute the tripartite principles that define conservation agriculture (CA) or NT systems farming (see FAO CA web site: http://www.fao.org/ag/ca/1a.html). The retention of crop residues and absence of soil inversion in NT systems may proliferate pests and disease outbreaks, thus crop rotations are particularly important for pests and disease control in NT farming systems (Morrison et al. 2017).

Crop rotation options can start from the very simple 1-year rotation cycle including only two crops, such as maize (*Zea mays* L.) followed by soybean (*Glycine max*. (L) Merr.), to more complicated 3-year rotation cycles involving as many as five crops. The choice of rotation cycle and the component crops depend on several agronomic and economic factors including source of moisture (rain or irrigation), soil nutrient status, input markets, crop duration, and crop uses, including consumption or marketing (Jodha and Singh 1990). In Australia for example, the sequence of crops can flexible, long or short phase, not repeated or fixed, and depends of locality (Wolfe and Cregan 2003; Lawes 2015). The long-phase rotation system involves several years of a pasture phase followed by a number of years of cropping. The short-phase rotation comprises alternating years of pasture followed by a crop sequence such as wheat followed by lupin. When the conditions are favourable, the rotation of two or more crops such as maize followed by soybean and then vegetables can be done within 1 year (Wolfe and Cregan 2003; Kirkegaard and Hunt 2010). Another interesting complex rotation comes from Brazil, NT production generally involves four main crops i.e. soybean, maize, wheat, and oats (Brown et al. 2001). Two crops are fitted in 1 year i.e. maize or soybean in summer and wheat or oat in winter (Brown et al. 2001). Some farmers may include other crops in the double-crop system, but this depends on the farmers production decisions and the costs.

Crop rotation can be considered as one of the best strategies for yield improvement, although it requires increased expertise, equipment, and different management practices. Certain insect pests and diseases may spread easily from one crop to the next through the crop residues and careful design and management is needed (Kirkegaard et al. 2014). The objective of this chapter is to discuss the agronomic importance of crop rotations in NT farming systems with a special focus on soil nutrient status, and pest, weed, and disease management. Additionally, crop rotations options suitable for various systems, including those of different scale and in different climatic regions, and the challenges and opportunities for effective rotation cycles are discussed.

2.2 Effect of Crop Rotation on Soil Fertility

Crop rotation influences soil fertility through several aspects and mechanisms including, soil erosion control through increased infiltration, reduced soil compaction, reduced soil crusting, nutrient addition such as N, soil organic matter build up, and increased biological activity (Franzluebbers 2002; Rusinamhodzi et al. 2009, 2011; Castellanos-Navarrete et al. 2012; Fuentes et al. 2012; Nyamadzawo et al. 2012). Yield increases under real farmer conditions are often used as a proxy for improved soil fertility. As can be shown in Fig. 2.1, crop rotation with NT is superior to NT without rotation, especially in the long-term (Rusinamhodzi et al. 2011). Although the magnitude of effects differ in time and place, there is widespread agreement on the positive effects of crop rotations on system productivity, including yield (Rusinamhodzi et al. 2012; Thierfelder et al. 2013). Most studies that have assessed crop rotation in NT systems generally reported positive effects on crop yields, agreeing with Karlen et al. (1991), who reported that rotations are likely to produce higher yields across soil fertility regimes. Higher yield for NT with rotation than with continuous monocropping is attributed to a combined effect of multiple factors that include reduced pest infestations, improved water use efficiency, improved soil quality as shown by increased organic carbon, greater soil aggregation, increased nutrient availability, and greater soil biological activity (Hernanz et al. 2002; Wilhelm and Wortmann 2004; Kureh et al. 2006).

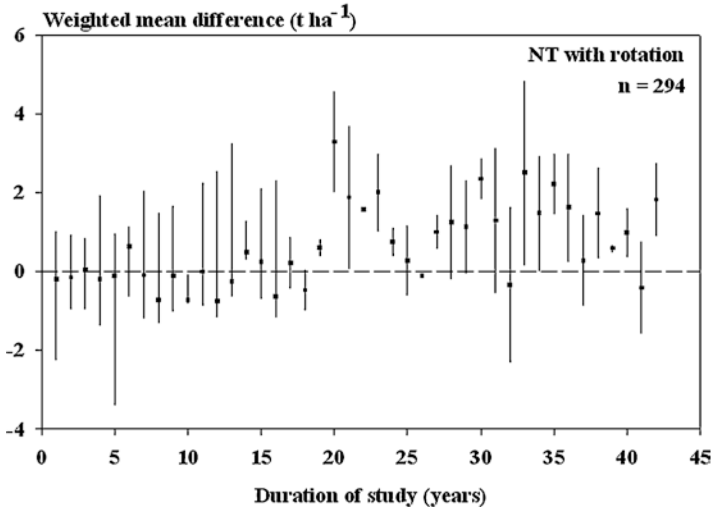

Fig. 2.1 Weighted mean differences in maize grain yield over time between no-tillage with rotation and no-tillage without rotation. Although effect sizes are generally positive, real yield benefits start after 20 years of production. (Adapted from Rusinamhodzi et al. 2011)

2.2.1 Effect of Crop Rotation and Soil N Status

Crop rotations involving legumes improve soil properties and reduce mineral N fertilizer requirements of the following cereal crop if biomass production is large and the harvest index is small (Ojiem et al. 2014; Franke et al. 2018). This is due to the decomposition of N-rich crop residues that the legume crop produces due to biological N fixation (Baijukya et al. 2006). Several factors determine the actual contribution of legume residues to the N nutrition of the next crop, including non-N nutrition provided to the legume, genetic potential, availability of the right strain of rhizobium for effective nodulation and symbiosis, as well as how the legume crop residues are managed at harvest (Giller 2001; Franke et al. 2018). Ideally, the legume residues should be retained in situ to maintain a positive N balance, especially in N-poor environments. In some cases, carefully planned nutrient management in combination with crop rotation can eliminate the need for purchased fertilizer. There is also the potential for non-N benefits in legume-cereal rotations e.g. during the legume phase of the rotation, the crop can utilize the residual soil P and K that were left-over during the non-legume phase of the rotation. There is also improved phosphorus (P) availability following a legume (Pypers et al. 2007). Legumes contribute to P solubilization through acidification of the rhizosphere due to proton release from their roots.

2.2.2 Effect of Crop Rotation on Soil Organic Matter (SOM)

The amount of organic matter in the soil is a common indicator of soil health and productivity (Cardoso et al. 2013). The build-up of SOM is directly related to the types of crops grown, root biomass production and distribution, above-ground biomass production, as well the management of the crop residues at harvest (Magdoff 1993). No-till in combination with high biomass crops, such as green manure legumes, have a very high chance of increasing SOM (Baijukya et al. 2005). No-till systems involving crop rotations are associated with reduced decomposition rates, which is beneficial in maintaining SOM mostly on the soil surface, though this depends on soil type and climatic conditions (Ogle et al. 2019). Powlson et al. (2014) after a meta-analysis observed that farmers who practice NT have a tendency to plough conventionally after a few years, such that the potential SOM benefits of NT are easily lost. For this reason, the actual effect of NT systems on SOM is contested or require a long time to show (Govaerts et al. 2009; Sapkota et al. 2012)

2.2.3 Effect of Crop Rotation on Biological Activity

Soil microorganisms respond positively to the amount of crop residue or soil organic matter content in the soil, especially the upper top soil (Green et al. 2007). Crop rotations that deliberately include more crops are likely to lead to more soil organic matter and biological activity (Magdoff 1993). Soil organisms that are active in the soil, include bacteria, fungi, actinomycetes, protozoa, yeast, algae, earthworms, and insects.

Increased organisms and their diversity in the soil is important for regulating decomposition, nutrient cycling, soil organic matter dynamics, and improvement of soil physical properties. A comprehensive synthesis of NT systems under the rain-fed conditions by Mafongoya et al. (2016) revealed high fauna population (termites, ants, centipedes, and beetle larvae) in NT systems compared with conventional tillage practices. Nhamo (2007) observed that at least 120% more termites and 60% more earthworms were observed under NT than the conventional practice. The abundance of termites and earthworms in NT suggests that NT with retention of crop residues increases biological activity. Ayuke et al. (2019) in a similar long-term trial reported significant increases in soil fauna taxonomic richness and abundance in NT systems compared with conventional tillage practices. The increased abundance of soil fauna under NT systems lead to improved soil physical properties such as infiltration, porosity, aggregate stability and hydrological properties (Briones 2014). Additionally, the presence of a legume creates of a favorable microbial community within the root zone (Yusuf et al. 2009).

2.2.4 Effect of Crop Rotation on Soil Physical Properties

Crop rotation can also lead to positive soil physical conditions in the soil. In rain-fed systems of agriculture, crop rotation plays an important role in water conservation and to some extent reduces challenges with soil salinity (Turner 2004). Although the interaction of NT and crop rotation are subtle and site specific and it is difficult the disentangle the contribution of each factor, the literature is replete with evidence of the positive influence of crop rotation. For example, Chan and Heenan (1996) observed that rotational effects on soil physical properties differed according to the crops in the rotation, and that the effect were likely related to these crops' different abilities to promote soil structure formation and soil structure stabilisation. Similarly, Salvo et al. (2010) reported positive effect of crop rotation on aggregate stability and particulate organic matter (POM) at different depths of soil. In another study, Lal et al. (1994) reported a significant interaction between tillage and crop rotation, with the least bulk density and greatest total porosity of 58% occurring in the rotated compared to the continuous monocrop treatments. The greatest infiltration rates have also been reported among crop rotations, for example, during maize vegetative growth in a soybean–wheat/clover–maize rotation (Katsvairo et al. 2002). As has been stated earlier, crop rotation increases biodiversity for both micro and macrofauna which play an important role in soil structure formation. The deep legume taproots combined with abundant earthworm populations create burrows in the soil profile which can lead to increased soil porosity, gas exchange, and improved moisture distribution in the soil profile.

2.3 Effect of Crop Rotation on Pest, Disease and Weed Management

Crop rotation is an important pillar for breaking the soil borne pest and disease cycle (Jensen et al. 2010) especially under NT farming systems. No-till farming systems are characterized by *in-situ* crop harvest residue retention, which can increase the likelihood of pests and disease build-up and carry-over in succeeding seasons (Hobbs et al. 2008). Changing crops every season helps naturally break weed, insect, and disease cycles, thereby reducing the reliance on chemical pesticides, and protecting the environment. Crop rotation has shown some significant control effect on diseases such as grey leaf spot in maize, take-all in wheat, and sclerotinia in soybeans (Dordas 2008).

Crop rotation has also shown promise in tackling fall army worm, a recent menacing pest that has destroyed maize fields in sub Saharan Africa (Tambo et al. 2019). Under low-input systems of the tropics where farmers have limited access to capital (Sanginga and Woomer 2009), crop rotation is often the only economically feasible method for reducing insect and disease damage. A rotation cycle may replace a crop that is susceptible to a serious pest or disease with another crop that is not susceptible, or starve out the pest due to absence of a suitable host. For example, Rusinamhodzi et al. (2012) reported reduced *Striga* infestation in a maize crop following pigeonpea in central Mozambique. Moreover, maize in rotation with pigeonpea without added N yielded 5.6 Mg ha^{-1}, six times more than continuous maize, which was severely infested by striga (*Striga asiatica*) and yielded only 0.7 Mg ha^{-1} (Rusinamhodzi et al. 2012).

2.4 Scale-Appropriate Crop Rotation Options

2.4.1 Crop Rotation Design

The first step for any cropping system design is a comprehensive soil test for soil nutrient status (N, P, K, Mg, Ca, Zn, Mn), pH, and soil organic carbon (SOC). A crop rotation sequence is then planned based on production objectives, as well as addressing any concerns arising from the soil analysis. One of the strategies of a successful crop rotation is to grow a high N demanding crop such as maize following a legume crop to benefit from the positive N balance left by the legume. Deep rooted crops are needed to take up nutrients from deeper layers and cycle nutrients, especially the more soluble nutrients such as nitrates. Crop rotations that promote increased biomass and provide a slow release of nutrients to the root zone are also beneficial. A well-planned crop-rotation system can help farmers avoid many challenges associated with NT, such as increased soil compaction, perennial weeds, plant diseases, and slow early season growth.

Based on results in the literature, cereal-grain legume rotations are the most ideal for small farms, especially dual-purpose legumes that can play a significant role in nutritional diversity at the farm level (Franke et al. 2018). This is because the legume will produce edible leaves and grains – and sometimes mature earlier than the main crop, thus covering critical food deficit periods before the main crop is harvested (Mucheru-Muna et al. 2009; Rusinamhodzi et al. 2012).

2.4.2 Challenges of Effective Rotation Cycles

Crop rotation is easier to design and apply on large farms, and many of the challenges of crop rotation apply to small farms. Most smallholder farming systems do not allow systematic crop rotations due to a plethora of reasons. The major challenges hampering small farmers, especially in the tropics, from practicing successful crop rotation and maximizing the benefits are based on the following factors:

- Small land sizes - inadequate for multiple cropping in a single season;
- Multiple uses of legumes crops – leaves consumed leading to reduced residue retention;
- Crop-livestock integration – crop residues fed to livestock;
- Poorly developed markets for legumes – poor seed and/or fertiliser availability for legumes, and limited markets for the sale of crop produce;
- Differences in planting techniques – the different seed sizes of different crops may need different equipment; and
- Farmers perception of risk – the legume phase is considered a loss

While positive plot-level benefits of associations and rotations are known and widely reported, applying these under farmers' conditions seems to be problematic. It is clear that the economic returns for rotation are marginal, not least because of low yield but also because the support services sector, especially the output markets, are either poor or non-existent. Thierfelder et al. (2013) reported that in eastern Zambia, farmers grow maize in rotation with cowpeas on small plots and record increased maize yield after cowpea of between 20% and 30%, but the legume phase is economically challenging due to small returns. It has been reported that in most cases economic considerations and dysfunctional input and output markets for seed and produce are responsible for slow adoption of rotations (Snapp et al. 2002; Rusinamhodzi et al. 2017). It is therefore critical that the legume component is dual purpose for it to the integrated into the farming system.

Generally, small-scale farmers in sub-Saharan Africa allocate their priority land to food security crops (maize and sorghum) and legumes are only planted later and on about 10% of the land, which means only a small portion can be put under rotation. Dual purpose legumes are desirable, but if crop residue is extensively harvested, starting with the green leaves for food or feed and finally the grain for food, it can reduce soil quality benefits due to reduced biomass return to the soil. Availability of seed for both grain legumes and green manure cover crops is often problematic especially when the rotational crops have little extra benefits other than soil fertility increase or protection against soil erosion. A possible solution has been to use green manure cover crops (GMCCs), that are planted in rotation, and inter- or relay cropped with maize to increase soil cover and contribute N. However, these are not preferred by farmers because of (a) poor financial returns during the legume phase, (b) GMCC compete for water and nutrients with the main crop, and (c) dysfunctional input-output markets for most of the GMCCs.

In farming operations of any scale, high levels of crop residue contribute to cooler and wetter soils at planting and can interfere with seed placement, sometimes resulting in uneven crop stands. In addition, maize residues with wide C:N ratio can cause immobilization (Cadisch and Giller 1997). The contribution of residual N in these fields means through crop rotation is more critical, with some N needed at planting to avoid N deficiency early in the season (Williams et al. 2018). Too much residue also interferes with the performance of herbicides, resulting in poor weed control from pre-emergent herbicides (Araldi et al. 2015). In wheat systems, the wheat cycle sometimes leaves the soil hard or compacted, limiting the potential of the succeeding NT crop, most likely soybean, or too many years of NT can lead to build-up of pathogens requiring conventional tillage after a few years (Kirkegaard et al. 2014).

2.5 Conclusions

Crop rotations are needed to achieve good agronomic practices in general, but more critically are an important integral component of NT cropping systems and are responsible for improving nutrition, and pests and disease control. Cereal-grain legume rotations are the most ideal for small farms, especially the dual-purpose legumes which play a significant role in nutritional diversity at the farm level. However, limited landholdings prevent the widespread adoption of cereal-legume rotations for smaller farms. Large scale farmers have many crop rotations options, and they are able to make profit due to fuel and labor savings with NT in combination with cultivating cash legumes on a large scale. In the future, the design of crop rotations has to address the following issues, especially for small scale farmers (a) small land sizes; (b) multiple uses of legumes crops including leaves; (c) crop-livestock integration and use of crop residues as livestock feed; (d) poorly developed markets for legumes; (e) differences in planting techniques between legume and non-legume; and (f) farmers perception of risk. It is concluded that crop rotation is an integral component of good agricultural practice and is much more critical in NT systems where pests and diseases outbreak can be high, and additional N from nitrogen fixation needed.

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Chapter 3
Challenges and Opportunities in Managing Crop Residue for Multiple Benefits

Raj Setia, Bhupinder Pal Singh, and Naveen Gupta

Abstract No-till (NT) is a farming system where crop is directly sown in untilled soil. The NT system coupled with crop residues retained on soil surface helps to increase soil organic matter, conserve soil moisture, improve erosion control, enhance agricultural sustainability, and reduced labor requirements. However, the influence of residue management on crop production in NT systems is complex and variable, due to both direct and indirect effects and their interactions in different climatic conditions. Soil organic carbon (SOC), a key indicator of soil health, increases on the soil surface under NT system, although there is often no change or a loss of SOC in deeper soil layers. This review has identified the key technological challenges in adopting NT systems and the strategies to overcome those challenges that relate to agronomic management, packaging, standardization, and adoption of farm machinery for seeding. The major strategies to overcome these challenges are: (i) farmers' participatory research through on-farm trials, including adaptive research; (ii) policy support for capacity building; and (iii) the manufacture of local machinery for implementation of NT technology in a region.

Keywords No-till farming system · Crop residue management strategies · Crop residue retention

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3.1 Introduction

Soil organic matter consists mainly of carbon (C) but also represents over 90% of the soil nitrogen (N) content and at least 30% of soil phosphorus (P) (Parton et al. 1988). Hence it is a major nutrient storage pool. The nutrients stored in SOM are made available to plants by soil microorganisms that decompose organic matter to CO_2 and inorganic nutrients that can then be taken up by the plant. Organic matter further influences soil fertility by binding nutrients, holding water, buffering soil pH, and maintaining soil structure. Soil organic matter is also in the spotlight for climate change mitigation strategies (Stella et al. 2019). This is at the foundation of the “4 per 1000 initiative” launched to promote the yearly increase of global soil organic carbon (SOC) stocks in the top 0.4 m of soils by 0.4% to counterbalance the anthropogenic greenhouse gas emissions (Singh et al. 2018).

Crop residues are an important source of soil organic matter, but appropriate management of crop residues is required to maintain soil quality and provide C and nutrients in soils. In general, crop residues are aboveground plant biomass that is generated after crop harvesting in agricultural fields. On a global scale, there was an increase in crop residue production by 33% from 2003 to 2013 (Cherubin et al. 2018). The total production of crop residues in the year 2013 was estimated at 5 billion Mg, of which 72% was from cereals, 12.5% from sugar crops, 7.6% from legumes, 5.5% from oil crops, and 2.4% from tubers (Cherubin et al. 2018). Among different types of crop residues, the Asian continent is the largest producer of crop residues from cereals (51.7%), tubers (47.4%) and oil crops (45.7%). However, the American continent is the largest producer of residues from legumes (67.8%) and sugar crops (49.5%) (Cherubin et al. 2018). Among cereals, rice (31% of total cereal residues), wheat (29.7%) and corn (28.2%) are the major contributors towards cereal residue production (Cherubin et al. 2018).

In general, crop residue cover is increased by conservation tillage, which includes reduced tillage and no-till (NT). Reduced tillage systems involve a reduction in the number of tillage operations, which increases residue cover left on the soil, whereas in NT a crop is established without any prior tillage. No-till systems (which include NT combined with residue retention and diversification of crop rotation) typically save energy, halt soil and land degradation, and lead to more efficient use of water and other inputs (Erenstein et al. 2008). As such, the NT system is a resource-conserving technology that enhances input-use efficiency. No-till farming systems can also increase soil organic matter, conserve soil moisture, improve erosion control, and enhance agricultural sustainability while reducing labor requirements.

The crops residue retention that makes up an integral part of the NT system is an important source of major nutrients [such as N, P, potassium (K), and sulfur (S)] through mineralization. In addition, some studies have reported that the input of crop residues in soil can enhance the decomposition of native SOM (“positive priming”) in some instances, thereby increasing the availability of nutrients from SOM reserves (Singh and Rengel 2007; Sarker et al. 2019). However, the net release of available nutrients from crop residues and native SOM depends on the balance between nutrient mineralization and immobilization, which is influenced by tillage-, residue- and soil-type (Sarker et al. 2019). Crop residues also play an important role in protecting soil from erosion, decreasing soil temperatures in hotter climates, reducing soil evaporation, suppressing weeds, and helping to maintain concentrations of SOM and associated aggregate stability (Carr et al. 2013; Plaza-Bonilla et al. 2015). However, the retention of crop residues in NT systems can also present several challenges, including making seeding operations and plant establishment more difficult and increasing the incidence of some diseases (Singh et al. 2018). In some environments (cooler climates) and some soil types (heavier textured soils with poor drainage), residue retention can also contribute to decreased soil temperatures and increase waterlogging, with associated problems for plant germination and growth (Meier and Thorburn 2016; Sánchez-Rodríguez et al. 2017).

In this chapter, the effects of crop residues on soil properties in NT farming systems and the challenges in crop residue management in different cropping systems are examined. The options to overcome the challenges in crop residue management are also explored.

3.2 Role of and Effect of Crop Residue in No-till Farming Systems

The residues left on the soil after the harvest of a crop can be managed in a variety of ways. In many countries, the burning of crop residue by farmers is a common practice to reduce residue loads and facilitate the seeding and establishment of the next crop. Alternatively, crop residues can be baled/removed for use off-site as feed, bedding material for animals, or fuel. Residues can also be incorporated into the soil in-situ in soil with tillage, or completely/partially retained on the surface as mulch (Singh et al. 2018). In mixed crop-livestock systems, residues may also be grazed in-situ by animals. The uses pattern of crop residues is not uniform across the world. In developing countries, crop residues are mostly used as feed for the livestock. For example, the use of rice straw as animal feed is common among rural households, although rice straw is not preferred as a cattle feed in north-west India due to its high silica content, where it is more commonly burnt (Singh et al. 2014). The use of maize residue and other crops vary, but also often provide relevant feed sources.

Residue retention in NT systems has advantages and disadvantages in terms of soil and moisture conservation, agricultural operations, and nutrient management. Compared with systems where residue is removed, the retention of residues in NT farming systems significantly increases the mean weight diameter of aggregates (Govaerts et al. 2007; Mulumba and Lal 2008; Kumar et al. 2014), which decrease erosion, minimize runoff, and increase infiltration (Sharratt et al. 2006; Govaerts et al. 2007; Prosdocimi et al. 2016). Increases in infiltration, combined with decreases in soil evaporation, help increase soil water content (Arshad et al. 1999; Singh et al. 2011a). The increased soil moisture and insulation of the soil surface in residue retained systems can also decrease soil temperatures and buffer soil temperature fluctuation by suppressing maximum temperature and elevating minimum temperature compared with a non-mulched soil (Singh et al. 2011c). Residues can also by lower wind speed at the soil surface, further helping to reduce erosion rates.

The effect of residue retention on weeds, pests, and diseases is variable and often site-dependent. Weed suppression can be increased in residue retained systems (Dash and Varma 2003; Rahman et al. 2005; Ramakrishna et al. 2006). For example, a number of weed species (*Chenopodium album, Digitariasanguinalis, Portulaca oleracea L., Phalaris minor,* etc.) can be suppressed by residue retention, which physically impedes weed growth while inhibiting weed germination due to allelopathic effects, and may increase weed seed predation (Scott et al. 2010; Chauhan et al. 2012; Ranaivoson et al. 2017). Although other weed species, particularly perennial grasses, can be increased under NT systems generally. Pests and diseases can also either be suppressed or encouraged by residue retention, depending on their required environmental conditions (Reynolds et al. 2015) (see Chaps. 7, 8, and 9 for a further detailed discussion on weeds, pests, and diseases in NT farming systems).

In general, retention of crop residues increases SOC and plant nutrients relative to systems practicing residue removal (Mandal et al. 2004; Govaerts et al. 2007; Carvalho et al. 2017; Ranaivoson et al. 2017; Cherubin et al. 2018). This can have positive impacts on both plant production and our ability to reduce the greenhouse gas footprint of agricultural systems (Singh et al. 2018). For example, the retention of residues may lead to reduced fertilizer requirements over the long-term, depending on the quality and quantity of residue (Scott et al. 2010; Page et al. 2013; Sahu et al. 2015; Ranaivoson et al. 2017), although some studies have shown that the capacity of residues to meet the N requirements of the subsequent crop may be limited depending on C:N ratio of residues (Sarker et al. 2019). Kirkegaard et al. (2018), for example, found that incorporation of wheat residues has the capacity to fulfill only 1–6% of the N requirement of the subsequent crop as the C:N ratio of wheat residues is high and causes N immobilization. Hence, in such situations, fertilizer-N inputs will be required to meet the crop demand in the short-term.

From a global database of 67 long-term agricultural experiments, West and Post (2002) found higher SOC levels under NT than conventional tillage (CT) systems and calculated that there was an average SOC sequestration rate under NT of 0.57 Mg C ha^{-1} $year^{-1}$ up to 0.3 m depth. However, when the distribution of SOC deeper in the soil is considered, meta-analysis and long-term studies have identified that conservation tillage mainly results in SOC gains on the soil surface, often with no change or a loss of SOC in deeper soil layers (Powlson et al. 2008, 2014; Dimassi et al. 2014; Olson and Al-Kaisi 2015). For example, a meta-analysis by Luo et al. (2010) compared 69 sets of paired data for NT and CT and showed a net gain in SOC stocks in the 0–0.1 m layer under NT, relative to CT. However, a net loss of SOC under NT was found in the 0.1–0.4 m, while SOC stocks were similar between different tillage systems in deeper (0.4–0.6 m) soil layers (Luo et al. 2010). This type of distribution is particularly apparent where inversion tillage is practiced and moves surface SOC to lower depths where it is buried in a region where poor aeration can lower decomposition rates relative to the soil surface (Olson and Al-Kaisi

2015). In such situations there may not be any overall difference in SOC stocks in NT v CT systems when the entire soil profile is considered, and in some instances NT systems can even have lower soil carbon stocks (Powlson et al. 2014). Hence, these results highlight the importance of considering the entire profile (e.g. 0–0.6 m) to thoroughly assess the influence of residue management practices on SOC gains or losses (Powlson et al. 2014). However, in regions where soil and climatic conditions are favorable for biomass production and where NT does not negatively impact yield, then net profile sequestration can regularly be observed to occur and this sequestration can help to reduce the greenhouse gas footprint of agricultural production (see Chap. 18).

Although there are many advantages in residue retained systems, the retention of residue at the surface also can present significant problems, for example, as it may cause blockages with traditional sowing machinery, particularly in regions where rates of biomass production are high e.g. the humid tropics (Lyon et al. 2004; Scott et al. 2010; Avci 2011; Sahu et al. 2015). High stubble loads can also reduce seed emergence, which affects plant establishment and the crop yield (Dean and Merry 2015). It has also been found that high stubble loads may decrease the effectiveness of pre-emergence herbicides, as they become bound to the residues, which may result in poor weed control (Scott et al. 2010; Carvalho et al. 2017). Conversely, in other environments, such as semi-arid areas, areas of low soil fertility, areas affected by soil constraints (e.g. acidity, salinity), or where competition for residue use is high (e.g. grazing) it may be difficult to produce significant quantities of residue to increase soil organic matter and bring about the subsequent benefits in soil structure and fertility (Singh et al. 2018).

3.3 Challenges of Crop Residue Management in No-till Systems

The NT approach, as an upcoming paradigm for raising crops, will require an innovative system perspective to deal with diverse, flexible, and context-specific needs of technologies and their management. There is a need to address the following challenges:

3.3.1 Understanding the System

The NT system is much more complex than conventional systems, and the site-specific knowledge of how to adapt NT to different environments and cropping systems is the main limitation of its spread (Derpsch and Friedrich 2009). There is a need to understand the basic physical, chemical, and biological processes in soil and their interactions, which determine the whole cropping system performance.

For example, surface maintained crop residues act as a mulch that reduces soil evaporation and maintains a moderate soil temperature regime (Singh et al. 2011b). However, at the same time, crop residues offer an easily decomposable source of organic matter and could alter pest populations or system ecology in other ways that could negatively affect the cropping system. In addition, the benefits of crop residue retention observed in one location may not be applicable under all conditions. The benefits/challenges of NT systems are location specific depending on agro-climatic conditions, farming systems, and socio-economic factors. For example, the effects of crop residue retention like increased aggregation and protection from erosion, compaction, and soil loss are increased when the residues are retained on the surface in areas with a humid tropical climate and high risk of soil erosion. However, in colder temperate climates, retaining residues on the surface results in lower soil temperatures, which can negatively affect crop production. In regions with high rainfall, excess soil moisture due to retention of residues can also create waterlogging. Therefore, there is a need to study the NT as a whole system and develop management strategies that are suitably adapted to the characteristics and needs of individual locations.

3.3.2 Technological Challenges

The basic principles of NT and the adoption of these practices under varying farming situations is key to the successful implementation of the NT system. These challenges relate to agronomic management, standardization, and adoption of farm machinery for seeding. Adaption strategies for NT systems are highly site-specific, and these need to be tested under varying soil and climatic conditions. In addition, a long-term research perspective is required. No-till systems with surface crop residues result in resource improvement only gradually, and benefits come about only with time. Indeed, in many situations these benefits may take more than 3 years to manifest (Pittelkow et al. 2015). Understanding the dynamics of changes and interactions among physicochemical and biological processes is basic to developing improved soil-water and nutrient management strategies (Abrol and Sangar 2006). Therefore, research in NT must have longer-term perspectives.

3.3.3 Building a System and Farming System Perspective

For building a new system approach, a core group of scientists, farmers, extension workers, private companies (seed companies, machinery suppliers), and various other stakeholders working in partnership mode is crucial to develop and promote new technologies. This approach is somewhat different than in traditional or conventional agricultural approaches, and little attention is often paid to building relationships and seeking linkages with partners.

3.4 How Residue Management and the Challenges Vary in Different Climatic Regions and Cropping Systems

The influence of residue management on crop production is complex and variable, and it results from direct and indirect effects and their interactions in different climatic conditions. A reduction in yield is sometimes caused by unfavorable weather conditions (e.g. wet years where residue retention can lead to waterlogging). In contrast, the opposite is true in drier years where the increased water retention in NT systems with residue retention provides a yield advantage. In regions where cropping is limited by water availability, the greater soil water conservation observed in residue retained systems will usually lead to increased yield, providing other agronomic challenges with the system (weeds, pests, diseases, nutrient management, etc.) are well managed (Pittelkow et al. 2015). However, Gupta et al. (2016) found that the growth and yields of wheat declined over successive seasons in NT based dry seeded rice-wheat cropping systems due to differences in seasonal conditions.

In their meta-analysis, Pittelkow et al. (2015) reported that residue retention is essential in the adoption of NT, and systems without residue retention will lead to a yield decrease regardless of climate. Many examples of this can be found in the literature. For example, in China, Gao et al. (2018) studied the impact of different residue management systems on root characteristics and maize yield. These authors found higher maize root dry weights (an increase of 18.5%), root length density (an increase of 13.7%), root surface area density (an increase of 29.4%) and summer yields (an increase of 15.1%) in plots where crop residues were pulverized and returned to the field compared to those where the residues were removed. Similarly, Li et al. (2019) found that residue removal reduced corn and wheat yields, while returning crop residue to soil resulted in increased wheat production per plant. In India, a significant yield reduction in NT wheat was observed compared to conventional tillage when residues were removed, but the surface retention of 100% rice residues significantly increased the yield of NT wheat by 11–30% in a rice-wheat cropping system on a sandy loam soil(Singh et al. 2014) (Table 3.1). Choudhary et al. (2018) also recorded 39% higher NT based (with residue retention) rice-wheat-mungbean and maize-wheat-mungbean yields compared with a conventional rice-wheat cropping system. In a maize-wheat cropping system on a sandy clay loam soil, maize yield in the permanent broad bed plots with residue and narrow bed

Table 3.1 Effect of crop establishment methods in wheat on its grain yield (Mg ha^{-1}) over different years in a rice-wheat cropping system

Treatment	2010–11	2011–12	2012–13	2013–14	Average
Conventional tillage	4.87a	5.32a	4.75b	5.30b	5.06b
No-till	3.71b	4.33c	4.46c	5.09c	4.40c
No-till+ rice residues	4.82a	5.51a	5.24a	5.64a	5.30a

Source: Singh et al. (2014)
Figures in a column having common letter(s) do not differ significantly ($p < 0.05$)

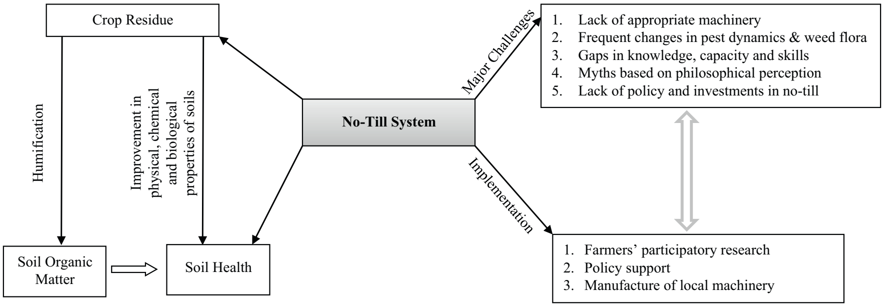
with residue were 28% and 15% higher, respectively, than that in conventional tillage plots (Chakraborty et al. 2010).

The type of cropping system, climate, and residue management can also interact to affect how residue removal affects production. For example, in the USA, Rakkar et al. (2019) found that the baling of residues reduced soil surface cover by 57%, whereas grazing reduced it by only 17%. Baling also reduced soil water, mainly due to higher evaporation, and increased the risk of erosion because of less surface cover. Jat et al. (2014) found that the benefits of NT in rice-wheat cropping system systems started appearing after 2–3 years, which was sooner than in maize-wheat systems (5 years) in Mexico (Govaerts et al. 2005) and China (He et al. 2011), and from a wheat-soybean system (7 years) in Brazil (Franchini et al. 2012). However, while many studies observe positive benefits from residue retention, other studies have noted no effect, particularly over the short term. For example, in a Brazilian study, Satiro et al. (2019) evaluated and developed a model that predicts the impact of straw removal on sugarcane yield. They reported that over the short term, straw removal reduced soil C in the surface 0.05 m but did not reduce yield. Similarly, Ulmer et al. (2019) reported that residue removal did not affect subsequent corn, soybean (*Glycine max*), or dry bean (*Phaseolus vulgaris* L.) yields.

3.5 Options to Overcome Challenges

While residue retention is an essential and integral part of the NT system, there is a need for policy analysis to understand how residue retention can best be integrated into the management of agricultural systems and how policy instruments and institutional arrangements promote or deter the uptake of NT and residue retention (Fig. 3.1). The following are some of the relevant policy considerations for the promotion of NT and residue retention:

- Efforts to adapt NT principles and technological aspects, particularly those around residue retention, to suit various agro-ecological, socio-economic, and



1. Lack of appropriate machinery
2. Frequent changes in pest dynamics & weed flora
3. Gaps in knowledge, capacity and skills
4. Myths based on philosophical perception
5. Lack of policy and investments in no-till

1. Farmers' participatory research
2. Policy support
3. Manufacture of local machinery

Fig. 3.1 Schematic diagram showing the effect of crop residues on soil health, major challenges, and the policies required for implementation of no-till farming systems farming systems, have been ongoing for more than a decade. Greater support from stakeholders, including policy and decision-makers at the local, regional, and national levels will facilitate the expansion of NT and residue retention while helping farmers to reap more benefits from the technology. There is a need to think about the problems faced in implementing NT technologies at the farmers' level. Under such situations, farmers' participatory on-farm research to evaluate/refine the technology in initial years followed by large scale demonstration in subsequent years is needed. Adaptive research is required to tailor NT principles and practices to local conditions, which should be done in collaboration with local communities and other stakeholders.

- Residue retention as part of NT systems can improve the environment by building up soil carbon and reducing greenhouse gas emissions of agriculture, reducing environmental pollution (e.g. due to the cessation of residue burning), and helping to increase groundwater recharge (due to increased infiltration rates). It thus provides many ecosystem services that are of benefit to the wider community. To encourage the uptake of NT and residue retention, it may thus be possible to rewarded farmers financially for the provision of these services.
- The NT system with residue retention can offer opportunities for diversified cropping systems in different agro-climatic regions. Packaging of agronomic management, and developing machinery for seeding and harvesting to ensure minimum soil disturbance in residue management for different edaphic conditions will be crucial to the success of NT. For example, in hilly areas, bullock drawn equipment will have greater relevance for small landholders than tractor drawn devices. Ensuring the quality and availability of equipment through appropriate incentives is essential. In these situations, subsidy support from national or local government to firms for developing low-cost machines will help in the promotion of NT and residue retention technologies. While some countries produce their own NT equipment, in others, the available implements and equipment are imported. Local machinery manufacture should increase availability, ensure that equipment is adapted to local conditions, increase employment opportunities, and reduce costs. The high cost of machinery needs policy support for upscaling its manufacture.
- Along with a useful resource database, the systematic monitoring of the socio-economic, environmental, and institutional changes should be an integral part of the major projects on NT.
- Policy support for capacity building by organizing training on how to manage residue retention within NT is needed. The availability of trained human resources at ground level is one of the major limiting factors to the adoption of NT. Training on NT should be supported at all levels. Efforts to adequately train all new and existing agricultural extension personnel on NT should be made in relevant departments.
- In developing countries, the other important thing for successful adoption of NT is the need to provide credit to farmers to buy the equipment, machinery, and inputs through banks and credit agencies at reasonable interest rates.

- The policies for food security (the availability of food and an individual's ability to access it) should involve the goal of livelihood security (resource and income earning activities). The appropriate climate-resilient practices and technologies for producing crops need to be identified and scaled up in rural areas. In developing countries, infrastructure and employment opportunities should be developed in rural areas to improve the existing rural livelihood security system so that farmers can adopt climate-resilient practices and technologies for cultivation of crops.

3.6 Conclusions

In NT farming systems, residue retention is considered to be effective for increasing productivity and sustainability, including soil fertility (a reflection of physical, chemical, and biological properties), soil water availability, and decreasing soil erosion in long-term scenario. The increases in soil organic carbon (SOC) observed under residue retained systems in some environments can also play a role in reducing greenhouse gas emissions from the agricultural sector while providing an opportunity to help meet the targets of the Paris Agreement. However, there are few limitations with residue retention, particularly around nutrient immobilization and the management of weeds, insects, and pests. The site-specific knowledge of how to adapt it to different environments and cropping systems is the main limitation of its spread. Nevertheless, research to identify ways to overcome these issues under different cropping systems may help in improving crop yield.

There is also a need to study NT as a whole system and develop management strategies that are suitably adapted to the characteristics and the requirements of individual locations. The major challenges of crop residue management in areas with semi-arid climates are how to produce enough residue and prevent residue removal due to competition with grazing animals/fuel. In temperate climates, the lower soil temperatures at germination and waterlogging in heavier soils limit yield, while in humid tropical areas, high residue loads can present challenges for seeding. Because there are many challenges in the management of crop residues in NT systems, policy considerations that promote NT systems in different parts of the world are still required. Government policies that are particularly important for directly or indirectly affecting NT systems include: farmers' participatory research to refine NT systems to a particular environment or location, ensuring quality and availability of equipment through appropriate incentives for promoting the NT technologies, and a shift in focus from food security to livelihood security.

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Chapter 4
Managing Cover Crops in No-Till Farming Systems

Paul DeLaune

Abstract Cover crops have long been used in agricultural production systems as a result of providing varying agronomic and environmental benefits. Although no-till (NT) is a leading approach to sustain crop production, reduce soil degradation, mitigate environmental concerns, and enhance ecosystem services, implementing cover crops can further enhance NT performance. In order to successfully adapt cover crops into NT systems, several factors should be considered. Goals should be determined based upon an individual's farming system, as success of one approach may vary depending on climatic and environmental conditions or simply management approaches. Proper management of cover crops can lead to improved soil function and health, have agronomic and economic benefits, and enhance environmental quality. The objective of this chapter is to provide a background of cover crop management approaches and selected potential benefits in NT cropping systems.

Keywords No-till · Cover crops · Nutrient cycling · Erosion · Weed suppression · Disease management

4.1 What Is a Cover Crop?

As noted by Magdoff and Van Es (2009), the terms green manure, cover crop, and catch crop are often used interchangeably. As outlined, a green manure crop may be thought of as a crop to maintain soil organic matter and improve nitrogen availability. A cover crop is grown to prevent soil erosion by covering the soil surface and holding the soil in place with living roots. Whereas a catch crop may be planted to mine available nutrients following a cash crop to prevent nutrient losses from the soil profile. As green manure crops are typically incorporated into the soil before planting a subsequent cash crop, this term does not apply to a true NT system.

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Table 4.1 Advantages and disadvantages of using cover crops

Advantages	Disadvantages
Reduce soil erosion	Must be planted when time (labor) is limited
Increase residue cover	Additional costs (planting and killing)
Increase water infiltration into soil	Reduce soil moisture
Increase soil organic carbon	May increase pest populations
Improve soil physical properties	May increase risks of diseases
Improve field trafficability	Difficult to incorporate with tillage
Recycle nutrients	Allelopathy
Legumes fix nitrogen	
Weed control	
Increase populations of beneficial insects	
Reduce some diseases	
Increase mycorrhizal infection of crops	
Potential forage harvest	
Improve landscape aesthetics	

Adapted from Dabney et al. (2001)

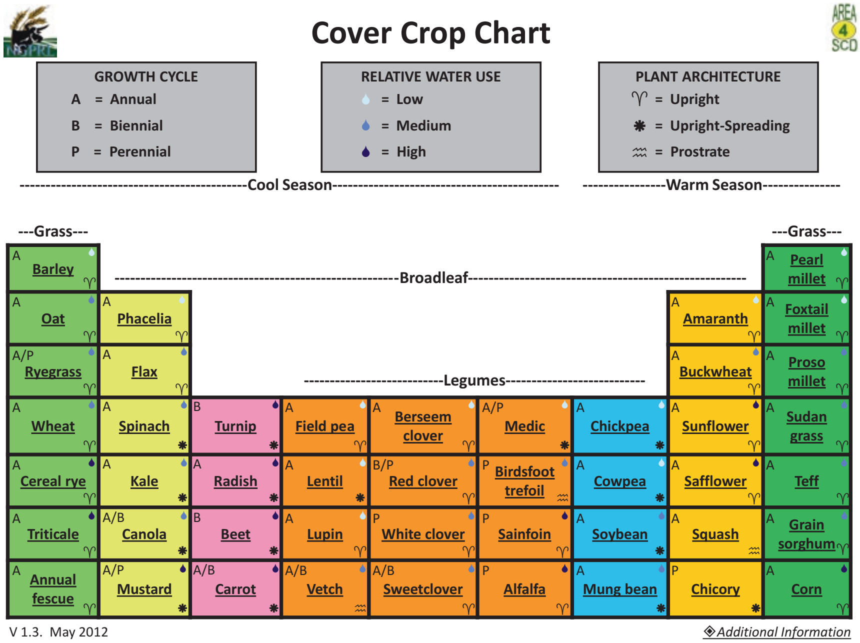
Hence, the term cover crop will be used to define a crop that is planted during a fallow period to provide potential soil and environmental benefits.

Although not a new technology, cover crops have received a new and increased interest in recent years. Much of this new attention may be attributed to increased awareness of continued soil degradation in cropping systems worldwide and the potential of cover crops to enhance soil health and function. Cover crops have been shown as a proven technology that can reduce soil erosion, increase nutrient use efficiency, increase soil carbon, improve soil physical properties, increase soil water infiltration, increase soil organic carbon, protect water quality, and aid in weed control. Research has presented doubts about whether NT on its own can effectively increase or even stabilize soil carbon pools (Baker et al. 2007; Doran et al. 1998). Blanco-Canqui et al. (2011) noted that the inclusion of cover crops in cropping systems could enhance NT performance by improving soil physical properties. Frasier et al. (2016) concluded that extra residue input by cover crops increased soil microbial biomass and led to enhanced biological activity and C sequestration, thus overcoming some limitations of monoculture NT systems. However, these significant benefits can vary by location and season. Dabney et al. (2001) noted that adoption of cover crops in cropping systems is based on the perceived balance between advantages and disadvantages (Table 4.1).

4.2 Cover Crop Selection

When incorporating a cover crop into a farming system, several questions should be considered in order to select the correct cover crop and achieve desired goals. Hence, desired goals and the environment should be considered and determined. There are various resources that provide guidelines and/or serve as a decision aid tool. Within the United States, Green Cover Seed (Kearney, Nebraska) provides a SmartMix calculator to aid in the recommendation of a cover crop mix based upon the users location, planting date, seeding method, cash crop, and selected goals (https://smartmix.greencoverseed.com/mix/start). A non-inclusive list of potential goals include: increase organic matter, reduce erosion, weed suppression, residue persistence, nutrient cycling/scavenging, supplemental grazing or haying, nematode control, salinity/pH tolerance, attract beneficial insects, nitrogen fixation, and/or alleviating soil compaction. While most farmers use single species of cover crops, mixtures of different cover crops into a multi-species mix or "cocktail mixture" may also be used. The United States Department of Agriculture – Agricultural Research Service also developed a Cover Crop Chart to assist farmers with the decisions on the use of cover crops in crop and forage production systems (Fig. 4.1). This chart provides information on the cover crop growth cycle, plant architecture, and relative water use. In addition, further details such as salinity tolerance, seeding depth, crude protein, C:N ratio, arbuscular mycorrhizal associations, pollination method, and nitrogen scavenging capability are provided for select species.

Along with production goals, the environment in which cover crops are grown is an important consideration. Justification for implementing cover crops in rain limited environments is more difficult compared to regions with less evaporative demand and/or more precipitation. A major concern among farmers within drier environments is that the amount of soil water used by the cover crop could



Cover Crop Chart

GROWTH CYCLE
A = Annual
B = Biennial
P = Perennial

RELATIVE WATER USE
○ = Low
◐ = Medium
● = High

PLANT ARCHITECTURE
♈ = Upright
✱ = Upright-Spreading
≋ = Prostrate

--Cool Season-- ---------------Warm Season--------------

---Grass--- ---Broadleaf--- ---Legumes--- ---Grass---

A ○ **Barley** ♈								A ○ **Pearl millet** ♈
A ◐ **Oat** ♈	A ○ **Phacelia** ♈						A ○ **Amaranth** ♈	A ○ **Foxtail millet** ♈
A/P ◐ **Ryegrass** ♈	A ◐ **Flax** ♈						A ◐ **Buckwheat** ♈	A ◐ **Proso millet** ♈
A ◐ **Wheat** ♈	A ◐ **Spinach** ✱	B ● **Turnip** ✱	A ○ **Field pea** ♈	A ○ **Berseem clover** ♈	A/P ○ **Medic** ✱	A ○ **Chickpea** ✱	A ● **Sunflower** ♈	A ◐ **Sudan grass** ♈
A ● **Cereal rye** ♈	A ◐ **Kale** ✱	A ● **Radish** ✱	A ○ **Lentil** ✱	B/P ◐ **Red clover** ♈	P ◐ **Birdsfoot trefoil** ≋	A ○ **Cowpea** ✱	A ● **Safflower** ♈	A ◐ **Teff** ♈
A ● **Triticale** ♈	A/B ◐ **Canola** ✱	B ● **Beet** ✱	A ○ **Lupin** ♈	P ◐ **White clover** ♈	P ● **Sainfoin** ♈	A ◐ **Soybean** ✱	A **Squash** ≋	A ◐ **Grain sorghum** ♈
A **Annual fescue** ♈	A/P ● **Mustard** ✱	A/B ● **Carrot** ✱	A/B ◐ **Vetch** ≋	A/B ◐ **Sweetclover** ♈	P ● **Alfalfa** ♈	A ◐ **Mung bean** ✱	P **Chicory** ✱	A ● **Corn** ♈

V 1.3. May 2012

◈ *Additional Information*

Fig. 4.1 Cover crop chart developed by the United States Department of Agriculture – Agricultural Research Service and available at https://www.ars.usda.gov/plains-area/mandan-nd/ngprl/docs/cover-crop-chart/

potentially reduce available soil water for the subsequent cash crop, which is a potential disadvantage that could hinder adoption (Dabney et al. 2001; Balkcom et al. 2007; Wortman et al. 2012). Research throughout semi-arid regions have shown that water use by cover crops can greatly reduce yields of subsequent crops (Unger and Vigil 1998; Unger et al. 2006; Nielsen et al. 2016; Holman et al. 2018). Nielsen et al. (2015) reported that cover crop water use was 1.78 times greater than evaporative water loss from a NT fallow treatment. However, greater precipitation storage efficiency was observed where cover crops were present compared with a fallow treatment (Nielsen et al. 2016). While water use by cover crops may be deemed a disadvantage, they can increase infiltration and precipitation capture efficiency (Keisling et al. 1994; Blanco-Canqui et al. 2011, 2015; Nielsen et al. 2016). To offset potential concerns with cover crop water use, timely termination of cover crops has been considered critical to prevent excessive water use or allow time to capture precipitation and recharge the soil profile (Unger and Vigil 1998). In NT systems that have low residue input and long fallow periods, cover crops could offset the soil degradation that occurs under such circumstances. For low residue NT cropping systems, addition of a cover crop has been shown to improve water infiltration and penetration resistance compared to conventional till (CT) without a cover crop (DeLaune et al. 2019). In contrast, actively growing cover crops may provide more rapid drying of soil in humid regions and allow for more ideal planting conditions for the cash crop.

4.3 Nutrient Cycling

Cover crops and crop rotation have been shown to enhance soil fertility, soil organic matter, and soil structure. Identification of cover crops that can be successfully established and terminated in time for nutrients to be available at key time points in crop growth cycles is critical for maximizing yields and reducing input costs. Planting winter or spring cereals has been shown to have the potential to scavenge residual nitrogen and reduce losses of nitrogen via leaching or surface runoff (Meisinger et al. 1991; Shipley et al. 1992; Dabney et al. 2001; Macdonald et al. 2005; Lyons et al. 2017; Thapa et al. 2018). Warm-season grass cover crops, such as millet and sorghum-sudangrass, and brassica species, such as radishes and canola, have also been shown to provide similar benefits (Macdonald et al. 2005; Schomberg et al. 2006; O'Connell et al. 2015). A global meta-analysis indicated that non-leguminous cover crops substantially reduced nitrate leaching into freshwater systems by 56% (Thapa et al. 2018). Furthermore, non-legume-/legume cover crop mixtures reduced nitrate leaching as effectively as non-legumes and significantly more than legume cover crops. Roth et al. (2018) determined that valuing the impact of cover crops on subsurface drainage N loading, soil erosion, and cover crop residue N mineralization has the potential to recover an average of 61% of the costs associated with cover crop implementation.

Reduction in soil nitrate concentrations from cover crops may be expected and these reductions can reduce the amount of nitrogen available to the cash crop (Doran and Smith 1991; Schomberg and Endale 2004). Wander et al. (1994) reported that cover-cropped soil had higher total C and N, particulate soil organic matter, and reduced water-dispersible organic C contents than CT soils, indicating more stable organic matter. However, in anaerobic rice soils, where there is slow decomposition, the presence of phenolics in soil organic matter has been shown to reduce nutrient availability (Schmidt-Rohr et al. 2004). Therefore, the use of cover crops with high quality biomass is required to increase soil nitrogen supply. The ratio of C:N is a good indicator of nitrogen mineralization potential (Wagger et al. 1998). A high quality residue may be defined as having a C:N value below 25–30, whereas greater values indicate a low quality residue. Otte et al. (2019) demonstrated that termination timing of rye can affect the quality and release of nitrogen. In general, early terminated cover crops can be expected to have higher rates of decomposition and nitrogen release (Fig. 4.2). In contrast, a later terminated cover crop may produce greater cover crop biomass quantity with reduced residue quality that decreases the decay rate and nutrient release. However, as in the case presented by Otte et al.

Fig. 4.2 Warm-season cover crop mixtures after chemical termination in a continuous no-till wheat system. Top picture shows warm-season legume/grass mixture at two termination dates: 59 days after planting (foreground) and 86 days after planting (background). Bottom picture shows a broadleaf mixture terminated 59 days after planting. Pictures were taken 53 days after early termination and 26 days after later termination. (Photo by Paul DeLaune)

(2019), a slower decomposition rate via a later terminated rye cover crop can balance nitrogen release with in-season corn nitrogen demands.

Adding legume cover crops, such as cowpeas, sunn hemp, hairy vetch, winter peas, and clovers, can provide nitrogen to the subsequent cash crop as well as stimulate the microbial biomass, which improves crop nutrition and soil structure (Ebelhar et al. 1984; Vyn et al. 1999; Watson et al. 2002; Crews and Peoples 2004; Balkcom and Reeves 2005). Seman-Varner et al. (2017) suggested that a legume cover crop may effectively scavenge poultry litter nitrogen in low nitrogen systems and result in increased residual nitrogen availability over time. A meta-analysis within the Argentine Pampas showed an 8% decrease in corn yield when following a non-legume cover crop, but a 7% increase when following a legume species (Alverez et al. 2017). In contrast, soybean yield was barely affected by species of cover crop. In some cases, nitrogen fixation from legumes could potentially result in nitrogen in excess of crop demands and exacerbate losses to the environment. To balance concerns with excess nitrogen through exclusive legume cover crops use, or concerns with nitrogen immobilization through high quantity, low quality grass cover crops, a mixture of legumes, grasses, and/or brassicas may be considered. Legume-grass cover crop bicultures have the potential to reduce nitrogen losses by scavenging nitrogen while also supplying nitrogen to subsequent crops (Ranells and Wagger 1997; Poffenbarger et al. 2015; Hayden et al. 2014; Frazier et al. Frasier et al. 2016, 2017). In addition to cover crop bicultures, cover crop mixtures composed of more than two species have been tested with the goal of enhancing the overall level and diversity of services provided by a cover crop (Creamer et al. 1997; Smith et al. 2014). Finney et al. (2016) concluded that the fact that cover crop C:N ratio predicted nitrogen retention, inorganic nitrogen supply, and yield services indicates that species functional traits (as opposed to biomass alone) are important for predicting ecosystem service provision from cover crop mixtures. However, Romdhane et al. (2019) found that cover crop management (i.e. termination strategies) rather than composition of cover crop mixtures had a greater effect on soil carbon and nitrogen in NT agroecosystems.

4.4 Water and Wind Erosion

Cover crops reduce soil loss by improving soil structure and increasing infiltration, protecting the soil surface, scattering raindrop energy, and reducing the velocity of the movement of water over the soil surface (Smith et al. 1987). No-tillage and other conservation tillage practices combined with cover crops can significantly reduce runoff and soil erosion losses (Langdale 1983; Langdale and Leonard 1983; Hartwig 1988). Kaspar et al. (2001) noted that erosion reduction caused by cover crops should be expected to be more pronounced in cropping systems that do not produce large amounts of residue, or in situations where residue is harvested. For example, Wendt and Burwell (1985) demonstrated the potential hazard of removing crop residue on soil loss, where annual soil loss from NT corn grown for silage (crop residue harvested from the field) was 22 Mg ha^{-1} compared to 0.6 Mg ha^{-1} for NT corn grown for grain (crop residue retained). However, addition of a wheat (*Triticum aestivum* L.) or rye (*Secale cereale* L.) cover crop in the NT silage system reduced annual soil loss from 22 Mg ha^{-1} to 0.9 Mg ha^{-1}. Similarly, Zhu et al. (1989) reported that annual soil loss was decreased 87% by common chickweed (*Stellaria media* L.), 95% by Canada bluegrass (*Poa compressa* L.), and 96% by downy brome (*Bromus tectorum* L.) cover crops compared to no cover crops in a NT soybean system. Blanco-Canqui et al. (2013) reported that sediment loss was 3.7 times lower and total P and nitrate loss in runoff was 3.4–4.2 times lower from triticale and spring pea cover crops compared to fallow in a NT wheat system.

Within semi-arid regions, cover crops have also historically been implemented to reduce wind erosion (Unger and Vigil 1998; Hansen et al. 2012; Blanco-Canqui et al. 2013). Wind erosion in the US Great Plains has been reported to be greater than 6 Mg ha^{-1} $year^{-1}$, and in some areas as high as 18 Mg ha^{-1} $year^{-1}$ (Hansen et al. 2012). Although competition for water resources may be greater in water limited environments, a cover crop, such as wheat, provides a standing residue that acts as a physical barrier from high wind and blowing sand (Fig. 4.3; McGregor et al. 1975). Blanco-Canqui et al. (2013) recommended that cover crop growth and/or termination should be near to times when water and wind erosion events are most likely to occur, as benefits are rapidly lost with time after termination in semi-arid environments. They concluded that adding non-legume (triticale) and legume (lentils and peas) cover crops during fallow periods reduced the soil's susceptibility to wind erosion through increased soil aggregate size distribution. While interseeding a rye cover crop into a corn system with harvested residue did not rapidly improve soil properties, Blanco-Canqui et al. (2017) hypothesized that the added soil cover

Fig. 4.3 Cotton emerging in no-till system without a cover crop (left) and a no-till system with a chemically terminated wheat cover crop. (Photo by Paul DeLaune)

provided by the cover crop could partly offset the effect of residue harvest on wind erosion.

4.5 Weed Suppression

A potential alternative to mechanical tillage for weed control is the use of cover crops, which have the potential to provide weed suppression by altering weed population dynamics (Mirsky et al. 2013). Cover crop residues can reduce weed seedling emergence by reducing the quality and quantity of light, as well as soil temperature amplitude (Teasdale and Mohler 1993; Mohler and Teasdale 1993). A cover crop's ability to reduce weed pressure is highly variable and often times requires biomass greater than that achievable within semi-arid environments (Sanderson et al. 2018). In addition, legume monocultures typically produce lower biomass than grain crops, such as rye, and decompose very quickly (Burgos and Talbert 1996; Yenish et al. 1996). While legume species may produce less biomass, they have also been shown to reduce weed density and growth in cropping systems (Fisk et al. 2001; Caamal-Maldonado et al. 2001; Harrison et al. 2004). However, Norsworthy et al. (2010) concluded that there may be minimal weed control benefits due to the rapid decay of legume species hairy vetch and Austrian winter pea, without the addition of herbicides. Research has shown that increasing cover crop seeding rates and adjusting planting dates may be necessary to maximize effective weed control (Brennan et al. 2009; Mirsky et al. 2011). MacLaren et al. (2019) found that cover crop biomass production is more important than diversity for weed suppression, with neither species diversity nor functional diversity affecting weed suppression by cover crops. Furthermore, they concluded that diverse cover crop mixtures remain valuable to perform multiple functions, but may contribute to weed problems if composed of poorly competitive species. Finney et al. (2016) reported that cereal rye and canola monocultures and mixtures containing these species exceeded the biomass threshold for weed suppression and controlled more than 95% of weeds, indicating that high-yielding monocultures are as effective as diverse mixtures.

Rye is a widely used and studied cover crop species with excellent weed suppression potential (Price et al. 2008; Mischler et al. 2010; Ryan et al. 2011; Korres and Norsworthy 2015). Weeds can be controlled by using cover crops to produce a mulch layer on the soil surface, with research showing an exponential relationship between mulch mass and weed emergence (Teasdale and Mohler 2000). For example, greater than 75% inhibition of the emergence of most annual weeds was obtained when rye mulch biomass exceeded 8 Mg ha^{-1} dry weight and mulch thickness exceeded 0.1 m. Roller crimpers have been shown to be beneficial by flattening cover crops to provide a mat over the soil surface, while at the same time effectively terminating the cover crop (Ashford and Reeves 2003; Kornecki et al. 2009; Mischler et al. 2010). Most studies report a higher termination rate of cover crops when roller crimpers are used at least from the flowering/anthesis stage of cover crops. Davis (2010) reported similar effectiveness in weed control between

Fig. 4.4 Cotton growing in a rye cover crop that was terminated with a roller crimper and herbicide. (Photo by Paul DeLaune)

chemically terminated and roller-crimper terminated rye and vetch in a NT soybean system, although soybean yields were reduced following rolled vetch. Keene et al. (2017) determined volunteer cover crops (hairy vetch and rye) resulting from incomplete termination with mechanical rolling can be problematic in subsequent crops and may reduce the benefits of organic rotational NT. A combination of rolling and chemical termination of a rye-vetch cover crop in a NT system has been shown to maintain excellent weed control throughout the growing season (Fig. 4.4; Miville and Leroux 2018). While weeds can be suppressed with high residue mats, crop emergence can also be affected. For example, a rolled cover crop consisting of foxtail millet alone and a mix of foxtail millet and cowpea negatively affected onion plant stand and overall yield compared to a cowpea cover crop and bare ground due to ground coverage and thickness of the grass (Vollmer et al. 2010).

Rye, sorghum, rice, sunflower, rape seed, and wheat have been documented as important allelopathic crops that release allelochemicals which not only suppress weeds, but also promote underground microbial activity (Jabran et al. 2015). The allelopathic potency of rye is due mainly to the presence of phytotoxic benzoazainones, which are released actively by root exudation or passively from plant residues (Schulz et al. 2013). Kruidhof et al. (2009) found that crop residues left on the soil surface decompose more slowly than residues incorporated into the soil, which may result in a slower release rate, but longer lasting supply, of allelochemicals. Rice et al. (2012) found that rye left on the soil surface was highly suppressive of weed biomass for 0–26 days and concluded that allelopathic contribution of benzoazainones may have been masked by physical suppression. Rice et al. (2012) suggested that benzoxazinoid compounds are not present in the soil for more than 2 weeks after rye termination and are found at concentrations too low to account for weed suppression. Thus, physical rather than allelopathic effects probably predominate when mature cereal rye is terminated and used as a surface mulch (Teasdale et al. 2012). Aqueous foliar extracts of sunn hemp, cowpea, and velvetbean residue has also been shown to express allelopathic tendencies and reduce weed germination

(Adler and Chase 2007). Termination timing of cover crops can also be important, as allelopathic effects have been shown to potentially carry over and affect cash crop performance (Adler and Chase 2007; Norsworthy et al. 2011; Li et al. 2013).

4.6 Pest Management

No-till systems alter pest dynamics due in large part to residues left on the soil surface that create a more diverse ecosystem than CT systems. Before planting a cover crop, specific pest/crop interactions that may become problematic should be investigated, as cover crops may harbor harmful insects, diseases and/or nematodes (Balkcom et al. 2007). Cover crops can impact disease and insect damage by changing soil chemical and physical properties, by releasing exudates and decomposition products that directly affect pathogens, by serving as hosts for competitors, parasites and predators, by changing above and belowground environmental factors, such as moisture levels and air movement, or by affecting the overall health of succeeding or concurrent crops (Sarrantonio and Gallandt 2008). As noted, these same strategies can work against crop managers if the cover crop attracts additional pests, or acts as an alternate host for pathogens and/or insects in the field. Other studies have shown increased incidence of pest and disease problems with cover crops, thus species selection should be considered (Louws et al. 1996; Brown and Glenn 1999).

One potential management method is to provide a living cover crop as a ‘refuge’ or relay strip to attract natural beneficial predators. Research has shown that planting of summer cover crops such as buckwheat and sunflower had a substantial impact on the abundance of western grape leafhoppers and western flower thrips, and associated enemies in vineyards (Nicholls et al. 2000). During flowering of these cover crops, lower densities of pests and larger populations of predators were noted and mowing of cover crops forced predators to adjacent vines resulting in reduced pest densities. Similarly, strips of cover crops such as crimson and balansa clover, wheat, rye, hairy vetch, canola, and/or a mixture of a legume-grass enhanced predator numbers in cotton systems (Parajulee and Slosser 1999; Tillman et al. 2004).

Cover crops have also been shown to reduce the risk of disease and, in turn, potentially reduce pesticide needs. Reduced disease in NT cover crop systems has been attributed to an inhibition of pathogen dispersal, or alteration in the microclimate that makes it less favorable to disease development (Ristaino et al. 1997; Mills et al. 2002). For example, a roller-crimped rye cover crop reduced the incidence of white mold in a NT soybean and dry bean system (Pethybridge et al. 2019). Ristaino et al. (1997) found that a NT wheat cover crop suppressed phytophthora blight in bell peppers, probably by reducing splash dispersal of the inoculum. Hairy vetch alone, or mixed with rye, reduced *Plectosporium* blight by 36%, black rot by 50% and reduced powdery mildew in pumpkins grown in NT compared to bare ground plantings (Everts 2002). Sorghum and ryegrass cover crops have been shown to reduce splash-dispersed pathogens in strawberries (Newenhouse and Dana 1989; Ntahimpera et al. 1998). Numerous studies have reported that Brassica spp.

biofumigation can reduce soilborne pathogens; however, flail mowing and incorporating into the soil are the most common approaches (Krasnow and Hausbeck 2015).

Several studies have focused on cover crop effects on plant parasitic nematode populations. No-till practices have been shown to increase nematode population densities compared to CT (Fortnum and Karlen 1985; Schmidt et al. 2017) and fail to suppress most plant-parasitic nematodes compared to cover crop rotation (McSorley and Gallaher 1993; Cabanillas et al. 1999). When nematodes become a problem in a cash crop, planting an appropriate cover crop can significantly decrease nematode populations. The suppressive activity of cover crops is due to their poor host status to nematodes, general stimulation of microbial antagonist, and the release of toxic products during decomposition (Magdoff and van Es 2009). Sunn hemp, cowpea, soybean, sorghum-sudangrass have all been found to suppress nematode populations compared to continuous corn; however, the winter cover crops vetch, lupine clover, and wheat did not (Wang et al. 2004). The decomposition of velvetbean and jackbean leaves significantly reduced (>50%) the development of phytopathogenic nematodes in the roots of tomato (Caamal-Maldonado et al. 2001). Schmidt et al. (2017) found that parasitic nematode densities tended to be higher under non-inversion than inversion tillage except where oilseed radish or black oats had been used as cover crops. A review by Hooks et al. (2010) revealed that marigold performed equal or superior to alternative methods for nematode management. Plant species that generally are considered for biofumigation for plant parasitic nematodes are found mostly in the family Brassicaceae, which are typically slashed or chopped and incorporated into the soil (Kruger et al. 2013; Dutta et al. 2019). Further research is warranted to determine the effectiveness of biofumigation in NT farming systems.

4.7 Management Considerations

Clearly, research has shown numerous benefits of cover crops in NT cropping systems. However, benefits can depend upon the environment and management. For example, a high biomass producing cover crop grown in humid regions should not be expected to produce similar biomass and subsequent benefits in semi-arid environments. The first step to successfully implementing cover crops into a NT farming system is defining a specific goal for using cover crops. These goals are often dependent upon the farmer's cash crop or other production goals. Blanco-Canqui et al. (2015) outlines desired cover crops and their respective characteristics based upon goals such as wind and water erosion, compaction management, soil nutrient management, weed suppression, biodiversity and wildlife habitat, grazing and haying, crop production, and pest or disease control. Single species cover crops may be ideal for some systems, whereas two or more species may be needed if multiple goals are pursued simultaneously. Thereafter, management options such as timing of planting, seeding rate, seeding method, crop rotation, fertilizer management, stand management via grazing, mowing, or haying, termination timing, and termination method can all factor into gains toward improved agronomic, economic, and environmental sustainability with additional ecosystem services. If mismanaged, cover crops lead to detrimental results such as depleting soil moisture, immobilizing nitrogen, reducing cash crop yields, and/or becoming an invasive weed. Thus, careful and educated planning and management will provide a greater chance of success to enhance NT farming systems.

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Chapter 5
Challenges and Opportunities in Fertilizer Placement in No-Till Farming Systems

Robert M. Norton

Abstract No-till (NT) farming systems are now widespread and are part of Conservation Agriculture. The adoption of any new system brings consequences, and NT means changes in fertilizer practices to realise the potential of improved soil conditions. Less soil mixing results in the vertical stratification of immobile nutrients and banded, deep placement of fertilizers away from the seeding rows is a common approach to address stratification. Lateral stratification will require adjustments to soil sampling strategies and soil test interpretations. Nitrogen dynamics also alter where crop residues are retained, requiring a review of the source, rate, time, and placement of fertilizers Wider seeding rows and higher fertilizer rates present an increased risk of fertilizer damage in the seed row. Banding nutrients away from the seed row with improved machinery design and selecting fertilizers with low damage potential are options to manage the risk of damage. A significant challenge to NT is to manage soil acidity, given the relatively low mobility of lime. Consideration of interventions with strategic tillage have been proposed to address lime incorporation as well as alleviate nutrient stratification, although the guidelines for the application of these strategies are still developing.

Keywords Nutrient stratification · Fertilizer damage · Nutrient banding · Soil acidity · Liming

5.1 The Need to Address Fertility in No-Till Systems

It is generally accepted that "conventional" tillage (CT) and crop residue burning has substantially degraded the soil resource base. As a consequence, the concept of no-till (NT) systems or Conservation Agriculture (CA) has developed to encompass what is now considered crop management best practice (Giller et al. 2015). This is

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defined as a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil management techniques protect the soil from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources, water and air, while optimizing yields (Gonzales-Sanchez et al. 2015). Fundamental to NT/CA is minimum soil disturbance, continuous soil cover with crops or crop residues and crop rotation (FAO 2015).

Adopting NT and crop residue retention presents a new set of challenges to farmers and land managers. This chapter will provide a perspective on nutrient management challenges (e.g. Angus et al. (2019)). The principles of 4R nutrient stewardship aim to develop nutrient best management practices based on the use of the Right nutrient source, applied at the Right rate, at the Right time, and in the Right place (Roberts 2007). In the transition to a NT farming system, all these elements and their interactions need to be reconsidered.

5.2 Impacts of No-Till on Soil Fertility

Stratification is one of the main consequences of moving to a NT system as the lack of soil disturbance can mean that nutrients are no longer mixed through the "plough layer". Stratification can be both vertical, where the nutrients are concentrated in one or more of soil layers, or lateral, where the nutrients are concentrated in the bands where they were applied.

An important component of moving to a NT or CA system is to combine crop residue retention with NT. Crop residue retention impacts on nutrient dynamics, by modifying nitrogen mineralization and immobilization as well as protecting the soil surface from wind and water erosion so preserving topsoil where organic matter and mineral nutrients are present.

It would seem obvious, but the development of improved soil conditions that result from NT should be expressed in higher crop yields, but as Van der Putte et al. (2014) noted, this is not always achieved. Appropriate crop protection strategies, plant nutrient supply, well-adapted varieties, and management practices that balance these activities represent the other aspects of achieving yield potentials. Where this occurs, increased yields will also mean higher nutrient removals and so a higher input of nutrients from either mineral or organic sources will be required. Adjusting fertilizer rates is an important aspect of achieving the higher yield potential due conserved soil moisture and preserved topsoil fertility through erosion prevention.

5.2.1 Vertical Nutrient Stratification

In NT systems, the surface soil is not remixed with soil deeper in the profile and so while mobile nutrients like nitrogen (N) and sulfur (S) can leach into the subsoil, immobile nutrients like phosphorus (P) and potassium (K) can become enriched in the topsoil. (e.g. Cornish 1987; Alam et al. 2018).

The degree of vertical stratification observed in NT systems will vary with soil pH, P fixing or K retention capacity, soil texture (sand or clay), profile type (duplex or uniform), and rainfall (leaching potential). As a result, stratification is likely to be highest in highly buffered soils, with low hydraulic conductivity, and in low rainfall regions. In NT systems in winter rainfall areas of south-eastern Australia, for example, P is generally less stratified in NT soils than in semi-arid regions due to higher rainfall (Vu et al. 2009; Armstrong et al. 2015). In the sub-tropical summer dominant rainfall grain production regions of northern Australia, the P and K availability decreases markedly down the profile (Grundon et al. 1985) so that winter crops growing in that environment cannot access those nutrients in the dry topsoil.

The impact of nutrient stratification on crop yield will largely depend on the timing of water supply. In environments that experience rapid and frequent drying of the topsoil, crops will rely more on subsoil nutrients than crops grown when the nutrient enhanced topsoil is moist (Bell et al. 2015). In regions where stored water is less important, nutrients in the topsoil may still be available, a consequence of the surface soil remaining moist for most of the growing season (Alam et al. 2018).

Addressing vertical stratification in NT systems requires identification of the locations where nutrients are depleted and then placing nutrients in those locations to make them root accessible. Rather than a diffuse mixing of soil and fertilizer, placing the fertilizer in a band near the seed enables higher fertilizer rates, depending on species and the edaphic conditions. Ma et al. (2009) found that placing fertilizers deeper in the soil profile could increase nutrient acquisition and utilization by plants as fertilizer nutrients are in the moist soil for a longer part of the growing season. The coincidence of water and nutrients will largely affect the response to nutrients placement, and this in turn is a consequence of soil texture, fertilizing history, nutrient mobility, and crop species, as well as tillage practices (Ma et al. 2009).

In Mediterranean-type or temperate climates, a yield response of winter crops to deep fertilizer placement mostly occurs on infertile sandy soils in low rainfall regions (Ma et al. 2009). This contrasts with the responses of winter and summer crops in northern Australia on soils with optimum-to-high nutrients but subjected to rapid and frequent drying of topsoil because of high temperatures and high evaporation demand during the growing season (Singh et al. 2005). Banding of nutrients into the subsoil has been evaluated in those summer rainfall areas, where a blend of P and K is banded at about 0.25 m on rows 0.5 m apart (Bell et al. 2015). This results in significant soil disturbance in the year of application and the rate applied is aimed at supplying adequate nutrients for four to six crops, and then the field is returned to standard NT practises for around 5 years.

A consequence of vertical stratification is that a standard soil testing depth (0.1 m) may overestimate the supply of nutrients. Soil test calibration relies on a standard sampling depth to relate to crop responsiveness. However, the sampling depth may need to be reconsidered under NT systems for P (Bell et al. 2013), although Yin and Vyn (2003) indicated that soil test K levels are generally not affected under NT. Lester et al. (2016) suggested that soil samples be taken from the 0.1–0.3 m layer in addition to the 0–0.1 m layer, and tests used for both bicarbonate extractable P and K, as well as for the less available acid extractable P and the less available pools of K. Diagnostic criteria are being developed to better identify situations where crop responses may occur with deep placed nutrients.

5.2.2 *Banding Fertilizer*

Under traditional tillage practices, seed and fertilizer are placed together in the furrow and often mixed with soil. The fertilizers used are often low nutrient analysis types, such as single superphosphate, applied at relatively low rates that are balanced to meet the demands of relatively low yielding crops. Alternatively, fertilizers are broadcast over the soil surface and either incorporated by sowing or by rainfall. Deep subsurface placed ammonium fertilizers (e.g. MAP, DAP), urea, potassium, and solid or liquid manure are also used and are more effective at improving deep rooting, nutrient uptake, and yield compared to broadcast fertilizers (Nkebiwe et al. 2016).

To deal with higher stubble loads, the spacing of seeding rows has increased from 0.12–0.15 m to 0.25–0.30 m for small grains such as wheat and canola, and wider with crops such as corn and soybean (Scott et al. 2013). As seeding rows become wider, the concentration of the fertilizer in the seed row increases, and when combined with minimal soil disturbance with a NT furrow opener, can lead to fertilizer damage to the seed (e.g. Carter 1967; Mason 1971; Scott et al. 1987; Grant et al. 2010; Mooleki et al. 2010). Banding the fertilizer away from the seed row is now a common strategy and allows higher rates of fertilizer to be applied at seeding, as well as reducing the competitiveness of some weeds such as wild oat in barley (Donovan et al. 2008). Compared to surface applied nutrients, subsurface banded fertilizer applications can assist in reducing nutrient losses, even on flat fields (Yuan et al. 2018).

The response to deep banded nutrients varies among species (Rose et al. 2009a). The roots of wheat and canola, but not lupins, have been reported to proliferate around P bands, although root distribution away from the bands was the same. Banding of P at 0.17 m increased canola P uptake and seed yields in low P soils compared to shallow (0.02 m) placement of P (Rose et al. 2009b).

The distribution of soil moisture has an important effect on the response to deep placement, and when the topsoil is moist most P is taken from the topsoil, but in above average seasons P banded below the seed increased plant P uptake in lupins (Jarvis and Bolland 1990) and wheat (McBeath et al. 2012). Banding near the seed (0.02–0.05 m) enables root proliferation around those bands and enhances the access of the plants to fertilizer P, while moist soil conditions improve the plant access to diffuse P in the soil (Officer et al. 2009a), and a similar relationship occurs with K in corn and soybean (Bordoli and Mallarino 1998; Ebelhar and Varsa 2000; Borges and Mallarino 2003), although Borges and Mallarino (2003) note that stratification of K is less pronounced than P.

There is also evidence that having N and P together in the band can improve uptake of both nutrients for wheat (Officer et al. 2009a; McBeath et al. 2019), flax (Lafond et al. 2003) and maize (Ma et al. 2013). Similarly, Weligama et al. (2008) showed that the greatest shoot growth was achieved where N and P were applied together irrespective of depth. They explained this partly in terms of enhanced root proliferation around the P bands and increased rhizosphere pH, while Officer et al. (2009b) measured higher root length density generally, but not necessarily, in proximity to P bands. There was a substantially greater, but still generalized, increase in root length density in a Vertosol when both N and P fertilizer were applied, although there was no response to N fertilizer alone.

The position of bands relative to the seed rows is also important. Immobile nutrients such as P and K should be in close proximity to the developing seed (Yin and Vyn 2003), but not close enough to cause damage to the developing roots or shoots. There have been adaptations to seeding equipment to separate seed and fertilizer (Desboilles et al. 2019) using ‘double chute/shoot openers’. The placement of seed can either be in paired seed rows with fertilizer beneath and between the rows, or as single seed row with the fertilizer band below and to the side. The effectiveness of side-banding and separation of seed and fertilizer has been demonstrated in wheat and canola (e.g. Johnston et al. 2001). Part of the evolution of seeding equipment in NT farming systems has been the development of mechanisms to separate seed and fertilizer and the narrow furrows created by disc openers makes separation even more important.

An extension of side-banding is to place fertilizers between seeding rows, termed mid-row banding. Each fertilizer band serves two seeding rows, and this approach can be done either at seeding (Norton et al. 2003) or in-crop (Wallace et al. 2017). This applies particularly to nitrogen fertilizers, where nitrification is inhibited in the bands where soil solution ammonia concentrations exceed 3000 mg kg^{-1} and pH exceeds 8 (Wetselaar et al. 1972), or nitrate concentrations become high enough to inhibit root growth (Passioura and Wetselaar 1972). Banding provides a slow-release form of N to wheat crops, thereby reducing excessive seedling growth and the risks of haying-off (Angus et al. 2014). In a NT system, nitrogen sources such as urea, fluid urea-ammonium nitrate, or gaseous ammonia can be “knifed” in using a straight disc or a very narrow point (Kelley and Sweeney 2007; Angus et al. 2014), and precision applicator guidance enables accurate placement between seed rows for post-sowing applications (Wallace et al. 2017).

5.2.3 Lateral Nutrient Stratification

As sowing row width has become wider to cope with high stubble loads at seeding, and fertilizers are banded in rows, horizontal or lateral stratification of fertility bands can occur. The consequence of this stratification is that P and K concentrations are higher in the banded zones, and pH can lower (Duiker and Beegle 2006). As a consequence, a soil sampling strategy to take account of banded fertilizers is required, otherwise soil test data may over-estimate P and K availability and under-estimate lime requirement.

Fernández and Schaefer (2012) proposed that where precision guidance is used and the drill row position it known, a ratio of 1:3 in-row to between-row samples seemed adequate to estimate soil fertility across a wide range of P and K fertilizer rates and soil test levels. Kitchen et al. (1990) suggested that, in a situation where a residual P band was obvious, a ratio of 1:20, 1:16, and 1:8 in-row cores to between-row cores could be considered for 0.76, 0.61, and 0.30 m band spacing, respectively. However, in a situation where the location of the P bands was unknown, random sampling is the only alternative, although the greatest errors occur when samples are taken on the bands in NT systems (Bolland and Brennan 2006).

An additional issue with lateral nutrient stratification is the choice of whether to sow on or between the prior sowing rows. Because of enhanced concentration of immobile nutrients in the row, it is tempting to sow back on the same row. However, there is evidence that crown rot (*Fusarium pseudograminearum*) inoculum can be at higher levels in the drill row and can lead to higher levels of disease, particularly if there is very little disturbance in the row, such as when a disc furrow opener is used (Verrell et al. 2009).

5.2.4 Changes in N Dynamics

No-till systems with residue retention can affect N cycling. Crop residues reduce soil temperatures, slowing germination (Bruce et al. 2005), reducing the amount of soil evaporation (e.g. Lascano and Baumhardt 1996) as well as slowing mineralization. During crop residue decomposition, immobilization of N is common and so reduces the immediate availability of N. The amount of N immobilized will be affected by the carbon to nitrogen ratio of the residue. High C:N materials (e.g. cereal residue) will have a higher net immobilization than low C:N materials (e.g. legume residue) (Peoples et al. 2017). Field results suggest immobilization rates of 5–13 kg N ha^{-1} with 1 Mg ha^{-1} of wheat stubble (Mary et al. 1996). Where stubbles are burnt, about 90% of the N in the residue is lost (Angus et al. 2019).

The net effect of NT and residue retention is to increase the overall demand for N (e.g. Mason 1992; Newton 2001). Kirkegaard et al. (2018) estimated that surface retained stubble in modern NT systems can immobilize sufficient N to reduce crop yields by 0–0.5 Mg ha^{-1}.

Where crop residues are retained on the surface, higher rates of top-dressed N may be required (Malhi et al. 1996; Grant et al. 2001). This is likely a consequence of the increased concentration of urease enzymes on retained materials, although increased immobilization of the applied N could also contribute. Under reduced or NT systems, changing the N source and placement would be alternatives to increasing the rate to account for potential losses. For example, Grant et al. (2002) proposed that using spring banded ammonia produced higher canola yields than either urea or urea ammonium nitrate (UAN) under reduced tillage. Similarly, Malhi and Nyborg (1992) found that under reduced tillage, the grain yield and N accumulation of barley were less than broadcast urea under CT. Responses to deep placed or side banded N were similar between the two systems. Reconsidering the source, rate, time, and place of fertilizer use is therefore a critical part of the transition from conventional to NT systems.

5.3 Fertilizer Damage in No-Till Seeding Systems

The trends for wider seeding rows and the use of furrow openers that provide little soil mixing in NT systems means the concentration of fertilizer within the seed row is higher. Even at relatively low rates, seedling damage can occur and reduce yields. For example, compared to deep place DAP, 50 kg DAP ha^{-1} drilled with the seed using a knife point furrow opener at 0.28 m row spacing with wheat seed was enough to reduce wheat plant establishment by nearly 20% and yield from 3.94 Mg ha^{-1} to 3.44 Mg ha^{-1} (McBeath et al. 2016).

It is possible to separate the time of fertilizer application from the time of seeding by either pre-drilling fertilizer or applying fertilizer in-crop as either top-dressed granular forms, as a fluid fertilizer, or as either form mid-row banded. These options work well for mobile nutrients such as N and S, but both pre-crop and in-season P application are less successful. Volatilization of urea and UAN spread on the surface in-crop can also lead to N losses of 2–24% of N applied (Turner et al. 2012), with higher losses on bare soils, under warm conditions, and with little rain. In the presence of crop residues, there may also be increased ammonia volatilization compared to bare soil because of the presence of urease in plant residues (Goos 1985). Placing N at 0.075 m below the soil surface is reported to result in negligible ammonia losses from urea (Rochette et al. 2013).

The relationship between furrow opener disturbance and seeding row width can be summarized in terms of “seed bed utilization” (SBU), which is an index of the amount of soil disturbance with the furrow opener compared to the area sown. A low SBU typically makes a uniform seeding job easier, but increases the risk of fertilizer toxicity. Figure 5.1 gives some examples of the pattern of disturbance of a range of common tyned furrow openers, with a 0.125 m conventional share giving seed spread of around 0.065 m (5.1A), while a 0.03 m spearpoint giving about 0.025 m spread (5.1D). Then using these openers at 0.15 m spacing, the SBU for the conventional share would be 0.43, while for the spear point the SBU would be 0.17.

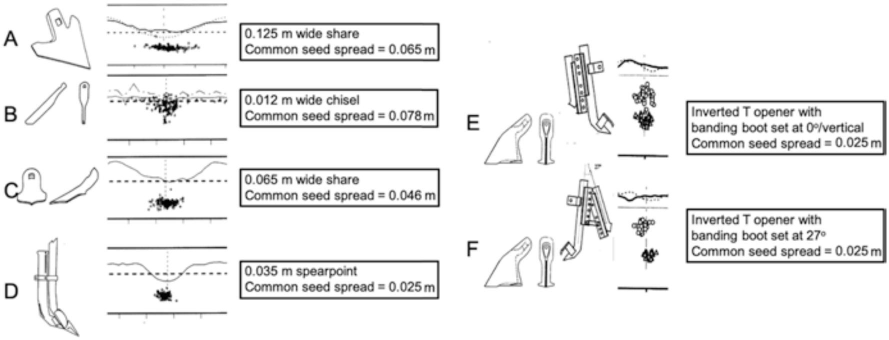

Fig. 5.1 Seed and fertilizer placement patterns with a range of tyned furrow openers. (Used with permission, University of South Australia)

While a low SBU means that the fertilizer is more concentrated in the seed row and so has a high potential for damage, other factors such as fertilizer type, soil texture, crop type, and soil moisture status also have effects, as discussed below.

The patterns of seed and fertilizer distribution shown in Fig. 5.1a to d have the propensity to cause seedling damage, and so the alternative strategies in Fig. 5.1e,f provide physical separation of the seed and fertilizer. In general, a distance of 0.025–0.035 m between the band of fertilizers and the seed is adequate to reduce seed damage (Grant et al. 2010).

5.3.1 *Fertilizer Type*

The two main aspects that contribute to fertilizer damage to seed are the osmotic or salt effect and the propensity of the fertilizer to produce ammonia (Carter 1967), although NH_4^+ toxicity has occurred at concentrations lower than can be explained by salt toxicity (Barker et al. 1970). There are also reports of fertilizer contaminants such as fluorine in single superphosphate leading to crop damage at high application rates (Loneragan et al. 1966). The acidity of fertilizers such as single superphosphate (Table 5.1) can also affect applied seed-surface inoculum of rhizobia in legumes.

Salt index (SI) is a measure of the salt concentration that a fertilizer induces in the soil solution. The SI is expressed as the ratio of the increase in osmotic pressure of the salt solution produced compared to the osmotic pressure of the same weight of $NaNO_3$, which is set as the reference value of 100 (Mortvedt 2001). High SI fertilizers can decrease seed germination and increase seedling injury. The SI does not predict the amount of damage, but does allow a comparison of different products. Table 5.1 gives the salt index of a range of fertilizers. In general fluid fertilizers, which are already in solution, give a lower osmotic pressure in the soil solution than granular products of a similar grade (Mortvedt 2001).

Table 5.1 The composition, approximate pH, salt index, water solubility and equivalent calcium carbonate (ECC) value per kg N of a range of fertilizers (IPNI 2011; Mortvedt 2001)

Fertilizer	%N	%P	%K	pH	Salt index per kg nutrient	H_2O solubility g L^{-1}	ECC kg $CaCO_3$ kg N^{-1}
Urea	46			~7	1.62	1080	3.6
Ammonium nitrate	34			~7	3.06	1900	3.6
Calcium nitrate	16			~6	4.19	1212	0
Ammonium sulfate	21			5–6	3.25	750	7.2
Potassium nitrate	13			7–10	1.22	316	0
Urea/ammonium nitrate	~30			~7	2.24	Fluid	3.6
Ammonium polyphosphate	10	15		~6	0.46	Fluid	3.6
Monoammonium phosphate	11	20		4.3	0.46	370	7.2
Diammonium phosphate	18	20		7–8	0.41	588	5.4
Triple superphosphate		22		1–3	0.22	–	–
Single superphosphate	9			<2	0.39	–	–
Potassium chloride			50	~7	1.93	344	–
Potassium sulfate			42	~7	0.85	120	–
Potassium thiosulfate			20	7–8	2.72	Fluid	–

Fertilizers containing ammonium (eg MAP, DAP, ammonium nitrate or sulphate), or which produce ammonium can damage seed germination and seedling development through the production of ammonia (NH_3) (Källqvist and Svenson 2003; Haden et al. 2011. Partial inhibition of germination occurred with low (<0.01 N) concentrations of ammonium salts (Barker et al. 1970). Ammonium can cause toxicity effects, but is adsorbed onto the cation exchange and is converted to ammonia, such that ammonium toxicity is an unusual event in the field. When corrected for N concentration, there are only small differences among N sources in terms of ammonia toxicity (Gelderman 2008), although Dowling (1998) and Moody et al. (1995) had contradictory evidence on the differences between DAP and MAP damage potentials.

Urea is most often the cheapest N source, and the use of enhanced efficiency products have been evaluated to improve its in-furrow safety. Treatments of in-furrow N fertilizers such as N-(n-butyl) thiophosphoric triamide (NBPT) (Grant et al. 2010), polymer coating (Mahli and Lemke 2013) and sulfur coated urea (Severson and Mahler 1988) have been shown to improve emergence in a range of crops compared to untreated urea, although damage is moderated by soil moisture conditions. Treatment of urea with these materials may enable increased in-furrow rates to be used depending on crop and SBU (Karamanos et al. 2004).

5.3.2 Crop Type, Soil Texture, and Soil Moisture

Tap-rooted species (canola, faba bean) are more susceptible to ammonium/ammonia bands that wheat, which avoid the toxic bands (Pan et al. 2016). In general, large seeded species are more tolerant to fertilizer toxicity than small seeded species, and seed with a thick testa are likely to be more tolerant than seeds with a thin testa. Canola is probably the most sensitive to fertilizer damage of the common crop species.

Soil moisture and soil texture also have effects on osmotic potential and ammonia retention, so that consideration of these factors with crop, fertilizer, SBU, and soil conditions is required to determine damage potential (Karamanos et al. 2008). Gelderman (2007) undertook as series of controlled environment assessments with a range of crops, soil textures, soil moisture contents and fertilizers to develop a comprehensive set of linear regression coefficients for in-furrow fertilizer rates and crop stand. These data were developed into a spreadsheet calculator and later into a web-based decision support tool (https://seed-damage-calculator.herokuapp.com) to assist with risk assessment under a wide range of conditions. This tool has been widely used by growers and agronomists, although it is relatively conservative in its recommendations because a linear, rather than a plateau, function is used to estimate crop damage. A summary of some of the recommendations derived from this decision support tool is shown in Table 5.2. These data are in general agreement with commercial sources of information such as Laycock (2019).

Table 5.2 Approximate safe rates of N as urea (kg N ha^{-1}) with the seed of canola and wheat for different soil textures and soil moisture status, with 10% acceptable stand loss using the web based seed damage calculator tool (https://seed-damage-calculator.herokuapp.com) as derived from (Gelderman 2007, 2008)

	0.02 m seed spread		0.05 m seed spread		0.10 m seed spread	
	Row spacing (m)		Row spacing (m)		Row spacing (m)	
	0.15	0.31	0.15	0.31	0.15	0.31
	SBU	SBU	SBU	SBU	SBU	SBU
Crop type & soil texture	14%	8%	29%	17%	57%	33%
Canola seed	Moist seedbed conditions (kg N ha^{-1})					
Coarse (sand)	3	1	8	4	16	8
Fine (clay)	6	3	15	8	64	34
Canola seed	Dry seedbed conditions (kg N ha^{-1})					
Coarse (sand)	2	1	5	2	10	5
Fine (clay)	3	2	8	4	15	8
Wheat seed	Moist seedbed conditions (kg N ha^{-1})					
Coarse (sand)	10	5	24	12	48	23
Fine (clay)	19	9	48	23	96	46
Wheat seed	Dry seedbed conditions (kg N ha^{-1})					
Coarse (sand)	6	3	14	7	29	14
Fine (clay)	10	5	24	12	48	23

5.3.3 Machinery Configuration

Desboilles et al. (2019) summarized the development of seeding machinery in Australia used in NT systems. Modern seeders have no tillage tynes, narrow furrow openers, wide seed-row spacing, press wheels, high underframe clearance, and the ability to separate seed and fertilizer. There has also been a move towards disc seeders, which are able to operate at higher speeds than tyned openers because of the high soil throw with the latter (Desbiolles and Saunders 2006). Disc openers also tend to more expensive than tynes openers with complex designs and poor penetration into hard soils (Barr et al. 2016). New types of furrow openers that can operate at high speed but with little soil throw are being developed (Desboilles et al. 2019).

Mid-row or inter-row banding can be used with adaptations to existing equipment, which enables separation of seed and nitrogen fertilizers in different rows. Mid-row banding can be successfully deployed in-crop given precise equipment guidance using either tyned or disc openers (Wallace et al. 2017). Another option for in-crop application of fluid fertilizers such as UAN is the use of a point injection applicator, which enable fertilizer placement in the root zone with little soil disturbance and also no need for rain to wash it into the root zone (Baker et al. 1989; Schlegek et al. 2003).

5.4 Liming in No-Till Systems

Acidification rates under NT systems can be higher than CT (Blevins et al. 1978; Conyers et al. 2003), possibly a consequence of less soil mixing, higher productivity, and higher rates of nitrogen use. The standard practice for addressing acidity is the use of lime (Moore et al. 1998; Conyers et al. 2003). Under CT, lime is placed at the surface of the profile and 2–3 Mg ha^{-1} worked into the topsoil between crops. Obviously under NT, mechanical incorporation is not undertaken, and the mixing of lime into the soil is contingent on the leaching of lime down the profile. This movement is a function of the soil texture and the amount of rainfall, but is often less than 0.075 m (Godsey et al. 2007).

Subsoil acidification occurs as a consequence of many processes, including acidification by deep rooted legumes (Loss et al. 1993) and nitrate leaching beyond the root zone (Tang et al. 2000). Acidification at depth is less amenable to amelioration with lime, particularly on clay or loam texture soils, due to its low leaching rate (Conyers and Scott 1989). Surface application of gypsum has been shown to reduce Al toxicity through the formation of a soluble Al sulfate complex (Pavan and Bingham 1982). Because gypsum is more soluble than lime, it will move much more readily into the subsoil and it has been found that the surface application of phosphogypsum reduced the level of exchangeable Al and improved crop performance in a NT corn system (Caires et al. 2011).

Applications of organic materials on the surface has also been shown to ameliorate subsoil acidity in leaching columns based on the hypothesis that organic molecules assist the downward movement of Ca, which in turn react with Al in the subsoil so reducing Al toxicity (Hue and Licudine 1999).

Direct placement of lime into the subsoil has been evaluated with mixed success, with little responses in some regions with loam soils (Swan et al. 2011; Li and Burns 2016) but a favorable response on deep sands with acidic subsoils (Gazey and Davies 2009). Lime can be injected through tubes behind ripping tynes (Li and Burns 2016) although the equipment is both expensive and complex. Kirchhof et al. (1995) developed equipment that could place lime into the subsoil via a slot 0.15 m wide and up to 0.8 m deep, where the soil was excavated, mixed with 20 Mg ha^{-1} of lime and then returned to the slot. While effective, the cost both of the lime and the specialized equipment has meant this option has not been pursued commercially (Davies et al. 2019).

Given the difficulty of moving lime into the soil either mechanically or by leaching, consideration has been given to the use of periodic or strategic tillage to mix lime and soil in otherwise NT systems (Dang et al. 2017; Conyers et al. 2019). It has been recognized that more aggressive tillage, such as the use of disc ploughs rather than tyned implements, gives better lime incorporation (Scott and Coombes 2006). More aggressive tillage options such as deep spading and mouldboard ploughing have also been reported to reduce the impact of acidity on deep sands (Davies et al. 2015). The review of these approaches by Dang et al. (2017) notes that while effective at achieving the amelioration of subsoil acidity, there is a need for better diagnostic criteria to incorporate strategic tillage into what would be considered a NT system without compromising the economic and environmental imperatives behind NT farming.

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Chapter 6
Selecting and Managing No-Till Planters and Controlled Traffic Farming in Extensive Grain Production Systems

J. Ross Murray, Jeff N. Tullberg, and Diogenes L. Antille

Abstract No-till (NT) adoption has occurred in parallel with the development of equipment that can effectively plant large areas of unprepared, residue-protected soil within a limited period when conditions are favorable. This chapter covers the functional requirements, major components and characteristics of NT planters (or seeders), noting the major classifications and their possible impacts on crop establishment. Soil and residue conditions are difficult to specify and highly variable, so predicting machine performance is challenging. Controlled traffic farming, which is often used in conjunction with NT, can facilitate planting by improving soil conditions and reducing machine-scale variability. It also reduces cropping energy requirements and improves trafficability and timeliness by restricting all heavy wheels to permanent traffic lanes. Infiltration, available water capacity, and soil biological activity all improve substantially in non-wheeled crop areas, while runoff, nutrient loss, denitrification, and soil emissions are reduced by controlled traffic farming.

Keywords No tillage · Planter classification · Planter types · Planter selection · Field traffic · Compaction · Trafficability · Timeliness · Soil biota · Controlled traffic

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6.1 No-Till Planters[1] – An Introduction

Planting is probably the most critical operation in current crop production systems. Crop yield, cropping reliability, cropping frequency, and crop returns all depend on the uniform and timely establishment of optimum plant stands in terms of both plant population and plant spacing. Establishment is also one of the most critical and vulnerable stages in crop development (Finch-Savage and Bassel 2016; Gommers and Monte 2018). It is estimated, for example, that up to 60% of the final yield potential for a wheat crop is determined at time of seeding (Thomason 2004).

There are two broad requirements for optimizing plant establishment in no-till (NT) cropping systems. First, plant breeders, seed growers, seed merchants, and research agronomists etc., have a responsibility to provide:

- Appropriate crop types, varieties, and high-quality seed; and
- Regional guidelines for varietal selection and recommendations on establishment factors such as time of planting, planting depth, established plant populations, seeding patterns, and recommended seed treatments etc.

These requirements appear largely met for the Australian grain industry, and the grains industries in many other developed regions, via “grower friendly and accessible” reports and recommendations arising from ongoing regional research and investigations (e.g. GRDC Grownotes™ Agronomy, Technical Manuals, and Alerts, etc). However, in other regions, particularly countries where NT is a relatively new technology and/or where research, development, and extension capabilities are low, poor guidance for farmers can be the norm.

The second requirement is for farm managers and machinery operators to be aware of the agronomic requirements for optimum crop establishment and the ability of planting/seeding machine types, and/or configurations, to meet these requirements over a range of soil types and cropping systems. This crop and machine information has to be interpreted in a meaningful way so as assist in:

- Developing and implementing year-round crop and land management strategies to optimize soil and crop residue conditions, for both crop establishment and planter operation, immediately prior to planting; and
- The selection, setting, and management of seeders and their components to maximize crop establishment at time of planting

While the agronomic requirements for crop establishment are well known, the relationships between soil conditions, residue conditions, management strategies, and planter attributes on crop establishment are not well understood, particularly in NT production systems. Progression through each stage of system transition from bare fallow, through reduced and minimum, to NT systems required parallel ‘enabling’ developments in both planter design and crop management strategies. These parallel developments, resulting largely from the incremental reductions in

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[1] The terms “Planter” and “Seeder” are used interchangeably here.

mechanical disturbance of soil and residue over the past 50 years, have given rise to current NT management strategies and planting machinery. Nevertheless, challenges remain, largely because:

- NT cropping systems are location-specific;
- There appears little clarity around the selection of planter type for particular cropping systems;
- Observed differences in planter performance are not necessarily attributed to design parameters (Breust and Vague 2016);
- Caution is required when considering the transferability of "take-home" messages from location-specific planter trials/investigations; and
- Information derived from investigating/reviewing the performance of specific planter components, independent of other machine and cropping system variables, can only be used to inform, rather than implement, change.

In this paper, the major components influencing NT planter performance are identified and the implications of their interdependent relationship on modern planters discussed. No-till/zero-till planters are then classified and their broad capability/suitability to particular NT cropping systems assessed on the basis of the furrow opener and seed placement components. This information is then used to inform a discussion on the selection and management of NT planting equipment.

6.2 No-Till Planter Components and Requirements

The major function of a planter is to facilitate crop establishment. In biological terms, crop establishment is the sequence of events that includes seed germination, seedling emergence, and seedling growth to the stage where seedlings could be expected to grow to maturity i.e. attain photosynthetic competence.

For a given seed lot, and in the absence of rainfall over the establishment period, establishment potential is primarily dependent upon the root-bed, seed-bed, and soil-surface conditions immediately prior to planting (Wood 1987). At time of sowing, the planting machine interacts with these pre-existing conditions to effect seed placement within the seed bed. Concurrently it determines the seeding rate, seeding pattern, depth of planting and, to a large extent, the resultant seed-placement environment. The degree to which the pre-existing conditions for establishment are enhanced or compromised by this machine interaction, can be seen as a fundamental test of planter performance.

To meet the collective requirements for all stages of crop establishment a contemporary planting machine is typically required to perform the following functions: (1) open a furrow; (2) meter and deliver the seed; (3) place the seed in the furrow; (4) firm the seed in the furrow; (5) cover the seed; (6) firm the seedbed and (7) perform other specific functions as required, e.g. apply fertiliser. In NT cropping systems the list of other functions to be performed by the planter is increasing. Examples include: the increased need to micromanage surface soil and residue to facilitate the use of pre-emergent herbicides; diversification of in row configurations to improve seedbed utilization; and increasing seed and fertiliser placement options to allow for higher rates of fertiliser application.

To be cost effective, these functions need to be performed at an acceptable forward speed, over the range of soil and soil surface conditions likely to exist at time of planting, with a high degree of reliability and durability, and, ideally, for the full range of crop types to be grown. Planting machines are therefore an assemblage of components, each designed to meet a particular function(s).

While operational differences exist, there is currently a high degree of commonality in the seed/fertiliser metering-and-delivery components on planters used in extensive NT grain production systems. Commonality arises from the distinct advantages of pneumatic seed- and-fertiliser delivery systems. These systems typically have: centralized commodity bins (for the seed and a range of crop chemicals); seed and fertiliser metering/blending systems; and a pneumatic delivery system to further divide and convey the metered products to each of the individual row placement devices across the full width of the planting machine.

Notwithstanding the importance of the seed/fertiliser metering and delivery components, it is the soil engaging components that open the furrow, place the seed, cover the seed and firm the seedbed that characterize NT planters, and determine their suitability for, and performance in, particular cropping systems. To enhance the performance of these soil engaging components, and furrow openers in particular, an additional range of soil/residue cutting and row preparation components are usually available for use on NT planters, if and when required. The typical type and sequencing of all these soil engaging components for NT planters is depicted in Fig. 6.1.

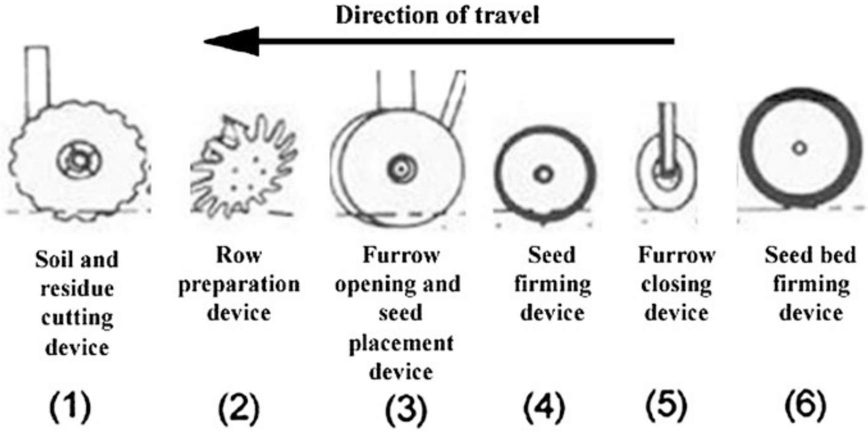


Fig. 6.1 The typical type and sequencing of soil engaging components for NT planters

Base unit of a single disc coulter type no till planter

Base unit ot a simple tine type no till planter

Base unit of a hybrid disc/tine type no till planter

Fig. 6.2 Examples of integral base units for disc-coulter, tine, and hybrid type NT planters

Some NT planters are not designed to accommodate all these devices and some devices can perform multiple functions, e.g. disc coulter type furrow openers perform a soil and residue cutting function. Nevertheless, inclusion and independence of function typically infers greater functional and operational flexibility. The role, and functional and operational requirements, of these major soil engaging components have been documented (e.g. Murray et al. 2006; Baker et al. 2007) and many types of these components have had their capability evaluated and/or reviewed (e.g. Desbiolles 2011; Sawant et al. 2016; Solhjou et al. 2011; Kleemann et al. 2013, 2015; Zhang et al. 2017a, b; Aikins et al. 2018, 2019).

In practice, device flexibility is significantly reduced by planter design constraints. On most NT planters the furrow opener, seed placement, seed firming (if available), seed covering, and seedbed firming devices are assembled in a fixed and highly-interdependently way, to form a single base unit. The base unit is manufacturer specific and virtually dictates: the type of furrow opener and associated seed/fertiliser placement options; the means of achieving furrow opener depth control; and the method of attaching the unit to the planter mainframe or seeding bar etc., as shown in Fig. 6.2.

Typically, there is no provision to change the type of furrow opener; but varying degrees of flexibility in seed placement, seed covering, seed firming, and seedbed firming devices are usually offered by way of interchangeable, base-unit compatible options supplied by the manufacturer or by retro-fit suppliers. Nevertheless, it is this integrated assemblage of particular components in the base unit that dictate the limits of a planting machines functionality, suitability, capability, and overall performance in a given cropping system. Adding planter compatible soil-and-residue cutting and row-preparation devices, if available, simply assist in modifying these limits. Matching the functional capability of the planter, as determined by the particular base unit components, to defined cropping system requirements, is therefore the most rational basis for selecting the type of planter to be used.

The importance of the furrow opener type and its associated seed placement device on crop establishment cannot be over-stressed. It is of fundamental significance to both planter selection and the management of NT cropping systems, as briefly outlined below.

6.3 The Classification and Broad Capability Assessment of Planters Based on Furrow-Opener Type and Associated Seed Placement Options

Irrespective of other soil engaging components, current NT planters can be broadly classified as disc (i.e. disc-coulter), tine, or disc/tine hybrid type planters based on the general type of the furrow opener used (Fig. 6.3). The particular type of opener used can be used to provide sub-classifications. Disc type NT planters can be typically sub-classified as single, double or triple disc types (Fig. 6.4) and tine type NT planters as point, knife, or inverted "T" types (Fig. 6.5). Because of the limited range and availability of hybrid disc/tine types, they are usually classified or referred to by the name coined by the manufacturer (Fig. 6.6).

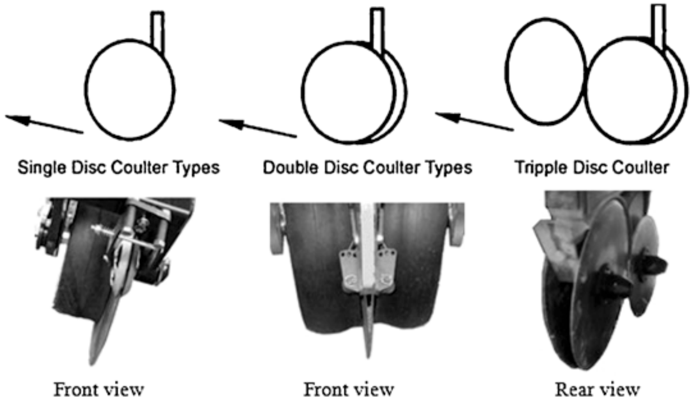
Quite accurate predictions about the general suitability of planters for particular cropping systems can be made from this level of opener-type classification based on an understanding of the mode of action used to create the furrow, and the characteristics of the resultant furrow shape. In general, with respect to opener mode of action:

Disc coulter type no-till planting unit

Tine type no-till planting unit

Hybrid (disc/tine) type no-till planting unit

Fig. 6.3 Examples of disc, tine, and hybrid type planting units



Single Disc Coulter Types

Double Disc Coulter Types

Tripple Disc Coulter

Front view

Front view

Rear view

Fig. 6.4 Examples of single, double disc and triple disc openers used on NT planters

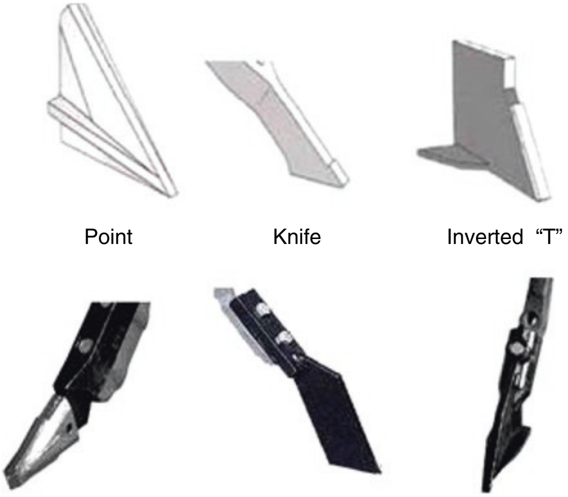
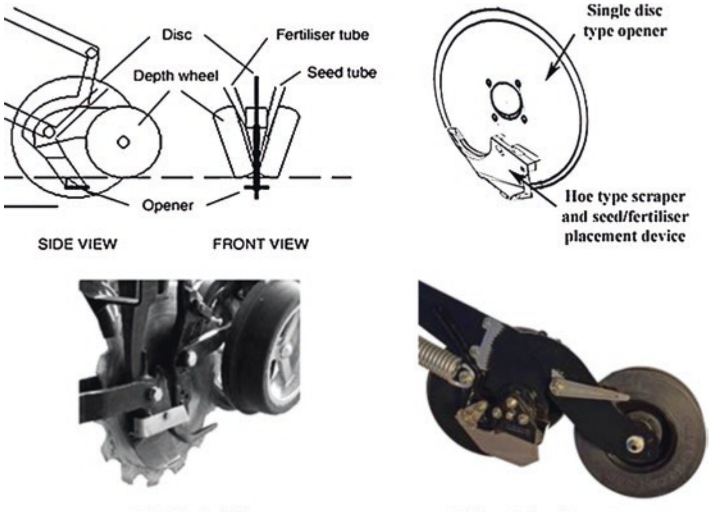


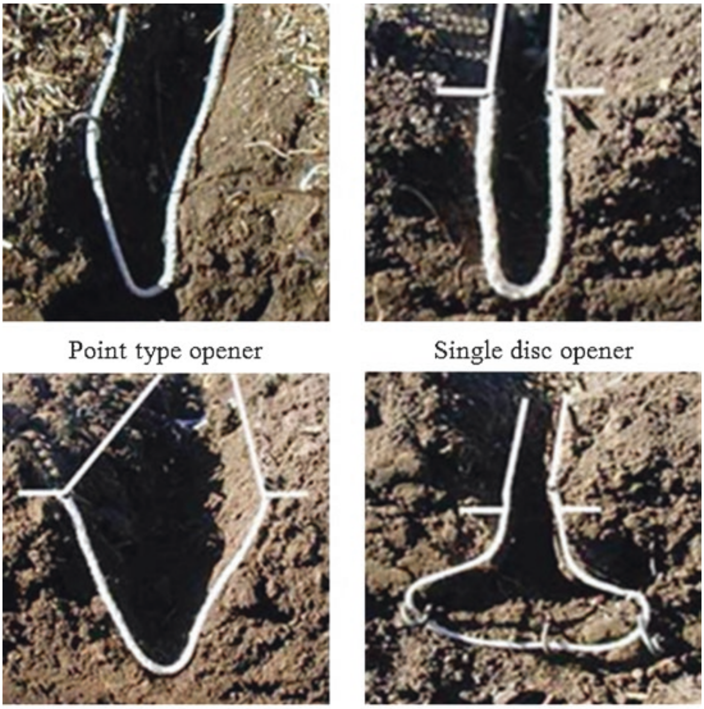
Fig. 6.5 Examples of point, knife and inverted "T" type tine openers



Bioblade™ Pillar Disc/Hoe Opener

Fig. 6.6 Examples of hybrid disc/tine type furrow openers used on NT planters

- Most tine-type NT furrow openers tend to open the furrow by displacing soil upwards and outwards on both sides to create a furrow (i.e. 'dig a furrow')
- Most NT disc-coulter type furrow openers either cut and displace soil upwards and to one side to create a furrow (i.e. 'cut and dig a furrow') or cut and displace soil downwards and sideways to create an open furrow (i.e. 'cut and press a furrow'), depending on the particular type employed;



Point type opener

Single disc opener

Double disc opener

Hybrid (Bioblade ™) opener

Fig. 6.7 Examples furrow shapes produced by different openers

- NT hybrid type openers tend to cut and lift soil to create an inverted furrow in the form of an inverted-‘T’ or ‘L’ shape; the soil essentially falling back into place after seed placement (i.e. cut and lift to form an inverted furrow).

Examples of the general shape of furrows resulting from the use of point, single angle disc, double disc, and hybrid type openers are shown in Fig. 6.7. Numerous researchers have made detailed assessments on both: opener type and setting effects on furrow shape (e.g. Rainbow 2000); and furrow shape effects on crop establishment prospects (e.g. Baker et al. 2007). For example, under soft soil conditions a double disc opener forms a ‘V’ shaped furrow with a firm base. This typically provides for good seed placement and facilitates seed covering and seedbed firming. However, operating under hard soil conditions with this type of opener typically results in a shallow ‘V’ furrow with a compacted base and side walls. This compaction reduces the ease of seed covering and may impede or restrict seedling root growth.

With narrow tine-type openers, increasing forward speed usually increases soil disturbance, displacement and moisture loss, producing a wider ‘U’ shaped furrow with reduced soil cover. Measures to increase cover often move both dry and wet soil into the seed zone, which can impede the rate and duration of moisture available

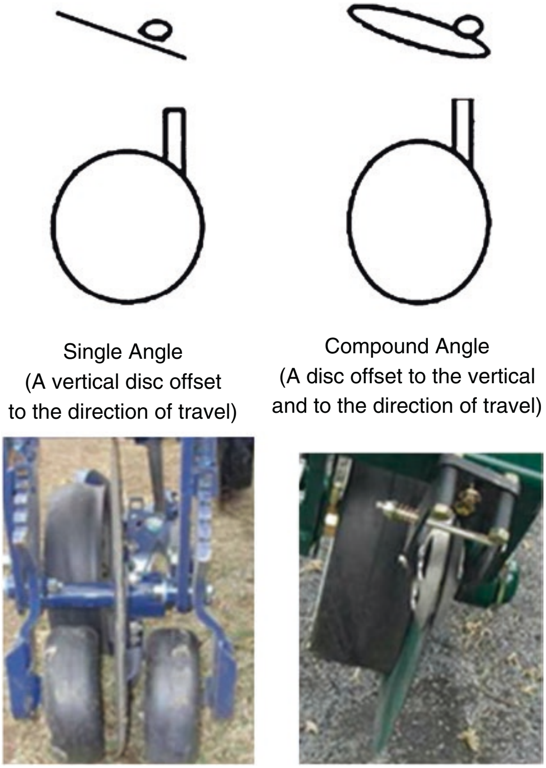


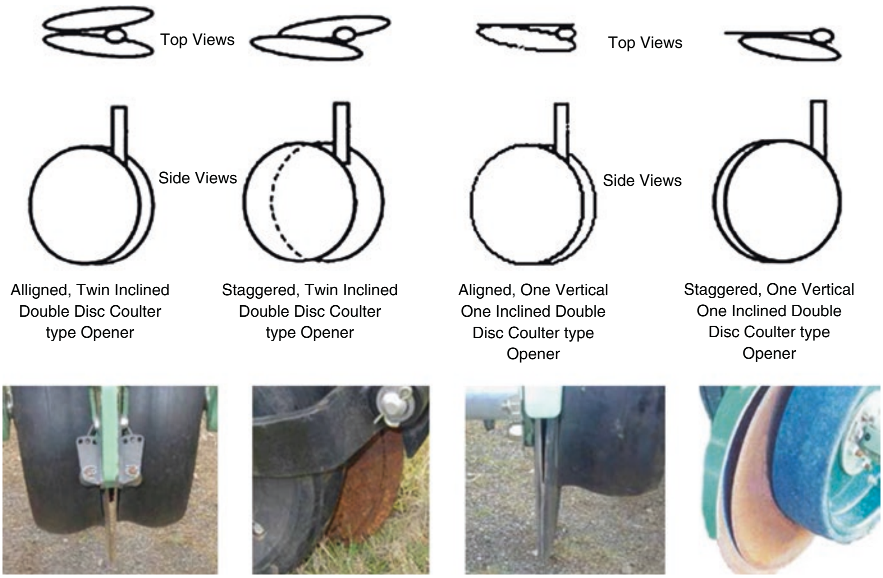
Fig. 6.8 Examples of single disc coulter type openers

to the seed. Placing seed in an inverted ‘T’ shaped furrow may improve establishment prospects as a result of less seedbed disturbance and moisture loss.

Wider tine type openers create more soil displacement and typically result in a deeper wider furrow after seed placement. Under marginal soil moisture conditions, water concentration in these furrows from ‘light’ rainfall events may make the difference between crop-establishment and crop-failure. Under higher rainfall events water concentration in the furrows may lead to crop failure due to waterlogging in the seed zone.

While differences do exist, caution should be exercised when making inferences about opener advantages and disadvantages on the basis of further sub-classification. For example, most single disc openers on NT planters may be classified as single angle or compound angle types (Fig. 6.8) and most double disc openers as twin-inclined or as one-vertical-and-one-inclined types; both with aligned or staggered variants (Fig. 6.9). Point type openers, for example, may be winged or wingless (Fig. 6.10). It would require an experienced and reflective practitioner to make meaningful performance assessments from possible further sub-classification within each type of opener for known soil conditions.

Placing seed and fertiliser at time of planting is typically achieved by using the planter’s existing furrow opener. In NT systems, adding additional dedicated-fertiliser-openers should be avoided, where possible, because of the resultant



Alligned, Twin Inclined Double Disc Coulter type Opener

Staggered, Twin Inclined Double Disc Coulter type Opener

Aligned, One Vertical One Inclined Double Disc Coulter type Opener

Staggered, One Vertical One Inclined Double Disc Coulter type Opener

Fig. 6.9 Examples of double disc coulter type furrow openers

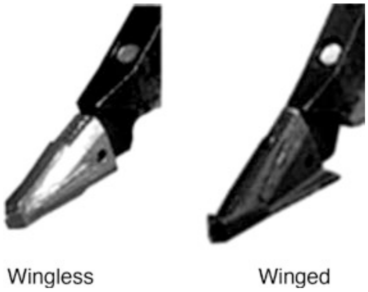


Fig. 6.10 Examples of winged and wingless tine points

increase in soil and residue disturbance, machine cost, machine mass, and the reduction in row spacing flexibility. Recent research in NT cropping systems has identified the benefits to be gained from diversification in both seed and fertiliser placement. The ability to place seed in a wider (ribbon) or twin row in addition to the traditional narrow row configuration (Fig. 6.11) assists with improving seedbed utilization. Banding of fertiliser (Fig. 6.12) allows for higher and more flexible fertiliser application rates without seed damage due to osmotic or ammonia toxicity.

Disc type opener placement devices are typically restricted to narrow or ribbon placement of seed, or blended seed and fertiliser (i.e. single shooting with or without blending). Hybrid type openers typically allow for single side banding of fertiliser in addition to seed, or blended seed and fertiliser placement (i.e. double shooting with or without blending). Tine type openers provide for a much more diversified range of placement options achieved by way of specialized furrow opener designs or furrow opener attachments. Figures 6.13, 6.14 and 6.15 show some seed and fertiliser placement options from a specialized tine opener with optional attachments.

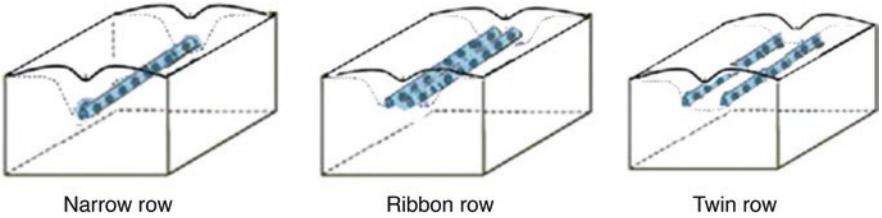


Fig. 6.11 Examples of seed, or blended seed and fertiliser, row configurations

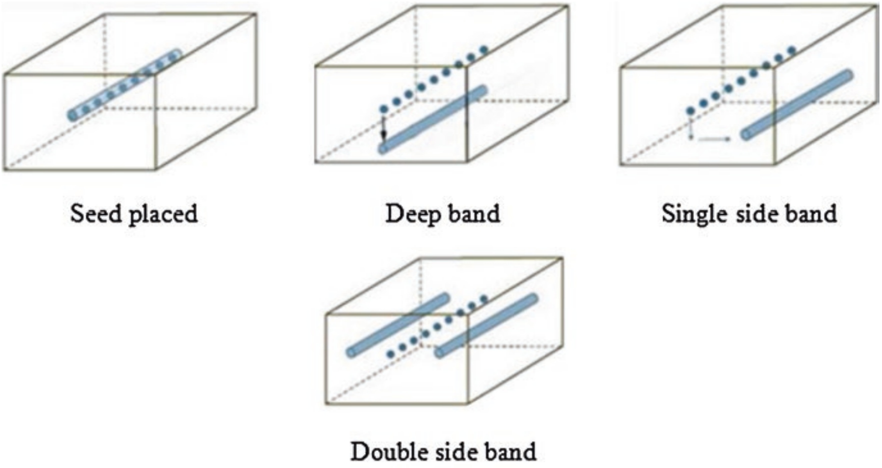


Fig. 6.12 Examples of solid fertiliser placement at time of planting

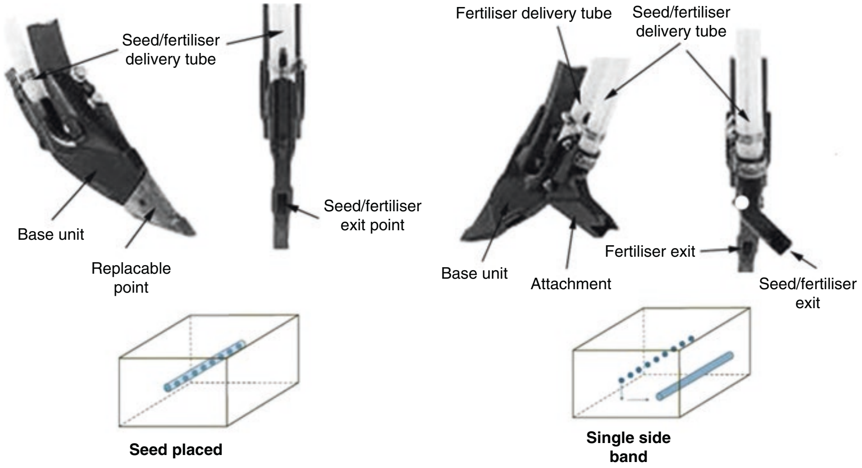


Fig. 6.13 Specialized tine type furrow opener with options to seed place or single sideband fertilizers

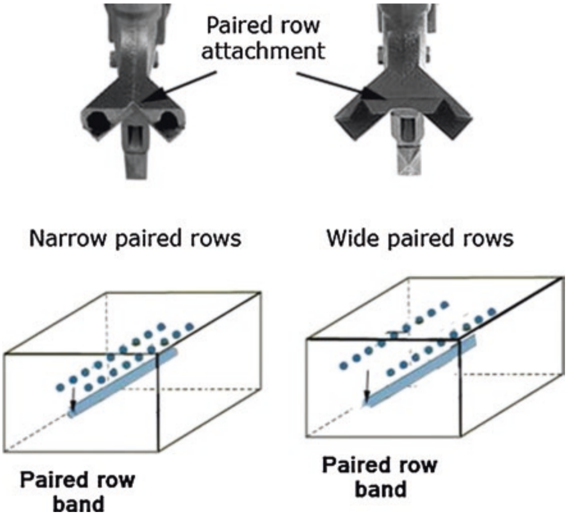


Fig. 6.14 Specialized tine type furrow opener with options to pair row seed and deep band fertilizer

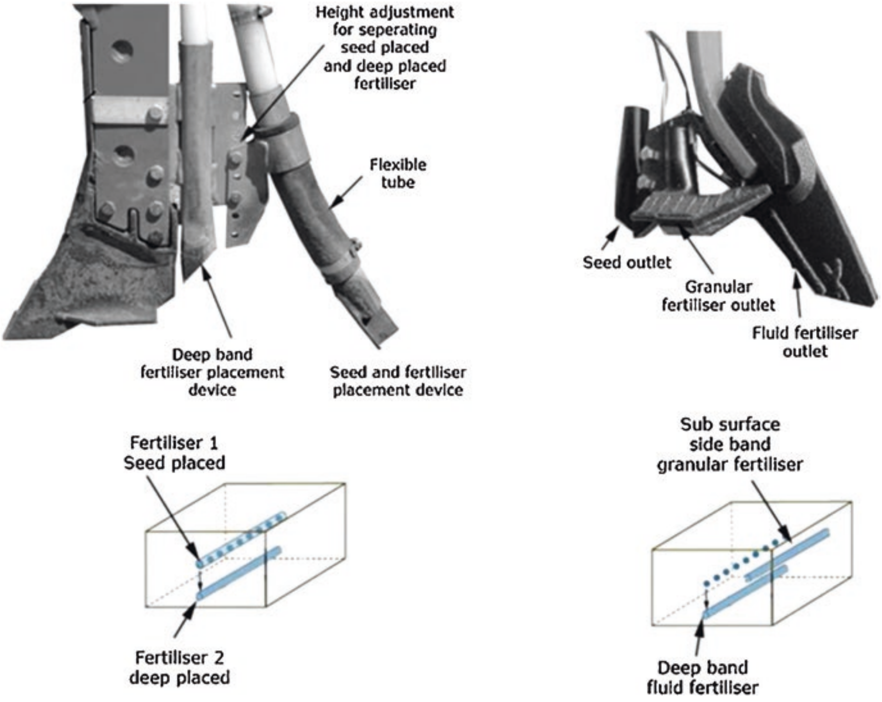


Fig. 6.15 Examples of placement options resulting from attachments to tine type furrow openers

A summary of the general advantages and disadvantages of planting machines, as inferred by the furrow opener type and associated seed and fertiliser placement options, is given below.

6.3.1 Disc Type Openers

Disc openers are less suited to hard conditions because of the weight requirement for penetration, and they also tend to "hairpin" rather than cut residues in soft or wet soil conditions. In cohesive soil types with higher moisture contents, disc operation is also impaired by soil adhesion to the discs and lower disc rotational speed. Larger discs tend to perform better than smaller diameter discs, but require more weight for penetration. While disc openers have a limited range of seed and fertiliser placement options, they may provide for improved seed placement; particularly in the case of double disc types.

Compared to double discs, single discs openers could be expected to operate over a wider range of soil type and conditions, under higher levels of surface residue, incorporate less residue into the seed seedbed, and create less overall disturbance to the seedbed. Within double disc types, those with staggered or one-vertical-and-one inclined discs have greater residue cutting and soil penetration ability.

6.3.2 Tine Type Openers

Tine type openers can work successfully over a wide range of soil type and conditions, require little weight for penetration, do not hair-pin residues, and have high flexibility in design options. The width, rake angle, depth, and speed of operation influence overall seedbed disturbance. Compared to wider openers, narrow openers operating at lower speeds could be expected to result in: lower seedbed disturbance and moisture loss; have less effect on the final soil-surface profile; reduced interference with adjacent openers; and have a lower draft requirement for the same depth and speed of operation. In the absence of a residue cutting disc, tine type openers are prone to blockage under higher levels of surface residue; with the extent of blockage dependent on factors such as the underframe clearance, shank shape, and the retrofitting of stubble tubes/guards. A wide range of seed and fertiliser placement options are available for tine type openers, which offer flexibility to disturb soil below the depth of seed placement, when required.

6.3.3 Single Disc v Tine Type Openers

Compared to single discs openers, tine type openers:

- Are cheaper to purchase and operate, less complicated, and easier to adjust;
- Require less weight for penetration;
- Can operate successfully over a wider range of soil types and conditions and incorporate less residue in the seed bed;
- Have far greater flexibility in design, interchangeability of other soil engaging components, and in seed and fertiliser placement options;
- Tend to create more seed bed disturbance and more soil and residue throw from the furrow; particularly so in the absence of a soil and residue cutting device;
- Are better suited to lower levels of surface residue and forward speed;
- Are better able to plant to moisture and manipulate depth of cover when deep planting; and
- Generally allow for greater crop safety when using pre-emergent herbicides

6.3.4 Hybrid Type Openers

Compared with other openers, the hybrid opener may result in lower levels of seedbed disturbance, lower levels of soil moisture loss, and reduced problems associated with backfilling furrows. However, there is little flexibility in design and componentry options, and their action is more akin to that of discs, rather than tine type openers.

System interactions may also reduce predicted performance. For example:

- Advantages gained from the ability of disc type openers to operate at higher speed may be offset by delays in planting as a result of their inability to effectively manage residue under higher soil moisture conditions at time of planting;
- The increased disturbance resulting from the addition of 'aggressive' row preparation devices to facilitate opener operation may negate some of the claimed benefits of moving from tine opener NT to disc opener NT.
- Maximizing residue retention and minimizing soil disturbance may not necessarily optimize crop establishment prospects or cropping profitability.

Planting machines based around single disc and hybrid type furrow openers have been on the market for in excess of 20 years. A detailed analysis of the advantages and disadvantages inferred by the opener type and associated placement options may go some way to explaining the current mix of planting machine types used in NT cropping systems, which are predominantly tine, far less disc, and a few hybrid types (Insightrix 2014; Kondinin 2015).

6.3.5 The Selection and Management of No-Till Planters

A major focus of crop and land management strategies in NT crop production systems is to ensure the seedbed and surface residue conditions at time of planting are matched to the functional and operational capacity of the existing planting machine. It is typically a cyclic process as growers transition towards a further reduction in the mechanical disturbance of both soil and residue to optimize NT system benefits. The typical process is as follows:

- Crop and land management strategies are initially focused on exploiting the performance capacity/capability of the existing planting machine;
- The existing planter and/or management strategies are modified to further facilitate the transition to less mechanical disturbance;
- When the current machines performance capacity/capability limits further transition it is replaced by a machine with improved performance capacity/capability; and
- The process is repeated.

Being able to identify current and future cropping system requirements and use this to inform planter replacement would allow for ongoing cropping system development and a reduction in the frequency of planter replacement.

While no single recipe for planter selection exists, there is often substantial information available to facilitate planter operation. For example, on how to manage soil, crops, and crop residues on a year-round basis to optimize seedbed conditions for establishment and minimize variability to assist planter operation and settings.

A study of sowing equipment and stubble management conducted by Insightrix in 2014 on behalf of four grower groups in Victoria, Australia showed that of the 330 farmers surveyed, 89% used or owned a tine type planter and 15% used or owned a disc type planter. Over the 7 year period, 2008–2014, the purchase of tine type planters exceeded that of disc type planters by a ratio of 3:1.

The six most important reasons for using a tine type were: best fit/reliable/convenient; satisfied with the results/prefer over disc; versatile/works in all soil conditions; accessibility/availability/convenient; inexpensive to purchase and maintain; and better incorporation of chemicals. The most important reasons for using a disc type were; less disturbance/direct drill/minimal tillage; improved seed placement and germination; trash farming/stubble management; versatile/works in varied soil conditions; less waste (fuel and water); and, improves moisture retention.

The survey also found 60% of growers were thinking of purchasing a new planter over the next 10 years and only 28% of growers were seeking information about new or different seeders for stubble management. This data suggests that selecting planter type on the general advantages and disadvantages of planting machines, as inferred by the furrow opener and associated seed and fertiliser placement options, is a useful first step. However, evaluating particular machines within that type requires a much more rigorous approach.

6.4 Controlled Traffic Farming

No-till seeks to optimize soil protection using crop residues and minimize the damage caused by disruptive soil tillage. It also attempts to address the damaging impacts of soil compaction by minimizing field traffic and optimizing biological amelioration of compaction effects. Unfortunately, compaction occurs instantly under the first traffic pass, while ameliorative processes in soil are slow. With about half of field area subject to wheel traffic in each (non-controlled traffic) NT cropping cycle, compaction damage is endemic in many NT systems. In highly mechanized systems with field machinery of 12.5–30 t mass, environmental sustainability and profitability can both be substantially impaired by this compaction.

Controlled traffic farming (CTF) avoids widespread compaction by keeping all heavy wheels on permanent traffic lanes, where it improves trafficability. It is an excellent fit with NT, and for example, now accounts for about 30% of Australian grain production. It is also important in providing better conditions for NT seeders, which work better when planting into uniform and relatively soft soil under evenly distributed residue. Such conditions allow high-quality seeding using simpler, cheaper, and less power-hungry seeders.

This section describes the development of CTF in Australia, and its direct, soil related effects. Its impact on NT seeding is subsequently described, together with its broader farm system in environmental benefits, which include reductions in energy requirements, soil emissions and N loss, together with improved soil health.

6.5 CTF Development

Unless traffic is controlled, the mix of machine operating widths and track widths dictates that about 50% of field area is trafficked by heavy wheels, even in NT systems (Kroulik et al. 2009). Without systematic guidance, this traffic is essentially random, so its impact – soil compaction – is endemic to mechanized agriculture. Whilst robotics might well reduce the compaction impacts of (e.g.) herbicide operation, there is little prospect of lightweight seeders and harvesters.

The most obvious way to manage soil compaction is to restrict heavy wheels to permanent traffic lanes and proposals to this effect date from the nineteenth century. This might best be achieved with wide-frame “gantry” farming vehicles, which were the focus of most research on this topic until 1990, but on-farm applications were rare (Vermeulen et al. 2010). In Australia, Arndt and Rose (1966) identified the issue of traffic damage, but their message was not heeded until Adem and Tisdall (1984) demonstrated the value of “permanent bed” cropping systems. Tullberg (1988) subsequently confirmed the energy effects of controlling traffic, noting that a small number of Australian grain growers were already doing this with conventional tractors modified to 3 m track gauge to match most grain harvesters.

Controlled Traffic Farming was developed as a package in a participatory research, development, and extension program in Australia in the 1990s (Yule et al. 2000). Large-scale adoption followed, assisted by the development of precise, satellite-based automatic field guidance systems ("2 cm RTK GPS autosteer"). This overcame the guidance issues of CTF, while the development of 3 m tractor modifications by small manufacturers overcame the incompatibility between tractor and grain harvester track gauge widths. Major manufacturers have subsequently produced more tractors capable working on a 3 m track gauge.

The Australian Controlled Traffic Farming Association (ACTFA), and its predecessors have arranged grower-focused CTF conferences at intervals since 1995. It also provides website access to CTF research results and case studies (www.actfa.net), and 29% of Australian grain was produced under CTF in 2016 (Umbers 2016). A small but growing number of European, North, and South American farmers have also adopted CTF, but adoption is slower where road travel is essential and traffic regulations disallow 3 m track-gauge equipment. ACTFA (www.actfa.net) now defines the fundamentals of CTF as:

- All machinery has the same or modular working and track gauge width, which allows establishment of permanent traffic lanes;
- All machinery is capable of precise guidance along those permanent traffic lanes; and
- Farm, paddock and permanent traffic lane layout are arranged to optimize surface drainage and logistics.

Controlled traffic farming is commonly seen as a natural companion to NT. It also facilitates greater cropping intensity (opportunity cropping), greater residue protection, and more precise placement of inputs. Traffic lanes can be seeded or unseeded, depending on system priorities and often determined by erosion risk. Observations indicates that they are commonly seeded in the southern regions of Australia where wind is the most common agent of erosion. In the northern region, where water erosion is the major hazard, they are commonly non-seeded.

6.6 Soil Compaction and Traffic

Compaction is often defined as an increase in soil density to values greater than those optimal for crop production. Dense subsurface layers occur without human intervention in some cropping soils, and surface layer compaction can occur from stock treading (Bell et al. 2011). Most compaction, however, and almost all deeper compaction, can be attributable to the wheels or tracks of farm machinery. This is unsurprising when heavy tractors and harvesters are used in most extensive farming systems, frequently operating when the soil in a moist, compactible state.

Compaction damage occurs almost instantly under traffic, but natural amelioration is much slower (Radford et al. 2007). It occurs very slowly, if at all in some "rigid" soils, so historical compaction is endemic in many regions where cropping is highly mechanized. Vigorous, deep-rooted crops can assist soil amelioration processes, but expensive, energy-intensive deep tillage is often the only practical way to produce rapid improvement. This can exacerbate problems when done in unfavorable soil moisture conditions, and benefits are rapidly undone by subsequent heavy traffic.

Compaction reduces porosity and increases soil strength, impeding root exploration of the profile. The combination of these factors can increase run-off, erosion, nutrient loss and watercourse pollution, while reducing soil biota, water and fertiliser use efficiency. In rainfed cropping systems, this will constrain yield and in irrigated systems it will require more frequent watering (Antille et al. 2016).

6.7 Compaction-Related Benefits of CTF

In CTF, all heavy traffic is restricted to permanent traffic lanes, occupying 10% to 20% of crop area, allowing most crop production to occur in soil uncompromised by wheel compaction. Direct effects of CTF in comparison to random-trafficked soil have been demonstrated in a wide variety of soils and cropping systems:

- Increased rainfall infiltration (Li et al. 2007);
- Increased plant available water capacity (McHugh et al. 2009);
- Increased soil biological activity (Pangnakorn et al. 2003; Rodgers et al. 2018);
- Reduced run-off and nutrient loss (Rohde and Yule 2003; Owens et al. 2016); and
- Reduced denitrification and greenhouse gases emissions, reduced energy input, and improved nitrogen efficiency (Tullberg et al. 2018; Antille et al. 2015, 2019a).

These effects all facilitate more sustainable and productive cropping, so CTF is generally associated with reduced production costs and environmental impact, and yield improvement (Chamen et al. 2015). It is nevertheless the case that research comparisons of crop yields from wheeled and non-wheeled soil do not always demonstrate a CTF advantage (Galambošová et al. 2017). This might be because such comparisons do not consider the indirect and system benefits.

6.8 Indirect and System Benefits of CTF

Motion resistance might be regarded as the energy penalty of creating compaction, and accounts for a substantial proportion of the power and fuel requirements of all NT cropping operations. Motion resistance is large in soft, cultivated soils, and significant in NT soils in “seedable” condition; but smaller on hard, compacted permanent traffic lanes. ASABE (2011) notes motion resistance reductions of 50% and 10% for wheels tracking similar wheels on soft and firm soil respectively. Similarly, motion resistance reductions of 20–40% were reported for traffic lanes by Luhaib et al. (2017), who also demonstrated the greater draught of tine openers operating in tractor wheelings, compared with that of identical tines operating in adjacent, non-wheeled soil. These values are consistent with the 15–30% overall reduction in fuel costs and power requirements noted by many CTF growers (Mitchell et al. 2019).

The CTF improvement in trafficability also reduces timeliness constraints by facilitating a more rapid start (or resumption of work) after rainfall events. This effect was observed by McPhee et al. (1995), where soil trafficability determined a grower's capacity to produce two or more crops a year, and had substantial impacts on enterprise profitability. It is also supported by a large volume and variety of anecdotal evidence, largely from grain producers presenting to ACTFA conferences (www.actfa.net/past-conferences/). The CTF grower planting a double crop while a non-CTF neighbors struggle to complete harvest of the previous crop, is a typical example.

Trafficability related timeliness benefit is always limited by the least trafficable part of the system, which can often be a low point in the traffic lanes. Good traffic lane drainage is critically important in this respect, and some consultants offer CTF layout design services based on precise topographic survey. In Australian practice, CTF grain growers have often achieved this by changing from "contour" to "down slope" operation, using a small number of very widely spaced, broad, "work over" contour banks to limit slope length. Good design must also support effective logistics, and account for factors such as sand dunes. This topic is discussed in some detail in the 'Layout' section of Isbister et al. (2014).

CTF growers also note the greater uniformity of non-wheeled beds, and the convenience of having all non-uniformity in a consistent spatial relationship with their equipment, rather than randomly distributed. Consistent positioning enables the use of different opener settings in traffic lanes and different herbicide treatments on those traffic lanes. It also facilitates practices such as "chaff decking" to deposit all weed seeds from the harvester sieves in traffic lanes where wheeling will accelerate decomposition. Chaff-decking is currently seen as a useful tool in the management of herbicide-resistant weeds.

Other indirect benefits of CTF are matters of grower observation, with most evidence available from in conference proceedings of the Australia Controlled Traffic Farming Association Inc. (ACTFA, https://www.actfa.net/), and documented by Antille et al. (2019b).

6.9 Seeding Impacts

Prior wheelings degrade seeder performance, largely by their impact on seeding depth, and by seed/soil contact effects of the coarser tilth produced after opener disturbance of wheeled soil. These effects can be counteracted in CTF cropping systems by adjustment of individual traffic lane planting unit press wheel downforce. This is not possible in non-CTF systems due to the randomness of prior wheeling locations. The CTF draught effects noted earlier also reduce the power requirement of tyne seeders operating in CTF, but this reduction might be not be large in comparison to the motion resistance of press wheels, frame wheels, and heavy air carts. CTF effects on disc seeders might be largely due to the reduction in disc unit down force made possible in the absence of random prior wheelings (which require greater downforce to ensure disc penetration).

CTF demands greater precision, but the more uniform soil/crop conditions of CTF, and consistent operating pathways, provide greater repeatability of crop/machine positioning. This can be valuable in allowing interrow or near-row seeding, which are sometimes used to enhance emergence in marginal soil or moisture conditions (Davies et al. 2018).

CTF adoption can be more challenging in non-grain cropping systems, but there are many successful examples in cotton (Antille et al. 2016), sugarcane (Aguilera Esteban et al. 2019) and horticulture (Pedersen et al. 2016). In some cases, excellent systems have been achieved with relatively minor system change (e.g. sugarcane row spacing), but in horticulture, CTF can entail significant limitation to crop choice and substantial equipment expenditure (McPhee and Aird 2013). Equipment and system changes have also been needed in cotton, but in the examples noted above, the outcome has been a more profitable and sustainable production system. The one common theme of almost all successful CTF adoption has been careful, long-term planning.

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Chapter 7
Challenges and Opportunities for Weed Management in No-Till Farming Systems

Vivek Kumar, Gulshan Mahajan, Sahil Dahiya, and Bhagirath S. Chauhan

Abstract Tillage has been used as a major weed management tool for several decades in conventional agricultural systems; however, it has also presented problems, such as degradation of soil health and high production costs. Therefore, a trend towards the adoption of no-till (NT) systems has emerged over recent decades. With the adoption of NT systems has come the elimination of a key component (tillage) of weed management strategies, resulting in a shift in weed dynamics across agricultural systems. Weed management is a challenging component of a successful NT system wherein the use of herbicides have become the most prevalent control method. This over-reliance on chemicals is not a sustainable long-term strategy as it imposes a high selection pressure on weeds, drives the problematic evolution of herbicide-resistant weeds, pollutes the environment, and causes health hazards. The use of biotechnology to develop herbicide-tolerant crops, such as those tolerant to glyphosate, has undoubtedly revolutionized the adoption of NT systems. However, many issues concerning human health and the development of weeds resistant to herbicides are arising as a result of the use of these crops. A recent ban on the use of glyphosate in a few countries may lead to further restrictions on the use of herbicide-tolerant crops, potentially resulting in a reverse in course from NT production systems to more conventional tillage systems. Therefore, the task of evaluating alternative weed management strategies with respect to NT systems presents challenges. Techniques designed to reduce competitiveness in weeds or enhance competitiveness in crop plants while reducing dependency on herbicides, such as

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modifying row spacing and orientation, adjusting planting density and sowing time, and use of competitive cultivars, mulching and cover cropping have been developed by agricultural scientists. Modified or strategic tillage and crop diversification are other potential strategies which can be used for weed management in NT systems. Potential non-conventional weed management strategies such as harvest weed seed control, allelopathy and precision weed management using remote sensing and robotics require further evaluation for their feasibility, efficiency and viability in these systems. This chapter highlights possible combinations of non-chemical, non-conventional and chemical weed management tools that can be used in an integrated weed management approach, presenting the potential for a favorable shift in the crop-weed balance in NT systems.

Keywords Conservation agriculture · Herbicides · Non-chemical

7.1 Introduction

Across field operations, a big share of energy is consumed by the tilling of soils. There are many benefits of tillage such as loosening of the soil, killing of unwanted plants, regulating the circulation of air and water within the soil and increasing the availability of nutrients from the soil for better crop growth (Reicosky and Allmaras 2003). Despite these benefits, conventional tillage (CT) also presents some negative impacts. Intensive tillage can adversely affect soil structure and result in excessive break down of aggregates, leading to potential soil movement via tillage/water erosion. Furthermore, this system is becoming unfeasible and unsuitable due to the increased cost of cultivation due to the rising cost of labor, energy sources and other inputs (Edwards and Smith 2005). Across agricultural production, tillage operations account for more than 25% of total costs (Carter 1996). The evaluation of an economically and environmentally viable system responsive to these existing concerns in conventional tilling resulted in the development of the NT or conservation tillage system. Central to conservation agriculture (CA) are the principles of permanent soil cover and minimum soil disturbance, achieved through zero or NT, direct drilling, minimum or reduced tillage, mulch tillage, and ridge or zone tillage (Reicosky and Allmaras 2003). NT is a practice in which the soil is left undisturbed from harvest to planting, with allowance for nutrient injection. Planting or drilling is accomplished by row cleaners, coulter, disk openers, roto-tillers or in-row chisels as a single operation designed to create a narrow insertion (Reicosky and Allmaras 2003).

The adoption rate of NT systems/CA has been estimated to have increased globally from 2.8 million ha in 1973–74 to 180 million ha in 2015–2016 (Kassam et al. 2018). The cropland area under conservation agriculture in 2015–2016 was an estimated 12.5% of global cropland area. This high adoption rate illustrates the adaptability of NT systems to different soil types, climate conditions and cropping systems. Thus, innovations under NT systems are presented as responsive solutions to problems occurring in CT systems.

Tillage has been used as a major agricultural weed management technique for several centuries. These operations uproot and dismember weeds, distribute weed seeds both horizontally and vertically, inhibiting or promoting weed seed germination and establishment (Clements et al. 1996). Tillage can also help in the incorporation of herbicides into the soil by removing or incorporating crop residue that might otherwise reduce the herbicides' efficacy. Thus, weed management is highly affected by any form of tillage operation.

NT systems often cause a shift in flora towards hard-to-control weeds, presenting a major constraint to their adoption due to an inevitable need for change in weed management strategies (Buhler et al. 1994). For example, a long-term study in a winter wheat (*Triticum aestivum* L.) cropping system showed a higher weed density under NT systems compared with the minimum and CT system (Blackshaw et al. 2001). While NT practices are helpful in restoring and protecting soil health, and are considered critical for achieving sustainable practices in global agriculture, they have led to an over-reliance on chemical weed control methods and resulted in the development of herbicide-resistant weeds (Price et al. 2011). Weed management strategies in NT or reduced tillage systems require a relatively complex approach, requiring different agronomic, technological and engineering approaches (Lafond et al. 2009). During the initial phase of adoption, these systems require dedicated efforts for weed management in order to achieve a specific threshold for sustainable practice.

7.2 Challenges

Although the concepts of NT or reduced tillage have been acknowledged for their advantageous effect on soil conservation, they have not been adopted across all regions of the world. For example, Africa and Europe are yet to widely implement conservation agriculture (Kassam et al. 2018). One of the major challenges to adoption are associated with the management of weeds.

7.2.1 Changes in Weed Dynamics

Effective weed management in NT systems depends on an understanding of the dynamics of weed seeds in the soil seed bank. Tillage systems greatly affect the composition of weed populations. Generally, it is assumed that in NT systems, weed populations are shifted from annual broadleaf weeds to annual and perennial grasses (Nichols et al. 2015). However, both the suppression and proliferation of annual and perennial weed species in NT systems have been documented (Moyer et al. 1994).

Part of the reason for the shift in weed populations is the difference in the vertical distribution of weed seeds in the soil across different tillage systems, with NT systems favoring seed retention at the surface of the profile (Clements et al. 1996). For example, in Australia, it was observed in NT wheat that the seeding system with minimum soil disturbance left more than 75% of the weed seeds in the top 1 cm soil layer, whereas the seeding system with high soil disturbance retained only 11% of the seeds in this layer (Chauhan et al. 2006). The distribution of the weed seed bank also influences weed seedling emergence. Seeds at a relatively shallow emergence depth are provided with suitable moisture and temperature, thus, they germinate and emerge more readily than those buried deeper in the soil. Additionally, weed seeds present on or near the soil surface are more readily killed by weathering, harmed by pathogens (Davis et al. 2005) and consumed by invertebrates and vertebrates (Cromar et al. 1999) as compared to deeply buried seeds. Thus, NT systems, which favor weed seeds being retained at shallow soil depths, maximize the depletion of the existing weed seed bank while also reducing its replenishment. In one 6-year study, seed bank in a NT system was reduced from 41,000 to 8000 seeds m^{-3} (Murphy et al. 2006). Existing research shows that NT systems can improve long-term weed management through limiting the seed input to the soil and depleting the weed seed bank.

7.2.2 Herbicide Resistance and Gene Flow

Cases of herbicide resistance have steadily increased in recent years, and globally, there are currently 502 unique cases of herbicide-resistant weeds (Heap 2019). Continuous, repeated and frequent use of herbicides results in increased resistance in weed communities (Chaudhry 2008). Such resistance is a significant issue in NT systems where weed management strategies focus mainly on herbicides. NT systems also interrupt mechanical incorporation of herbicides into the soil, posing a serious challenge for using soil active herbicides in these systems. Thus, post-emergence herbicides have become the only option for weed control, resulting in an over-reliance and subsequent evolution of resistance to single or multiple herbicides (Puricelli and Tuesca 2005). For example, dependence on post-emergence herbicides in wheat has resulted in the evolution of multiple herbicide resistance in *Phalaris minor* Retz., the most problematic weed in wheat in the Indo Gangetic Plains of India (Chhokar and Sharma 2008).

The commercial release of glyphosate-tolerant crops has revolutionized the adoption of minimum and NT systems because the use of these crops tends to make weed management more effective and less costly (Carpenter and Gianessi 1999). However, governments of many countries are considering putting restrictions on glyphosate usage in agriculture (Brookes et al. 2017). Considering the role of glyphosate in the adoption of NT systems, a restriction on its use may result in farmers shifting from no or reduced tillage systems back to a conventional system.

With the establishment of herbicide-tolerant crops has also come the serious problem of gene flow from these same crops into associated weeds that are now themselves herbicide-resistant (Owen and Zelaya 2004). For example, gene flow from herbicide-tolerant Clearfield® rice (*Oryza sativa L.*) to weedy rice (*Oryza sativa L.*) has been reported in Arkansas, USA (Burgos et al. 2014). Therefore, alternative options to specific herbicides should be included in weed management strategies to support the adoption of NT systems where resistance to herbicides has occurred. There is a need for advanced work employing biotechnology and molecular genetics to improve herbicide resistance mechanisms of tolerant crops, as well as further research into synthesizing herbicides with novel modes of action.

7.2.3 Climate Change

The impact of climate change on crop-weed association has been well established, wherein problems relating to weeds could be exacerbated (Malarkodi et al. 2017). Tillage has the potential to affect soil moisture, light availability, and diurnal temperature variations and thus, weed seed distribution in the soil, ultimately impacting the seed dormancy, seed mortality and emergence pattern of weeds (Mohler 1993). Dormancy cessation and the germination process are strongly linked with specific environmental conditions such as light and alternating temperature regimes (Presotto et al. 2014; Vanderlook et al. 2008). Seed germination of many rice weeds has been shown to be stimulated by light (Chauhan and Johnson 2010). Similarly, it has been observed that temperature influences weed infestation in breaking dormancy through the change of seed physiology (Presotto et al. 2014). In NT systems, crop residue is retained on the soil surface, influencing weed seed germination due to effects on soil moisture, temperature, light availability and soil surface insulation (Nichols et al. 2015). For example, lower levels of light stimuli and less fluctuation in soil temperature under NT systems produced lower emergence of *P. minor* in comparison to CT systems (Gathala et al. 2011; Franke et al. 2007).

Knowledge of weed ecology and biology could be used as a tool for effective weed management under projected climate change scenarios. The effect of NT systems on environmental factors such as light, temperature, and moisture, and their impact on weed infestations needs to be further explored in order to develop efficient weed management strategies for a changing climate. In the wake of climate change, soil temperature and moisture are the most important factors that regulate weed emergence under CT and NT systems and a predication of timing of weed emergence through hydrothermal time seedling emergence model could help in optimizing weed control timings.

7.3 Opportunities/Potential Solutions

As there are many challenges for weed management under NT systems, no single response will provide solution across all settings. Careful planning is required in the implementation phase of any weed management system, particularly in the early years of adoption where weed levels remain high. A number of weed management strategies are available in NT systems, the choice of which depends on the ecological and socio-economic circumstance of the farmer.

7.3.1 Strategic and Modified Tillage

In the situation of the build-up of herbicide-resistant weed populations, strategic tillage, where occasional tillage is conducted in an otherwise long-term NT system, can assist in sustaining a system's long-term productivity (Dang et al. 2018). For example, Dang et al. (2018) reported reduced weed infestation and improved crop profitability and productivity through introduction of strategic tillage in the first year following tillage. Lower weed populations were also observed in the second and third year when compared with NT. Crawford et al. (2015) also reported that weed populations in NT systems were significantly decreased at 3 months after the imposition of a single tillage operation. However, the influence of strategic tillage on weed infestation in the second year was found to be variable, depending on the weed seed bank history. The utilization of strategic tillage or opportunistic use of tillage operations can be used as an important tool for integrated weed management (IWM) in an otherwise NT system. However, the successful implementation of strategic tillage requires information on the potential and historical weed seed bank present.

7.3.2 Enhancing Crop Competition

7.3.2.1 Stale Seed Bed

Stale seedbed is one technique which may be incorporated as an effective tool for decreasing weed infestation in NT systems where a majority of seeds are retained in the topsoil. Under this method, germination of weed seeds is promoted prior to crop sowing with light irrigation or rain. The emerged seedlings are then destroyed with the application of non-selective herbicides such as glufosinate, glyphosate or paraquat, or by any other method. The weed seed bank in the soil's upper layer is depleted using this method, resulting in improved crop competition through reduction of subsequent weed emergence (Kumar and Ladha 2011; Singh et al. 2009). Mahajan et al. (1999) reported significant impact from the stale seedbed technique in the reduction of weed presence in a NT wheat crop. Similarly, the implementation of the stale seedbed method as a component of an IWM strategy under NT direct-sown rice is recommended in many areas infested with weedy rice, a highly problematic and difficult to manage weed (Chauhan 2013; Delouche et al. 2007).

7.3.2.2 Narrow Row Spacing

Altering planting geometry in order to narrow row spacing has been demonstrated to increase competitiveness in crop plants and thus has the potential to be an effective part of IWM strategies in NT systems. The competitive relationship between weeds and crops is regulated by light availability (Ballare and Casal 2000). Canopy coverage, biomass accumulation, and solar radiation interception are dependent on the plant population of a crop, which has a cumulative influence on its weed smothering potential (Anwar et al. 2011). Modification to planting geometry in favor of the crop (narrowing row spacing) is a way to potentially increase light interception by the crop canopy and to reduce light interception by weeds. Bernstein et al. (2014) reported better weed suppression in NT rye (*Secale cereale* L.) with a narrow row spacing of 0.19 m as compared with 0.76 m row spacing.

7.3.2.3 High Planting Density

Planting density of a crop determines canopy coverage, solar radiation interception, and dry matter accumulation, which cumulatively influence the weed smothering ability of the crop (Anwar et al. 2011). A majority of studies investigating the potential of planting density for weed management only show results from this strategy when implemented in direct competition with existing weeds and not when utilized under weed-free conditions (Mohler 2001b; Anwar et al. 2011; Chauhan et al. 2011). Weed competition is higher in NT systems as most of the weed seeds are retained at shallow soil depths. Thus, a high plant density can be used as a potential weed management tool in these systems, which may suppress the germination or further growth of weeds. In NT wheat and rice crops, increasing planting density has been reported to influence crop-weed competition through shifting the competitive balance in favor of the crop (Chauhan 2012). For this strategy to be used as a weed control method, there is a need to evaluate the resulting yield benefits in contrast with the cost incurred with the increased seed rate.

7.3.2.4 Row Orientation

Solar radiation interception by the crop can be increased through adjustment to the directional orientation of row crops, thus reducing the availability of light for weed growth (Mohler 2001b). Crop rows oriented in the east-west direction (i.e., at a right angle to the sunlight direction) have been shown to reduce the growth of weeds in wheat, barley, canola, and lupin through imposing a higher shading effect on weeds in the inter-row spaces (Borger et al. 2010). Directional manipulation of crop rows is an effective method to integrate into an IWM strategy as it is an environmentally friendly approach which costs nothing to implement (Mohler 2001a). Further study into the effectiveness of this method is required as its impact may vary according to the agricultural system in place, the major weed species present and the crop variety selected.

7.3.2.5 Sowing Time

In NT systems, sowing time can be adjusted to enhance competitiveness in favor of the crop. Due to the mechanism of seed dormancy, germination of many weeds is bound to a particular season. If information regarding the emergence time of problematic weeds is known, an adjustment in crop sowing dates can be implemented in order to time crop emergence prior to that of weeds, providing a competitive advantage. Similarly, the sowing of crops can be delayed to allow the germination and subsequent killing of weeds prior to crop sowing (Nichols et al. 2015). In NT systems, early planting of wheat by 1–2 weeks allows the crop to become established before the emergence of *P. minor* (Chhokar and Malik 1999; Chauhan et al. 2012). Under NT in India, *P. minor* populations were observed to be 68% and 80% lower with early sowing (25th October) as compared to normal (10th November) and late sowing (25th November), respectively. Similarly, sowing of barley 4–6 weeks early in the semi-arid northern Great Plains of the USA has been shown to reduce weed biomass and weed seed production (Lenssen 2008). Gürsoy et al. (2014) also reported lower weed density and biomass, and significantly higher lentil seed yield with late sowing as compared to early sowing. However, delayed sowing may be riskier as compared to early sowing with respect to reduction in crop yield, therefore, it should only be adopted in the scenario of severe weed infestation (Mohler 2001a).

7.3.2.6 Competitive Cultivars

The growth habits of specific crop cultivars influence crop-weed competition as they can vary in germination and emergence speed; early dry matter accumulation and canopy closure; leaf attributes such as leaf area index, flag leaf length and angle; light interception ability; tillering potential; height, and resource-competitive root systems. Early maturing varieties within a species have rapid early growth, which provides them with the crop-weed competitive advantage over slow-maturing ones (Mahajan et al. 2011). Depending on the types of weeds present in the field, the above-mentioned criteria should be taken into account when selecting a variety for cultivation. For example, basmati rice cultivars have been found to be more suppressive to weeds as compared to non-basmati rice cultivars (Singh et al. 2009). However, NT specific crop cultivars have not yet been developed or released, resulting in cultivars that were developed for a conventional system being used in NT systems (Kumar and Ladha 2011). Therefore, a focus on developing such cultivars which are high yielding and competitive with the weeds specific to NT systems, is required for strengthening IWM programs.

7.3.2.7 Allelopathy

The utilization of allelopathy to smother weeds is included among the list of emerging tools for IWM strategies. It is an effective alternative to chemical weed control as allelopathic compounds do not have toxic and residual effects (Bhadoria 2011). Allelopathy can be implemented through the utilization of allelopathic cover crops, the addition of allelopathic crops in rotation, or the spraying of plant water extracts in order to control weeds. For example, rye cover crops have been reported to effectively suppress weeds in NT soybean crops (Bernstein et al. 2014). In conservation or NT systems, much of the crop residues are left on the soil surface, thus, allelopathy could be even more advantageous in these systems. The use of rye mulch has been observed to suppress weed biomass in NT tobacco (*Nicotiana tabacum* L.), sunflower (*Helianthus annuus* L.), and soybean systems (Shilling et al. 1985). In rye-corn crop rotation, rye has the potential to smother *Portulaca oleracea* L. and *Amaranthus retroflexus* L. in the following corn crop (Tabaglio et al. 2013). Similarly, foliar application of water extracts of the allelopathic crop has also been demonstrated to suppress weeds successfully in different crops (Bajwa 2014).

Some crop cultivars are superior in their allelopathic ability and this contributes to making them weed suppressive. By selecting these allelopathic cultivars, weed management programs can be strengthened (Olofsdotter et al. 2002). The allelopathic ability of crop plants can be improved through the use of advanced techniques such as biotechnology and screening, potentially offering a competitive advantage against weeds (Wu et al. 2003; Olofsdotter et al. 2002). Thus, allelopathy has the potential to be a viable alternative for sustainable weed management under NT systems.

7.3.3 Crop Diversification

By growing a single crop or crops with similar management practices, some weeds become dominant and hard to manage. Crop diversification provides more opportunities for weed management, especially in NT systems. For instance, in continuous cereal-based cropping, monocot weeds such as *Alopecurus myosuroides* Huds. become dominant in minimum tillage systems (Froud-Williams 1983), and the rotation of cereals with crops of different growth habits can assist with management. Similarly, by replacing wheat with potato (*Solanum tuberosum* L.), sunflower, oilseed rape (*Brassica napus* L.) or berseem clover (*Trifolium alexandrinum* L.) for

2–3 years in a rice-wheat cropping system, *P. minor* infestation can be reduced significantly (Brar 2002).

There are two general principles which have been suggested for weed management through crop diversification (Liebman and Staver 2001):

- *A broad range of mortality factors and stressors should challenge the weeds.* Repeated diversification of crop sequences alters the environment in which a weed can become established. Over time, diversified crop sequences suppress weed density by creating inhospitable or fatal conditions throughout the life history of each weed species present. Effective weed management can be achieved by adopting those crop sequences that include crops suited to different seasons, as well as through alternate use of annual and perennial crops.
- *Weeds should be deprived of plant growth supporting resources* Weeds are well-adapted for rapid establishment at microsites for light, water and nutrients left unutilized in mono-cropping systems. After their establishment, they compete with crops for plant growth supporting resources and cause yield losses. As annual crop mixtures often exploit a greater range and quantity of resources compared with single crops, they can be more efficient for weed suppression through resource preemption. Cover crops also cause a reduction in weed establishment and growth by competing for resources when main crops are dormant or absent.

7.3.4 Mulching and Cover Cropping

The role of mulching with crop residue, either through crop residue retention or manual application, should be considered within IWM systems. A major role of mulching is to cover the soil surface, which prevents solar radiation from reaching the soil to inhibit or delay germination and emergence of weeds. As crop residues are generally left in fields under NT systems, this method is selected as a default weed management strategy. In Australia, a pot study demonstrated 64–75% less emergence of *Sisymbrium thellungi* O.E. Schulz with the application of wheat residue as compared to no residue (Mahajan et al. 2018). Similarly, a 48% reduction in weed density was reported in wheat when sown in heavy residue mulch with Turbo Happy Seeder (Singh et al. 2013). However, for the effective use of crop residue as mulch, even distribution of mulching material is a prerequisite to reaching its potential benefits.

Similarly, growing a cover crop may be used as a potential weed management strategy in NT systems due to the ability of cover crops to compete with weeds for resources and inhibit weed growth through allelopathy (Price et al. 2008). Selection of a cover crop is made on the basis of its capacity for soil surface coverage and high biomass production (Fageria et al. 2005). Prior to planting the subsequent crop, the cover crop is terminated using herbicides, mowing or rolling (Creamer and Dabney 2009). In south-western Australia, black oat (*Avena strigosa* Schreb.), a fast-growing and high biomass producing crop, is grown as a cover crop shown to reduce the growth of several weeds, including *Lolium rigidum* Gaud. (Flower et al. 2012).

7.3.5 Precision Weed Management

Precision weed management is an efficient and site-specific approach involving the timely and targeted application of herbicides, that leads to reduced usage rates and improved environmental safety (Christensen et al. 2009; Young et al. 2014). It responds to the natural heterogeneity in soil characteristics and weed occurrence overlooked by traditional label recommendations for uniform application rate across an entire field (Nordmeyer 2009). This heterogeneity in weed population and distribution patterns is increased under NT based systems due to the lack of tillage operations that could cause weed seeds to be more uniformly distributed over a wide area (Brown et al. 1994). In this situation, global positioning system (GPS) technology and soil sensors are used to precisely map soil variability (Mertens et al. 2008). Continuing technological advances in modeling, robotics and remote sensing will enable more widespread adoption of this weed management strategy in the future (Freckleton and Stephens 2009; Christensen et al. 2009).

7.3.5.1 Modeling

Modeling is an effective method to accurately evaluate weed infestation. Weed modeling uses many statistical and mathematical tools to develop a specific representation of a given reality (Freckleton and Stephens 2009). An accurate model of weed seed bank dynamics, emergence patterns, weed flora shifts, competitiveness, canopy structure, and potential yield losses is developed through data collection using sensor technology (Christensen et al. 2009). These decision-making models and tools are then used to identify and predict the impact of changes to environmental factors, soil conditions, mechanization and crop husbandry practices to weed dynamics (Christensen et al. 2009). The emergence pattern of weeds under different tillage systems could be assessed through the development of a suitable hydrothermal model, serving to further strengthen IWM practices. WEEDSIM, PALEWEED, GESTINF, GWM and HERB are currently the most useful deterministic population models used to deliver information about weed density, weed infestation patterns and weed cover in a given area over a period of time (Christensen et al. 2009; Freckleton and Stephens 2009).

7.3.5.2 Remote Sensing

Natural heterogeneity in weed occurrence presents the potential for application of herbicides on a site-specific, need-only basis through the successful delineation of patch boundaries. Detection of weed patches or mapping of weed populations in cultivated areas can be done with the help of remote sensing tools. Remote sensing instruments measure variation in spectral reflectance between weeds and other vegetation using either aerial and satellite remote sensing, on-ground remote sensing or unmanned aerial vehicles (UAVs) (Bajwa et al. 2015). In cereal and legume crops, many weed species have been successfully mapped with the help of remote sensing, especially with higher-resolution imagery in row crops. *Elytrigia repens* (L.) Desv. ex B.D. Jackson, *Setaria* spp., *Taraxacum officinale* G.H. Weber ex Wiggers, and *Chenopodium album* L. have all been mapped against NT corn at seedling stage with stubble and bare soil background (Lamb and Brown 2001). Thus, remote sensing provides a non-invasive method for gaining a synoptic view of a targeted weed population.

7.3.5.3 Robotics

With the development of autonomous robotic systems, weed management strategies are no longer confined to the use of herbicides or manual methods. Current research is focused on the use of robotics and targeted tillage for the purpose of balancing conventional weed reduction through tillage with the management advantages of NT systems. Robot rigs equipped with weed detection-type sensors and the dual ability to selectively apply herbicides or tillage treatments have been developed (Somes 2016). These innovative approaches are being evaluated to reduce weed populations in NT systems where robotics can reduce the replenishment of weed seed bank with minimal soil disturbance (Widderick and McLean 2017). The use of robotic systems has also been estimated to reduce weed management costs by 90% (Anonymous 2016). Robotics thus present the opportunity to alleviate current reliance on herbicides and their adverse effects on environmental and agricultural sustainability (Slaughter et al. 2008).

7.3.5.4 WeedSeeker

The WeedSeeker spot spray system is a new technique that senses the presence of weeds in an area, guiding a nozzle to spray a precise quantity of herbicide on weeds while avoiding application on bare ground. This system may provide an efficient alternative in areas where weeds occur intermittently. In fallow systems, weed management is generally done by uniform application of non-selective herbicides such as paraquat or glyphosate. However, patchy weed distribution in these systems causes the deposition of the majority of herbicides on bare soil or crops rather than on weeds. Therefore, spot application of herbicides using WeedSeeker in these systems may result in the reduction of herbicide usage, improvement in weed management and a considerable reduction in costs (Bennett and Pannell 1998). Riar et al.

(2010) found equally effective weed control and a 45–72% reduction in herbicide costs when comparing the LASC applicator with an open broadcast application in NT systems.

7.3.6 Harvest Weed Seed Control (HWSC)

Harvest weed seed control is an effective approach to weed management in which weed seeds are prevented from entering the seed bank by destroying them through crushing, burning, or removal during, or soon after, crop harvest (Walsh et al. 2013). Arresting the weed seed entry to the soil seed bank is a practical method for reducing the influence of weeds in upcoming crops, while also ensuring the sustainability of herbicide-based weed management programs (Walsh et al. 2013). This strategy has produced weed seed destruction ranging from 75% to 99% at the time of harvest (Walsh et al. 2013). Those weed species that retain sufficient quantities of seed at a suitable height for collection by combine harvester are the most amenable to HWSC practices. Weed populations generally shift towards small-seeded annuals in NT systems (Duary et al. 2016). These small-seeded weeds (e.g., *Sonchus oleraceus* and *Conyza sumatrensis*; Fig. 7.1) which emerge at the surface could create problems under such systems. The maximum emergence of *Echinochloa colona* (L.)

Fig. 7.1 Problematic weeds in conservation agriculture systems: *Sonchus oleraceus* (top panel) and *Conyza sumatrensis* (bottom panel). Biotypes of both species have developed resistance to glyphosate in Australia. (Source: Bhagirath Chauhan)

Link, for example, has been observed under NT practices (Singh et al. 2015). By harvesting the weed seeds during crop harvesting, however, a large portion of the weed seed bank is eliminated (Norsworthy et al. 2016). Therefore, HWSC could be useful in the reduction of the weed seed bank near the soil surface in NT systems.

7.3.7 Integrated Weed Management

Any single weed management method may not offer effective and season-long weed control in NT systems. Therefore, a set of alternative weed control methods should be evaluated for broadening the spectrum and efficacy of weed management strategies. For example, the utilization of sowing times and tillage systems could form a component of IWM. The interaction effect of tillage and sowing time demonstrated by Oyarzábal (1989) shows that shattercane [*Sorghum bicolor* (L.) Moench] population decreased in the NT system when planting dates were delayed. However, there was no observed effect of sowing dates within a CT system. Similarly, the interaction of tillage systems with crop residue retention for the purpose of weed management needs to be explored. In a study comparing the effects of CT, NT and NT integrated with residue mulch, weed biomass was found to be nearly half of that found in the NT along with residue mulch treatment as compared with the NT treatment (Ngwira et al. 2014). A synergistic effect of NT with crop rotations for reducing weed populations has been shown in several studies (Murphy et al. 2006; Anderson 2005). The interaction effect of tillage with herbicides was studied by Walia et al. (2005) and reported that NT wheat, when applied with a preplant paraquat spray, exhibited less biomass accumulation of *P. minor* as compared with NT and CT sown wheat without paraquat application. Additionally, the component of recently emerging weed control methods such as precision weed management, harvest weed seed control, and strategic tillage can also be integrated with other methods. Thus, it is clear that weed management in NT systems is a complex and multi-dimensional issue which can only be achieved by IWM approaches.

7.4 Conclusions and Future Direction

The adoption of NT systems has been encouraged in recent years despite the associated weed management challenges that have emerged. Issues of weed infestation, diversity, distribution, growing patterns, and resistance levels have arisen in different ways to those found in conventional systems. Therefore, those weed management strategies suitable for conventional systems may not be readily applicable to NT systems. Chemical weed control has been a widely adopted method under NT; however, indiscriminate use of herbicides has caused the problematic evolution of herbicide-resistant weeds, increased costs of herbicides, weed species population shifts, surface water pollution, herbicide residues in the food chain, health hazards and adverse effects on non-target organisms. Several cultural weed control methods that enhance crop competitiveness, such as narrow row spacing, high planting density, row orientation, sowing time and competitive cultivars could be implemented in these systems.

After studying all the aspects of weed infestation patterns and weed management approaches in NT systems, it can be concluded that weed management is a complex and multi-dimensional issue, and good weed control can only be achieved through a combined and multi-dimensional weed management approach. Therefore, integration of weed control methods is the only option for sustainable and promising weed management in NT systems. Efficient surveying of weed species, accurate weed recognition, weed patch dynamics detection, timely weed control operations, proper monitoring and surveillance for herbicide resistance cases, rotational use of herbicides and depletion of weed seed banks are all essential in NT systems. The recent incorporation of harvest weed seed control, precision weed management, strategic or modified tillage, and allelopathy to NT systems in many regions also present further opportunities for optimal implementation for effective weed management.

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Chapter 8
Challenges and Opportunities in Managing Pests in No-Till Farming Systems

Ebony G. Murrell

Abstract Tillage has both positive and negative effects on pest management in agriculture, depending on the pest being managed. This chapter discusses the pros and cons of no-till (NT) systems in regard to pest pressure. The success and environmental sustainability of pest management in NT systems depends on the agricultural methods that are used in tandem with the cessation of tillage. Insecticides are often used in NT systems, meaning that pesticide runoff from fields and damage to nontarget insect species remain as much, if not more, concerning in NT agriculture versus conventional tillage (CT) systems. Crop rotation, use of pest-resistant crop varieties, manipulation of planting and harvest dates, retention of crop residues, and intercropping are alternative practices that are fully integrative with NT systems. These practices, when paired with NT agriculture, can promote soil microbiota that improve plant defenses, encourage colonization of beneficial predators and parasitoids, and reduce pest abundances and the need for insecticide treatments in NT fields.

Keywords Pesticide · Biological control · Neonicotinoid seed treatments · Crop diversification · Border management · Perennials

8.1 Definitions

In this chapter, a “pest” is defined as any organism in the Kingdom Animalia that either causes direct damage (via herbivory, grain consumption, etc.) or indirect damage (via plant disease transmission, tunneling in fields, etc.) to cash crops. Pests include a diverse array of invertebrates such as mites, nematodes, insects, and gastropods. Some vertebrates, such as birds and mammals, are also considered pests and are included in this chapter.

In the literature, the term “pesticide” is broadly employed to describe any chemical that is used to control any noxious organism in cropping systems: animals, fungi,

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and weeds. In this chapter we will use "pesticide" only to refer to chemicals that control animal pests.

8.2 How Does No-Till Affect Pests?

How wonderful it would be if all pests disappeared as soon as the last plow ceased furrowing the soil. Alas, pests are wily beasts and not so easily thwarted. So long as a crop exists, they will come to dine. However, *which* pests feast versus fall in a no-till (NT) system depends on the species of pest, and how each reacts to the environmental conditions that exist in conventional till (CT) versus NT systems.

Tillage is merely one agricultural tool of many that can be used to directly manage pests. Given the vast differences among pest species' life cycles, modes of feeding, and crop preferences, it should come as no surprise that pest species should – and do – react differently to tillage and the cessation thereof. Pests whose populations are lower in CT systems are generally species that live at least part of their life cycle in or on the soil surface, and thus perish as a result of being buried, exposed to predators, or subjected to desiccation when the soil is tilled. Examples include *Helicoverpa* caterpillars (Lepidoptera: Noctuidae) (Dang et al. 2015), wireworms (Coleoptera: Elateridae) (Stinner and House 1990), slugs (Gastropoda: Agriolimacidae) (Douglas and Tooker 2012), and rodents (Mammalia: Rodentia) (Witmer et al. 2007). In contrast, pests that have little or ephemeral contact with the soil are unaffected by tillage and therefore do not increase when tillage ends. Examples include thrips (Thysonaptera), aphids (Hemiptera: Aphidoidea), and some foliar beetles, such as the alfalfa weevil (Coleoptera: Curculionidae) (Barney and Pass 1987).

If direct suppression were the only mechanism by which tillage affected pest populations, one would expect that NT cropping systems would be more prone to pest damage than CT systems, as cessation of tillage would cause a net increase in pests. However, empirical evidence shows that net pest damage to crops in NT systems is more often equivalent to, or lower than, damage in tilled systems (Stinner and House 1990). One of the major reasons for this is that tillage affects not only pests themselves, but the biological agents that control pests. These biological agents are called "natural enemies," and include the following:

- Predators – Spiders (Arachnida: Araneae), harvestmen (Arachnida: Opiliones) ground beetles (Coleoptera: Carabidae);
- Parasitoids – insects that lay their eggs inside live pests. When the eggs hatch, the larvae consume the living pest from the inside. Examples include parasitoid wasps (Hymenoptera: multiple families) and flies (Diptera: Tachinidae);
- Entomopathogens –microinvertebrates (Nematodes) or fungi (*Metarhizium* spp., *Beauvaria spp.*, *Lecanicillium* spp., etc.) that infect insect pests and eventually kill them.

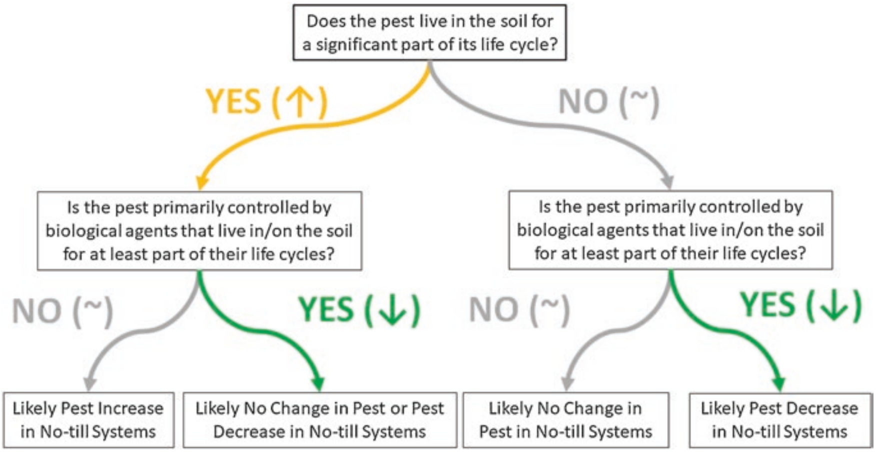

Fig. 8.1 Flow chart demonstrating predicted pest population response (↑ = positive, ↓ = negative, ~ = variable or neutral) to NT and biological agents. When the positive effects of NT on biological agents are taken into account, the probability of a given pest species increasing in NT systems is reduced

All the biological agents listed above live in the soil or on the soil surface. While some species of spiders and ground beetles do well in disturbed areas such as conventionally-tilled fields (Clark et al. 1997; Rivers et al. 2017), most of these natural enemies are negatively affected by disturbance (Witmer et al. 2009; Tamburini et al. 2016). When tillage is reduced or eliminated, natural enemy populations can rebound, thus helping to manage pests that might otherwise increase in NT systems.

The effect of tillage on pests, therefore, is predicted to depend upon two factors: whether the pest species itself is affected by tillage, and whether the biological agents that naturally manage it are affected by tillage (Fig. 8.1). The disproportionate benefit of NT to natural enemies is likely a major reason why NT cropping systems are often equally or less subjected to pest damage than CT systems. A meta-analysis of reduced tillage effects on pests supports these predictions (Stinner and House 1990), showing that across 45 studies and 51 arthropod pest species, only 28% of species increased when tillage was reduced or eliminated, while 43% decreased with reduced tillage and 29% were unaffected.

Of course, in all cropping systems there are multiple factors other than tillage that can affect pest and natural enemy populations. Some of the factors and practices that can be used to further tip the system in favor of biological control agents and/or reduce pest populations will be covered in this chapter. Nevertheless, it is important to first know the fundamental relationship between pests and biological control agents, and how the balance between those two can change when adopting NT agriculture. Since the overall goal of a NT system is, in principle, sustainability, pest management plans within NT systems should be designed to preserve or enhance biological control of pests whenever possible.

8.3 Pesticides in No-Till Systems

8.3.1 Are More or Fewer Pesticide Used in NT Agriculture?

There is confusion in the literature and in public perception as to whether NT systems use more or fewer chemicals for pest management than CT systems. Most studies that focus on "pesticide" use in, and runoff from, NT systems are referring specifically to herbicides (Warnemuende et al. 2007; Isensee et al. 2010; Johnson 2013; Elias et al. 2018), not animal pesticides. Additionally, the public perception is that NT agriculture uses more chemicals (Friedrich 2005); under this broad term, the public may erroneously incorporate animal pesticide use under the same umbrella as herbicides. At the other extreme, the literature sometimes claims NT agriculture uses fewer insecticides than conventional agriculture without evidence to support the claim (Derpsch et al. 2010).

Studies on animal pesticide use in NT are fewer than herbicide studies, and most that do exist have been conducted on insecticide use in corn in the United States. Duffy and Hanthorn (1984) found lower insecticide application rates in NT versus CT in US cornfields. Bull et al. (1993) and Day et al. (1999) found similar reduced insecticide use in conservation NT versus conventional corn. In contrast, Lin et al. (1993) reported greater insecticide use in NT cornfields compared to conventional fields tilled with a moldboard plow, and a survey of more than 4800 cornfields in the Midwest United States found that insecticide use was increased in NT systems compared to tilled fields (Fuglie 1999).

The above evidence suggests that pesticide use does not necessarily increase in NT systems, although there is considerable variation (sometimes greater use, and sometimes reduced use). However, it should be noted that (A) these studies only describe insecticide applications in one crop in one geographic region; (B) these studies predate the widespread use of transgenic crops (e.g., Bt-trait corn); and (C) these studies discuss only foliar and drench pesticides, not seed treatments, and predate the now widespread use of neonicotinoid seed treatments in North America. More empirical research is clearly needed to determine how non-herbicide pesticide use changes with NT adoption in current NT cornfields, other cropping systems, and in other parts of the world.

8.3.2 Pesticide Runoff in No-Till Agriculture

The quantity of pesticides used in NT agriculture is an important area of study, but so also is the environmental fate of those pesticides, and how NT may affect dispersion and breakdown of pesticides. The herbicide literature has shown some increase in herbicide runoff from NT versus CT fields (Warnemuende et al. 2007; Isensee et al. 2010; Elias et al. 2018). However, insecticides may react differently. Reducing tillage has the effect of increasing macropore size in the soil such that, except during heavy rain immediately after application, pesticides are more likely than herbicides to settle into the soil and break down, rather than entering the watershed (Shipitalo et al. 2000). At least one field study seems to support this, as NT cornfields in the US have shown lower runoff of tuberfos, a corn rootworm insecticide, than CT fields (Mamo et al. 2013).

A notable exception to this is NT vegetable rotations in which plastic mulch is used for weed suppression. Pesticide runoff is much higher in these systems than in systems without plastic (Arnold et al. 2004; Rice et al. 2007). No-till vegetable farmers can avoid this negative effect by planting vegetative strips and mowing them to produce a vegetative mulch cover instead of using plastic (Rice et al. 2007).

For more information about pesticide fate in NT systems, see Chap. 17.

8.3.3 Neonicotinoid Seed Treatments: The Case for Disproportionately Negative Effects on No-Till Systems

The application of pesticides is normally in response to the increase of a pest in the field and associated economic damage to the crop. However, in North America prophylactic insecticide treatments, specifically the application of neonicotinoids as seed treatments, have increased over the past 16 years (Douglas and Tooker 2015). Neonicotinoids are a class of insecticide that cause overstimulation of neurons in invertebrates, leading to paralysis and death (Simon-Delso et al. 2015). They are toxic to a wide variety of invertebrate pests, including aphids, whiteflies, leafhoppers, flies, and moths (Kundoo et al. 2018). First available commercially with the release of imidacloprid in 1991, neonicotinoids can be applied as foliar sprays, soil drenches, and in irrigation water (Elbert et al. 2008). However, due to their systemic properties and relatively low toxicity to mammals, they began to be widely applied as seed treatments in corn, soybean, cotton, and wheat in North America in the early 2000s (Douglas and Tooker 2015). As of 2011 in the United States, between 79–100% of corn seed and between 34–44% of soybeans are sold pre-treated with neonicotinoids (Douglas and Tooker 2015).

While neonicotinoids have been shown to reduce pest feeding on crop seedlings (Magalhaes et al. 2009; Saeed et al. 2016; D'Ambrosio et al. 2018), recent studies have demonstrated that they may have a disproportionately greater negative effect on natural enemy populations. Neonicotinoids can be transferred across trophic levels and cause disproportionately toxic effects on predators versus their prey (Douglas et al. 2015). In NT soybean fields in the US, crops seed treated with thiamethoxam had 67% greater slug activity, 33% reduced predation, and significant yield loss compared to untreated-seed crops (Douglas et al. 2015). In cotton crops, thiamethoxam and imidacloprid both negatively affected predator populations, though imidacloprid was less toxic (Saeed et al. 2016). In cornfields with seed treated with clothianidin, insect predators of different guilds were reduced by 31–66% compared to untreated-seed crops (Disque et al. 2019). Field evidence even suggests that weed populations can be affected indirectly by neonicotinoid toxicity to weed-seed predators (Smith et al. 2016).

Though the effects of neonicotinoid seed treatments on predators can be found in CT and NT systems, these effects may cause proportionally greater harm in NT systems. Since the basic underpinning of NT pest management is the increase in natural biological control agents, the reduction of these agents can cause unexpected increases in other pests (such as the increase of slugs in soybeans noted above). The prophylactic use of neonicotinoids also undermines the basic tenets of responsible pest management: namely, monitoring for pests first and then treating with chemicals only when pests are sufficiently abundant to warrant treatment (Tooker et al. 2017).

8.4 Managing Pests Sustainably in No-Till Systems

In any agricultural system, including a NT system, a variety of integrated pest management practices should be employed to maximize pest management while minimizing the chance of pests developing resistance to any single practice. In this section we will cover some of these practices. Most of them are also used in CT agriculture, but here we will discuss how these practices integrate with NT systems.

8.4.1 Conservation Tillage

Conservation tillage, or the retention of at least 30% of crop residues on the soil surface, is often employed to suppress weeds, retain soil moisture, and reduce erosion. Most NT agriculture retains at least some residue on the soil surface, though this residue is sometimes harvested for other purposes, such as selling for bioenergy production (Wilhelm et al. 2007). The ground cover and moisture retention provided by residues can enhance populations of beneficial biological control agents (ground beetles, entomopathogens, and predatory nematodes), but they can also increase populations of certain pests, such as slugs, rodents, and plant parasitic nematodes. Slug damage to seedlings, particularly in the initial years of adoption of conservation tillage, can be significant; however, such damage can be reduced by drilling seed at 40–50 mm instead of 30 mm, limiting use of broad-spectrum insecticides to increase populations of slug-predatory ground beetles, and timed application of molluscicides (Glen and Sysmondson 2003). Crop residues may also increase parasitic nematodes in the soil; however, the increase is often soil type and crop specific (Minton 1986), and more recent research failed to find significant yield loss in NT systems despite changes in the parasitic nematode community (Govaerts et al. 2006, 2007). Rodents can be managed via management of border crops (see Field Border Management below). However, for most pests, the gains in biological control in conservation tillage are greater than the increase in habitat provided by crop residues. Therefore, retention of crop residues is, and should continue to be, considered an integral part of NT cropping systems, except in the cases where residue-specific problems such as fungal pathogens are the primary cause of yield loss (see Chap. 9 on disease).

8.4.2 Crop Diversification

Rotating crops is especially important in NT systems for crop protection against soil-dwelling pests. Cash crop rotations can help to break the life cycles of certain pests, such as rotating corn with soybeans to manage corn rootworms (Witmer et al. 2009). However, rotation of cash crops can sometimes be limited by available markets for alternative crops, or limited cash crop species adapted to regional climates and soil conditions.

Cover cropping and intercropping are practices that can either substitute for, or preferably supplement, cash crop rotation. Cover cropping, the practice of planting non-commodity species in between cash crops within a rotation, ensures minimal exposure of soil to erosion, especially when paired with conservation tillage. Grasses (Lundgren and Fergen 2011), legumes, and legume-grass mixtures (Tillman et al. 2004; Pullaro et al. 2006; Jackson and Harrison 2008) provide excellent habitat for predators of insect pests. The roots of grass cover crop species (Kabir and Koide 2002), and legumes (Karasawa and Takebe 2012; Njeru et al. 2014), can also help to preserve or enhance endophytic fungi in the subsequent cash crop; which can in turn increase cash crop defenses against pests (Murrell et al. 2019).

Intercropping, the practice of planting complimentary vegetative species in between rows of cash crops, can also reduce pest pressure; for example, wheat pests have been generally shown to decrease in wheat intercropped with legumes, brassicas, or cotton (Lopes et al. 2016). The mechanism for pest management varies depending on the intercrop. In some cases intercrops attract predators that then consume crop pests; for example, sweet alyssum intercropped with lettuce attracts predators which consume lettuce aphids (Brennan 2013). Other intercrops crops, like *Desmodium*, produce chemical compounds that deter pests from visiting or laying eggs on the cash crop (Hassanali et al. 2008).

8.4.3 Crop Variety

No-till farmers should select for crop varieties that are resistant to the most damaging pest or pests in their region. These varieties may be pest-resistant hybrids, or in the United States and Australia they may be genetically modified (GMO) crops, such as Bt corn. For any crop with partial or complete resistance to pests, it should be noted that the resistant crop variety is only one component of a successful pest management plan. Failure to integrate the use of resistant crops with other pest management practices (crop rotation, trap cropping, etc.) can lead to over-reliance on the resistant crop variety, and lead to more rapid adaptation of the pest to that variety (Cullen et al. 2013).

8.4.4 *Fertilization*

Organic fertilizers, particularly compost and manure, can help to reduce pest insect populations (Garratt et al. 2011). This can occur directly via pest avoidance of organically fertilized crops (Phelan et al. 1995; Hu et al. 2016), or indirectly via an increase in predator populations (Birkhofer et al. 2016). For NT agriculture it is especially important to use organic fertilizer with low weed seed content, such as compost, composted manure, or vermicompost.

8.4.5 *Field Border Management*

Rodents can be a particular problem in NT grain fields, as the cessation of tillage allows rodents to establish burrows in crop fields (Witmer et al. 2007). Zinc phosphide pellets, which are toxic if ingested by mammals, can be applied in crop fields; however, the reduction of rodents in the field is often only temporary as more rodents migrate from grassy borders into the crop field (Hygnstrom et al. 2000). Grassy borders also allow rodents to overwinter more successfully and thus reestablish more rapidly in crop fields the following spring. Therefore, in fields where rodents are a recurring problem, the field borders should be mowed or burned at the end of the growing season.

8.4.6 *Pesticides*

Pesticide use within a NT system should be in keeping with the principles of integrative pest management (IPM). Pest populations or pest damage should be monitored, and pesticides applied only when the economic treatment threshold for that pest has been reached. When possible, pesticides should also be used that target the specific type of pest causing the most damage (miticide, systemic insect growth regulators for chewing larval pests, etc.). It is tempting to use broad-spectrum insecticides for rapid control of pests; however, these pesticides can also wipe out natural enemy populations, making the crop more vulnerable to future pest infestations (Symondson et al. 2002). If a broad-spectrum insecticide must be used, it should be applied only to the parts of the plant most likely to contain the pest, and applied at times when natural enemies are less active.

Prophylactic use of neonicotinoids should be avoided by planting untreated seed (or seed treated with only fungicides). This may be more difficult to accomplish in countries like the United States, where the majority of many crop seeds are pretreated with neonicotinoids (Douglas and Tooker 2015).

8.4.7 Planting Date

Many invertebrate pests have life cycles that are highly predictable based on the accumulative amount of time a geographic region has had temperatures above a critical minimum needed for insect growth. The term for this temperature-based time measurement is growing degree days (GDDs). For certain agricultural pests, such as the seed corn maggot, scientists have developed GDD-based models that predict the emergence of the pest. Using such models, farmers can time their planting dates to reduce overlap of seeds and seedlings with seed corn maggots, therefore reducing damage incurred by this pest (Broatch et al. 2006).

Even in the absence of GDD models, planting date can still be manipulated to reduce overlap of critical crop development stages with pests that target the crops at those development stages. For example, planting fast-maturing cowpea varieties early in Nigeria reduces the overlap of maturing crops with post-flowering pests (Asante et al. 2001).

8.5 Special Topic: Perennials in No-Till Agriculture

Perennial herbaceous species provide unique attributes for pest management in NT agriculture. Alfalfa, for example, can provide excellent habitat for natural enemy populations, which can carry over physically into adjacent cash crops (Zhao et al. 2013) or temporally into the subsequent cash crop in a rotation (Schipanski et al. 2017). Ecosystem services generated by perennial habitat, such as intercropped prairie strips with corn, can be disproportionally greater than the area the strips occupy and exceed the yield loss incurred by devoting acreage to planting those strips (Schulte et al. 2017).

Most perennials in NT systems are either companion crops or harvested for forage (grasses, alfalfa, clover, etc.). However, perennial grains are beginning to enter the commercial market, with the development of perennial rice (Zhang et al. 2014) and Kernza® (DeHaan et al. 2018; McMillan 2018). There are also breeding programs to develop perennial barley (Westerbergh et al. 2018), buckwheat (Chen et al. 2018), cereal rye (Acharya et al. 2004), sorghum (Cox et al. 2018), sunflower (Van Tassel et al. 2017), and wheat (Hayes et al. 2018).

These perennial grains integrate perfectly with the goals of NT agriculture, but they also will provide unique challenges in pest management. Perhaps the greatest challenge is that crop rotation, at least on an annual scale, will no longer be a viable management option. Habitat permanence coupled with lack of tillage could increase resident populations of some pest species in perennial fields. To avoid increased reliance on pesticides, agroecologists will need to adopt pest management techniques like those developed for alfalfa (Summers 1998). They may also need to develop pest management techniques that are more commonly used in forest and orchard systems, such as pheromone trapping and mating disruption (Kovanci et al. 2009; Kamarudin et al. 2010). Intercropping, border plantings, and diversification of fields at the landscape level could also be used to enhance diversity in space, as a substitute for the diversity in time that occurs in crop rotations.

8.6 Conclusions

While a few specific pests, such as slugs and rodents, may increase in NT agricultural systems, most pest populations decrease or are unaffected directly by conversion to NT. In contrast, beneficial soil organisms and natural enemies generally benefit from the greater soil stability, reduced disturbance, and increased ground cover provided by conservation NT agriculture. For the most effective long-term management of pests in NT systems, practices that promote biological control of pests should be employed: increasing crop diversity through rotations, cover cropping, and intercropping, using organic sources of fertilizer, manipulating planting dates, and selecting pest resistant crop varieties. Insecticides should be employed as only part of an integrated pest management strategy, and when possible should be applied in such a way as to minimize their impact on natural enemy communities.

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Chapter 9
Challenges and Opportunities in Managing Diseases in No-Till Farming Systems

M. Kathryn Turner

Abstract Under NT management, there are several pathogens that often increase, such as *Rhizoctonia solani* and *Fusarium* spp., or decrease, such as *Gaeumannomyces graminis* and *Pratylenchus neglectus*. While NT farming can lead to more inoculum in residue, soil, weeds, or volunteers, and changes in the microclimate that may affect disease development, there are management approaches that can reduce disease. Some of the most effective approaches include crop rotation, planting resistant varieties, and use of fungicides and herbicides, as well as managing stubble residue and mechanical disruption during planting. Additional research is needed for many crops that have potential to yield more in NT than in CT systems, and in South America and Asia where NT is implemented on the greatest area of land.

Keywords No-till · Disease management

9.1 Management of No-Till Farming Systems

For disease management, one of the most important distinctions between no-till (NT) and conventional tillage (CT) farming systems is the plant residue that is left on the surface of the soil from the previous crop. No-till management involves planting directly into residue from the previous crop with no tillage or soil disturbance to form a seedbed before planting (Baker et al. 1996; Paulitz 2006). The method leaves surface residue remaining intact, with at least 30% or 1.12 Mg ha^{-1} of residue remaining according to the USDA's definition (Smiley and Wilkins 1993) and up to 70% retained in some systems (Baker et al. 1996). The intact residue can serve as a source of inoculum for the subsequent crop. The residue is colonized by micro-organisms, some of which can be pathogenic and cause disease under favorable conditions.

Another factor in NT systems important for the emergence of disease is the use of planting methods that minimize soil disturbance. Planting methods have

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implications for pathogens surviving on and below the soil surface and on the physical disruption and dispersal of pathogen vegetative and sexual propagules.

Disease occurs only where there is a susceptible crop, virulent pathogen, and an environment conducive to the survival of the pathogen and its life cycle stages necessary for infection. Changes in the soil microenvironment affect pathogen populations. Tillage affects moisture, temperature, and pore space, which affect plant pathogen survival, reproduction, and abundance.

This chapter focuses on disease management, primarily in systems in which NT practices can out-yield or equal CT because these are the areas where NT is likely to continue to expand in the future. However, the scientific literature is lacking for many of these crops and regions of the world. There are eight countries that comprise 97% of the global no-till acreage reported, with 46.8% of the global NT acreage in South America (Derpsch et al. 2010). However, most research has been conducted in the United States, Canada, and Australia, with very few studies published from South America and Asia. These areas need greater research on disease management because successful practices are regionally specific.

Based on meta-analysis, the largest factors that drive the yield differential in NT systems are the crop species and to a slightly lesser extent, aridity. Oilseed, cotton, and legume NT yields matched CT, while wheat yielded slightly less in NT systems (2.6%), and maize and rice yielded less (>7.5%) (Pittelkow et al. 2015). With only slight differences in wheat production, there have been many research studies conducted to determine how to manage disease in small grain NT production systems. For maize and rice, the yield discrepancy between CT tillage and NT makes the system less cost-effective, which may explain the limited published studies on NT disease management for these crops. For legumes, oilseeds and cotton, disease management research across a wider geographic range may help to make systems even more profitable.

9.2 Challenges of Disease Management

Additional sources of inoculum No-till management has been used in cereal grain production in Australia, Canada, Argentina, and Brazil but is not commonly employed in Europe or in the Pacific Northwest of the United States (Paulitz 2006). A significant barrier to adoption of NT in these areas is the potential increase of residue- and soil-borne pathogens. No-till systems pose challenges in the management of pathogens where substantial inoculum comes from stubble of the previous crop or from the soil. For pathogens that are present on the residue, the rate of residue decomposition affects their ability to survive until the next host crop is planted. Under NT practices, residue decomposes at a lower rate on the soil surface as a result of lower temperatures due to shading and lower water potential due to infiltration (Summerell and Burgess 1988). If burned, partially buried, or managed in a CT system, the residue decomposes more rapidly.

Weed and Volunteer Seedlings as source of disease In CT systems, tillage is used to eliminate weeds and volunteer seedlings that harbor pathogens and create a "green bridge" where biotrophic pathogens that depend on living tissue can survive until the next crop. In the Pacific Northwest, barley and wheat plantings are particularly susceptible to root rot when planted into volunteer wheat and barley or weedy pasture (Roget et al. 1987; Smiley et al. 1992). The volunteers and weeds maintain or increase inoculum levels, resulting in higher disease levels in the subsequent crop. Control of volunteers and weedy hosts is important for controlling viral and soil-borne diseases by reducing the amount of primary inoculum (Kirby et al. 2017).

Micro-environment Soil-borne and residue-borne pathogens are heavily influenced by soil moisture and temperature, which are affected by tillage. As Bailey and Duczek (1996) describe, soil has higher moisture and is lower in temperature in NT systems due to the retention of additional crop residue. This can cause diseases to either increase, decrease or remain unchanged. The observed changes in intensity depend on environmental factors and are variable depending on the year and location grown. For example, low leaf disease severities in wheat were observed in dry hot conditions in Saskatchewan between 1987 and 1992, limiting differences due to effect of tillage, but the years following experienced higher moisture promoting higher disease levels and yield loss in tilled systems (Bailey et al. 1992).

9.2.1 Diseases that Are Reduced in No-Till Systems

There are several diseases that generally decrease in NT systems. Pathogens can be reduced in NT managed systems due to greater competition within the microbial communities that develop and diversify over time when soils are not disturbed, and through changes in the environmental factors that affect pathogen life cycles and dispersal. One example of a disease that often declines in NT systems is take-all disease of cereal crops (Baker et al. 1996). Take-all is caused by the fungal pathogen *Gaeumannomyces graminis* (Sacc.) Arx & Oliver var. *tritici.* When compared with burned and CT treatment, the NT treatments with crop rotation and either burning, stubble removal, or no stubble removal in dryland wheat production all had lower levels of take-all disease (Paulitz et al. 2010). This long term decline in take-all has been observed worldwide and is due to antagonistic *Pseudomonas* spp. that accumulate in the rhizosphere and produce antifungal compounds (Weller et al. 2002; Paulitz et al. 2010). But in a dryland wheat study, species that produce antifungal compounds were also increased in burned and plowed treatments, suggesting that the differences in the NT treatments were due largely to the effect of crop rotation. In other studies, take-all disease was generally limited due to the reduced movement of soil (Baker et al. 1996).

Nematode populations are also commonly reduced under NT practices. The root-lesion nematode *Pratylenchus neglectus* (Rensch) Filipjev Schuurmanns & Stekhoven population was lower in winter wheat-spring barley-canola NT systems where stubble was left standing or mechanically removed, as compared to

CT. However there was also no difference in two of the five years (Paulitz et al. 2010). Root damage caused by another parasite, the cereal cyst nematode (*Heterodera avenae* Woll.), was also found to be reduced, or no different, in NT systems around the world (Roget et al. 1996). Damage from cereal cyst nematode was reduced in three studies in southern Australia (Rovira and Simon 1982; Roget and Rovira 1985; Roget et al. 1996), with no difference in a fourth study (de Boer et al. 1991). Reduced disease from nematodes was attributed to less root damage in the NT treatments. Roget et al. (1996) concluded that it was unlikely that juveniles were trapped in weedy hosts or volunteers, but that the reduction was likely due to limited movement of nematodes and cyst dispersal from lower soil disturbance.

Common root rot caused by *Bipolaris sorokiniana* (Sacc. in Sorok.) Shoem. generally declined under NT compared with CT across several studies in North America, though no differences were observed in some years and locations (Bailey and Duczek 1996). While inoculum was reduced, the inoculum density did not affect disease severity. The authors suggested that the reduction in disease in NT systems could be due to reduced sporulation due to exposure to freezing temperatures, to which the fungus is sensitive. Other causes of lower disease could be the shallower planting depth used in NT, as more root rot occurs with deeper seeding, or the lower temperatures and higher moisture of NT since *B. sorokiniana* causes greatest disease severity under high temperature and low moisture (Bailey and Duczek 1996).

Charcoal rot, caused by *Macrophomina phaseolina* (Tass.) Goid. is the most common root disease of soybeans in Brazil (Wrather et al. 1997) and is most severe under hot and dry conditions. Almeida et al. (2003) found a greater proportion of infected roots in CT treatments compared to NT in dry conditions (<840 mm annual rainfall) and no difference under wet conditions. They attributed the differences observed to the lower water loss and soil temperature in the NT system due to residue coverage and lower light penetration. In moist areas that have frequent droughts, NT could reduce the chance of crop losses due to charcoal rot.

Fusarium crown rot, which was found to be higher in asparagus in Michigan when disked in the spring and fall compared to NT (Putnam and Lacy 1977). In this instance, disease levels may have been reduced in NT due to a reduction in mechanical damage due from tilling that can allow pathogens to more easily infect plants through open wounds.

9.2.2 *Diseases that Are Increased in No-Till Systems*

There are also several diseases that often increase in severity under NT practices. Among these, Rhizoctonia root rot, caused by the fungal pathogen, *Rhizoctonia solani* (Kühn) is the most common soil-borne disease that increases under NT management (Baker et al. 1996). It is widespread across crops, including many cereal, legume, and vegetable crops (Fig. 9.1). Rhizoctonia root rot is typically a minor disease of cereals in CT systems, but can be devastating in NT systems when planted into cereal stubble (Stubbs et al. 2004). Bare patches in wheat, barley and durum

Fig. 9.1 Rhizoctonia solani lesions on common bean plants. (Photograph courtesy of H. F. Schwartz, Colorado State University, Bugwood.org)

caused by Rhizoctonia root rot were first observed in the United States in 1984 in Oregon, Idaho, and Washington and was only found in fields planted using conservation tillage practices, including NT direct drilling into stubble, sowing with minimal tillage, or tillage the day of planting (Weller et al. 1986). Many studies in southern Australia have also demonstrated an increase in Rhizoctonia in NT systems (MacNish and Lewis 1985; Rovira 1987; de Boer et al. 1991). Subsequent studies in wheat have shown that *R. solani* populations and resulting disease were higher in NT (Paulitz et al. 2010). However, when left in continuous NT management for 7–10 years, Rhizoctonia rot diminished (Kirby et al. 2017). This may result from natural disease suppression as microbial communities become more diverse over time without disturbance.

In vegetable NT systems, young seedlings are directly exposed to *R. solani* from the surface residue causing poor stands and deformed plants. Moldboard plowing compared to reduced tillage methods reduced *R. solani* populations by 75% after corn, 16% after legumes, and 12% after vegetables (Sumner et al. 1986a, b). Among many vegetables tested, Sumner et al. (1986a, b) also found diseases of snap bean and lima bean were caused by *R. solani* and an unidentified basidiomycete, when following corn in NT systems. They found root and hypocotyl cankers as well as postemergence damping off to be less common in CT treatments (Sumner et al. 1986a, b). However, large populations of *R. solani*, do not necessarily result in disease development or reduced yield. For example, despite higher *R. solani* concentrations in NT systems, there were no major yield losses during the course of a 6 year study, which was attributed to potential compensation from adequate moisture levels or microbial suppression (Paulitz et al. 2010). And although Rhizoctonia root rot was more severe in NT spring barley compared with moldboard plowed, there was no relationship with yield; barley yield was actually higher in the NT managed treatments due to less loss of water in the tilled plots prior to planting (Smiley and Wilkins 1993). The trend was not isolated to particular years or locations; Smiley and Wilkins (1993) found the yield was highest in treatments with the highest consecutive years of NT management across locations.

Fig. 9.2 *Fusarium* head blight of wheat. (Photograph courtesy of Donald Groth, Louisiana State University AgCenter, Bugwood.org)

Other common fungal pathogens of NT systems are *Fusarium* spp., which also cause significant damage to many crop species, including wheat (Fig. 9.2). In Germany, France, Switzerland and Croatia, higher disease incidence of Fusarium head blight in wheat following maize has been observed in NT and reduced tillage systems (Basch et al. 2008; Vrandečić et al. 2019). Disease caused by *Fusarium* spp. is likely higher under reduced tillage due to changes in soil moisture, temperature, and seeding depth (Bailey and Duczek 1996). In vegetables, reduced tillage increased root rot with symptoms from *Fusarium* (Abawi and Crosier 1992).

In studies conducted in NT vegetable systems, several additional pathogen species were associated with root disease. Abawi and Widmer (2000) found lower yield in snap beans in New York due to disease in reduced tillage compared to intensive tillage. In addition to *Fusarium* and *Rhizoctonia, Thielaviopsis* was also attributed to increased root rot in NT vegetable production (Abawi and Crosier 1992). Southern blight caused by *Sclerotium rolfsii* Sacc. survives saprophytically on residue on or near the soil surface. Yield losses due to southern blight were greater in reduced tillage systems compared to deep tillage in carrot and tomato in tropical regions, and in lettuce in Australia (Sumner et al. 1986a, b). Cercospora leaf spot (*Cercospora cruenta* Sacc.) and rust of cowpea (*Uromyces* spp.) and early bight of tomato, caused by *Alternaria solani* (Ell. & Mart.) L.R. Jones and Grout, were found to be more severe in reduced tillage than with moldboard ploughing (Sumner et al. 1986a, b). The authors attributed the higher disease levels more to the overall plant health due to access and uptake of nutrients and tillage compaction rather than a change in the pathogen community.

9.2.3 Diseases Not Affected by Tillage

Root diseases caused by pathogens that survive for long periods of time in the soil and are not impacted by disturbance may remain unaffected by NT, or even decrease in severity due to competition with other microbes and more limited dispersal. In vegetable production systems, *Pythium* spp. are usually not affected by conservation tillage methods; possibly because *Pythium* spp. can survive for several months as oospores in the soil (Sumner et al. 1986a, b). The inoculum is likely not increased substantially by the presence of residue on the surface. Fusarium in vegetable production in the southeast US was also not affected by tillage practice, with rotation more important in management of *Fusarium* spp. (Sumner et al. 1986a, b).

9.2.4 Disease Variability in No-Till Systems

There are many cases of disease that are influenced by environmental conditions. Take-all severity has been somewhat variable by region (Roget et al. 1996), with reductions observed in Britain (Brooks and Dawson 1968; Lockhart et al. 1975; Bockus et al. 1994), increases in the northwest United States (Moore and Cook 1984), and either no effect or increase in southern Australia (Kollmorgen et al. 1987; de Boer et al. 1991). Some of this variability is due to temperature or moisture differences. In Kansas, the soil temperatures in plots with residue left to shade the soil surface were 8–10 °C cooler than unshaded plots and had the higher severity of take-all with lower wheat grain yields (Bockus et al. 1994). Higher soil moisture of NT systems also facilitates greater microbial activity and faster decomposition of infected residue and limitation of *G. graminis* (Garrett 1938). However, while higher soil moisture reduces take-all disease in some environments, temperature was the driving factor in take-all disease development in Kansas (Bockus et al. 1994). In areas where high temperatures exist with high summer rainfall, take-all may also be more severe under NT management, which reduces the soil temperature enough to allow the pathogen to survive in the presence of adequate moisture.

9.3 Management Options to Address Disease Challenges

The management practices to address disease challenges in NT are similar to those used in CT. But, as emphasized by Baker et al. (1996), correct identification of the pathogen is essential as the management measures for a pathogen may differ in efficacy between NT and CT.

9.3.1 Crop Rotation

The order of rotation is the most important factor in reducing disease in dryland production in both NT and CT systems. If a crop is not rotated, the severity of disease may also become higher over time due to the evolution of more aggressive pathogen strains (Bailey and Duczek 1996).

Root disease severity in vegetable crops, including lima bean, cowpea, cucumber, and spinach, have exhibited higher disease levels due to conservation tillage practices. Disease levels of reduced and CT tillage treatments were the same, however, when grown in a different crop rotation (Sumner et al. 1986a, b). This indicates that increases in disease due to reduced tillage could be mitigated by changing the crop rotation.

Rotations of multiple years before planting similar crop species, such as broadleafs and cereals, are needed to achieve disease reduction (Bailey and Duczek 1996). Although other management techniques can reduce the severity of Fusarium head blight in cereals, the disease reduction is not sufficient without altering the rotation sequence so that wheat does not follow maize (Vogelgsang et al. 2011). In some cases, longer rotations may be needed when pathogens remain viable for long periods of time. The fungal pathogen, *B. sorokiniana,* which causes root rot in wheat, has spores that remain viable up to 4 years (Bailey and Duczek 1996). Rotations are very effective in limiting disease, but may require multiple years and do not allow flexibility to plant the most profitable crop.

9.3.2 Genetic Resistance

For pathogens that have a very wide host range, or infect all economically important crops for a region, crop rotation may not be a feasible method of disease control. One example of this is in the control of charcoal rot on soybeans in Brazil. Charcoal root rot affects both corn and soybeans, as well as cotton, peanut, sunflower, sorghum, and other vegetable crops (Almeida et al. 2003). In these instances, disease resistant cultivars often offer the most cost-effective solution.

In perennial grain cropping systems, yearly rotation is also not possible. Perennial grain crops are being developed to restore capacities of native grasslands, preventing erosion and maintain water and nutrients. But the perennial nature of the system poses a challenge in elimination of the annual rotation schedule. In these instances it is important that the crops selected for development have broad genetic diversity (Jensen et al. 2016) and strong genetic resistance to disease (Turner et al. 2013). Genetic resistance is being combined with other management techniques and a diverse soil microbial community that develops over time, to reduce diseases in perennial grain crops.

Genetic resistance is also available for ubiquitous, aerially dispersed pathogens and their diseases where rotation is not effective (Paulitz 2006), for some long-living pathogens that infect roots (Kirby et al. 2017), and is an important tool for reducing mycotoxin accumulation in maize and cereal grains (Campa et al. 2005). Genetic resistance provides a control strategy that does not require additional costly inputs or additional labor in management. For many soilborne pathogens, however, genetic resistance is not available, and growers are more reliant on cultural practices.

9.3.3 Chemical Control of Disease

In combination with crop rotation and genetic resistance, chemical control provides a solution for high value crops grown in environments conducive to high disease pressure. Baker et al. (1996) suggest using chemical control to complement rotation. This chemical control includes both fungicides to manage disease and herbicides to manage weedy or volunteer plants that could harbor pathogens of insect vectors of pathogens.

9.3.3.1 Fungicide

For foliar fungicides to be cost effective, grain prices must be sufficiently high (Bailey and Duczek 1996) and environmental conditions conducive to disease development. Often when moisture conditions are optimal for high yield potential, they are also likely to produce high disease pressure from numerous fungal and bacterial pathogens.

To avoid applying chemicals when environmental conditions are not conducive for disease development, modeling programs have been designed that are specific to crop, pathogen and disease, and location. An example is the FusaProg developed in Switzerland, which incorporates cropping factors, previous crop, soil and straw management, and cultivar susceptibility with growth stage and weather conditions in a model that predicts the toxin content of wheat prior to harvest (Musa et al. 2007). In Canada there is a similar program called DONcast (Schaafsma and Hooker 2007) and in France and Belgium there is a program called Qualimètre® (Froment et al. 2011). These programs allow growers to determine a threshold of tolerance to determine when to apply fungicides optimally.

One limitation to these tools is the need to calibrate them to each location and design models specific for local conditions. When the DONcast model was applied to the Czech Republic, the most predictive parameters included the previous crop, total precipitation and average temperature in April, and total precipitation and average temperature 5 days before anthesis; but in other regions additional factors like cultivar, fungicide use, climate factors during different times in the growing season, leaf wetness, and growth stage were more relevant (Van Der Fels-Klerx and Booij 2010). When considering other crops, there are different parameters to consider as well. In maize the best fitting model developed for Argentina and the Philippines included predictors of insect damage, and weather at four time periods (Campa et al. 2005); in Italy the optimal model included longitude, maturity class, sowing date, and growing weeks (Battilani et al. 2008).

9.3.3.2 Herbicide

Chemical application to control weeds and volunteer crops also require a significant investment to the producer and will be driven largely by the value of the crop and the potential for crop losses due to disease. Volunteer crops and weedy hosts facilitate a ‘green-bridge’ of living tissue that can harbor pathogens and insect vectors until the next crop germinates. In CT systems, the field would be tilled prior to planting to remove weeds, including volunteers, and prepare the seedbed. To avoid this overlap of susceptible plants in NT systems, herbicide can be applied to kill the weeds and volunteer seedlings. After a herbicide treatment, delaying planting by at least 21 days after spraying prevented transmission of bacteria in continually cropped cereals (Baker et al. 1996).

Breaking the “green bridge” period before planting when volunteer cereals or weedy hosts of *R. solani* are growing is one of the most effective practices in decreasing Rhizoctonia rot in barley (Smiley et al. 1992). Roget et al. (1987) showed that Rhizoctonia rot in direct-drilled wheat was lower and grain yields were higher when volunteer pasture comprised largely of barley and ryegrass was sprayed 3–6 weeks prior to planting. *R. solani* can colonize dead or dying weeds and volunteers and contribute to higher levels of infection if planted too quickly after spraying (Smiley et al. 1992). When volunteer barley was killed by spraying the canola crop, the canola was infected with *R.solani* and began dying within 2 weeks (Paulitz et al. 2010). The timing of killing weed and previous crop is thus crucial for control of disease when the crop can host the same diseases.

Besides herbicide chemical weed control, non-chemical controls can be used to manage weeds and volunteers including flame weeding, steam weeding, knife rolling, or hand weeding (Baker et al. 1996). These methods require additional labor or specialized equipment, but are valuable in systems where herbicide use is not possible.

9.3.4 Stubble and Residue Management

Management of standing stubble and crop residue is particularly important in NT agriculture, providing a method to reduce the population sizes of some residue-borne pathogens. For example, burning stubble reduced *Fusarium psuedograminearum* and *F. culmorum* in winter wheat-spring barley-canola NT system to levels no different from CT tillage (Paulitz et al. 2010). The authors of this study also found that inoculum was higher when stubble was mechanically removed or left standing, but that stubble removal had no effect on *R. solani* inoculum concentration. Burning has also been used successfully to control *Sclerotium oryzae* (Catt.) in rice, Blind seed disease of grasses, and Cephalosporium stripe of wheat (Skoglund et al. 1999).

Although burning has been shown to be effective in reducing infected residue, some concern exists that burning could reduce total carbon which would could be detrimental for maintaining and improving soil quality (Basch et al. 2008). But Chan et al. (2002) found that burning did not affect the total carbon as much as tillage, which explained 80% of the variation. Particulate organic carbon and mineralizable nitrogen were also reduced more by tillage than by burning. These results indicated that tilling can have a much greater negative effect on soil health than burning.

Another method of reducing stubble involves chopping residues finely for faster decomposition. When wheat follows maize in rotation, *Fusarium* spp. that cause head blight were reduced by planting less susceptible wheat varieties and by fine chopping maize residues (Oldenburg et al. 2007). However, although disease was reduced, the levels of mycotoxin still exceeded European standards and altering the rotation sequence was also recommended (Vogelgsang et al. 2011). Methods to break up residue can thus have some effect on disease severity, but may require use in combination with other control approaches.

9.3.5 Mechanical Disruption of Soil and Root Pathogens

Without intensive tilling, there are other management practices that can be used to control diseases. Planting techniques that disturb the soil 0.05 m below the seeding depth using a thin implement at the time of planting, have been effective at reducing Rhizoctonia and take-all; using a modified seed drill designed with narrow sowing points for minimal soil disturbance resulted in lower disease levels than the standard NT drills that disturb the soil at a shallower depth (Roget et al. 1996). When this specialized planting technique was combined with a chemical fallow treatment, disease levels were comparable to CT methods (Roget et al. 1996). Jarvis and Brennan (1986) also found that direct drilling with a modified combine drill with tines that penetrated to 0.10 m reduced Rhizoctonia rot severity. While this practice disturbs the soil slightly below the location of the seed, it does not mix or stir the soil yet provides enough disturbance to disrupt the hyphal growth of *R. solani* to reduce disease incidence.

9.4 Conclusions

Diseases caused by pathogens like *Rhizoctonia* and *Fusarium* are known to increase in NT systems, but these pathogens and their diseases can be managed through rotation, genetic resistance, and use of chemicals, with other important disease reductions achieved through management of stubble residue and mechanical disruption during planting. So far, there are no disease problems of NT agriculture that are insurmountable or untreatable (Baker et al. 1996). However, the research to support the adoption of NT agriculture is specific to region and crop. Additional research is needed for cotton, oil seeds, vegetables, and legumes that have potential to yield more in no-till than in CT systems, and for targeted environments in South America and Asia where no-till is implemented on the greatest area of land.

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Chapter 10
Strategic Tillage for the Improvement of No-Till Farming Systems

Charles S. Wortmann and Yash P. Dang

Abstract Farming with no or zero tillage (NT) is a valuable practice in many agroecosystems, but problems may develop that can be solved, or NT may otherwise be improved, by occasional strategic tillage (ST). The practice of ST has been evaluated in numerous studies. Problems addressed by ST in research have included weed control, soil compaction, water infiltration, SOC sequestration, vertical stratification of soil properties, and runoff of soluble nutrients. Very often ST has had no or small short-term positive and negative effects. Increases have occurred more frequently than decreases with ST for water infiltration, erosion, P availability, and grain yield. Decreases have occurred more frequently than increases with ST for dissolved nutrient loss, weed numbers, microbial biomass or activity, bulk density of the surface soil, and soil compaction. Benefits with no associated detrimental effects were more likely to occur with deep inversion tillage compared with shallow tillage. Successful ST requires careful consideration of the production situation and the problem to be solved and then making a good choice of the tillage type, depth, timing, and frequency.

Keywords Compaction · Erosion · No tillage · Occasional tillage · One-time tillage · Strategic tillage · Weed · Zero tillage

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10.1 Introduction

The benefits of continuous no-till (NT; in this chapter, NT refers specifically to continuous no-till or zero tillage and excludes reduced and conservation tillage, no-tillage rotated with tillage, and other alternatives) are well-proven, especially for reducing soil erosion, evaporative loss of soil water, energy use, and equipment needs. Of great agronomic significance is the typical increase in soil organic C (SOC) in the surface 0.1 m of soil, often accompanied by increased soil aggregate stability, improved water infiltration and increased resistance to erosion. Yield is often increased with NT compared with the common tillage practices where soil water deficits commonly occur, but increases are less likely with humid conditions.

There can be significant challenges associated with NT. Compaction and water repellency can constrain NT success (Blanco-Canqui and Ruis, 2018). Dang et al. (2015a) reviewed information on the build-up of soil- and stubble-borne diseases, insect pests and herbicide-resistant weeds with NT in the northern grain region of Australia and found that these issues often constrained NT productivity. Surface soil enrichment and sub-soil depletion of soil properties also develop with NT and may limit plant nutrient uptake (Pierce et al. 1994; Garcia et al. 2007), while soluble nutrient and herbicide runoff may often increase with NT (Gaynor et al. 1995; Mickelson et al. 2001; Devlin et al. 2009).

Strategic tillage (ST) of NT (also called one-time or occasional tillage) may address problems with NT. The purpose may be one or several, such as to: improve control of weeds, diseases or insect pests; fracture a compaction layer; incorporate a soil amendment, such as lime or manure; reduce nutrient stratification; increase SOC at greater depth; or reduce crop residue accumulation (Quincke et al. 2007a; Melero et al. 2011; Fidalski et al. 2015). While there is much evidence that ST can be conducted without serious negative consequences, there is ongoing concern that "*Years of soil regeneration can be lost to a single tillage event*" (Grandy et al. 2006). The practice of ST should be in response to some opportunity and well-identified purpose, as there may be a significant risk of erosion associated with ST and ST is likely to have some added cost. To be successful, ST needs to be well-justified and well-matched with the purpose for which it is being conducted with consideration given to the most appropriate type, timing and depth of tillage (Dang et al. 2015a).

10.2 Impacts of Strategic Tillage

The impacts of ST on soil, management and environmental properties have varied (Table 10.1). With a few noted exceptions, the effects of ST are only reported as negative or positive if statistically significant at $P < 0.05$.

Table 10.1 Studies of strategic tillage for no-till systems considered in this review

Study location and soil type/ texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
AU, sand, loam	MP	Weeds	Yield	↑	Data collected over 2 years	Douglas and Peltzer (2004)
			Weed No.	↓		
USA, Sandy loam, loamy sand, silt loam, sand	MP	Weeds	Yield	↑	Data collected over 1–2 years cover crops also employed to decrease weed loads.	Price et al. (2016)
			Weed No.	↓		
AU, Lixisols and chromic Solonetz	Scarifier or offset disks	Multiple	SHC, yield	NS	Measurements made over 4 seasons	Conyers et al. (2019)
			SA	↓		
USA, loam	Disk harrow	Herbicide loss	Runoff, herbicide loss, BD, SHC	↓	First year after tillage, exact time unspecified	Warnemuende (2007)
USA, loam	Vertical tillage	Nutrient loss	N in runoff	ns	1 week after tillage	Smith and Warnemuende-Pappas (2015)
			Erosion, runoff, soluble P	↑		
USA silt loam	Disk, chisel and harrow	Nutrient loss	Runoff, N and P in runoff, SHC	↓	2–3 months after tillage	Smith et al. (2007)
USA, clay	MP, disk harrow	Unspecified	CO_2 flux	↑	1–2 days after tillage	Reicosky et al. (1997)
SP, clay loam,	MP	Compaction	SOC, WSC, AC, DHA, Glu	↓ (MP)	3 months after tillage	Melero et al. (2011)
	Chisel		MBC/N	NS(MP)		
			SOC, AC, MBC/N, DHA	NS (Chisel)		
			WSC, Glu	↓(Chisel)		
BR, Oxisol	–	Compaction, nutrient stratification	Yield	NS	6 months after tillage	Fidalski et al. (2015)
			BD	↓		

(continued)

Table 10.1 (continued)

Study location and soil type/ texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
USA, clay loam,	Offset disk	Compaction	Runoff	↑	3 months after tillage	DeLaune and Sij (2012)
Turkey, Vertisol	MP	Compaction, nutrient stratification	BD, PR, SW,	↓	1 year after tillage	Celik et al. (2019)
			SA, macro and total porosity	↑		
AU, Vertosol (v) (10) Sodosol (s) (2) Dermosol (d) (2)	Chisel, narrow chisel, disk, offset disk, prickle chain, Kelly chain, tyne, scarifier	Various over 14 properties	Grain yield, profitability, CO_2, CH_4 (v/s), runoff (d), erosion (s), weeds (s)	↑	Monitored over 3-years	Dang et al. (2018)
			BD, SOC, POC, P, TMA (d/s), runoff (v), erosion (v/d), N_2O	NS		
			BD (s), SW, POC, TMA (v), infiltration (s/d), weeds (v,d)	↓		
AU Sodosol/ Solonetz	Chisel	Weed control	MBC/N, TMA, CLPP	NS	1 year after tillage	Liu et al. (2016b)
AU Dermosol/ Calcisol	Chisel	Weeds	MBC, TMA, Catabolic activity	↑	13 months after tillage. Greater effects in chisel compared to offset disk	Liu et al. (2016c)
	Offset disk					
AU Vertosols	Chisel, disk	Weeds	Grain yield, SW, pH, BD, EC, P, SOC, MBC, metabolic activity	NS	4–7 weeks after tillage	Liu et al. (2016a)
AU, Vertosol, Sodosol Dermosol	Cultivator, Kelly prickle harrow	Weeds, pests	Runoff (s/d), erosion (s), CO_2 (s)	↑	Several months after 3 ST operations	Melland et al. (2017)
			Runoff (v), erosion (v/d), N_2O, CO_2 (v)	NS		
			CH_4 oxidation (s)	↓		

Study location and soil type/ texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
AU, Vertosols	Chisel plough, offset disk	Weeds	MBC, enzyme activity, CLPP	NS	2–17 weeks after tillage	Rincon-Florez et al. (2016) and Radford and Thornton (2011)
AU, Vertosols	Chisel	Unspecified	Enzymatic activity, metabolic diversity, CLPP	NS	15 weeks after tillage	
AU, Vertisols	Chisel & blade (every year)	Weeds	Grain yield	NS	22 crops average	
Aridisol			SOC (0–0.2 m), weeds	↓	After 9 years	
AU, Vertisols (3)	Chisel or offset disk or chain harrows	Weeds	Grain yield	NS	1st & 2nd crop	Crawford et al. (2015)
Sodosols			SOC, P, BD, POC, SW, FDA (0–0.1 m)	NS	After 3 months	
Dermosol			Weeds	↓	In-crop	
USA, silt loam	MT or sweep (three occasions)	Weeds	Grain yield	↑	1st & 3rd crop	Kettler et al. (2000)
			SOC, TN (0–0.075 m)	↓	After 5 years	
			pH, BD (0–0.075 m)	↑	After 5 years	
			Weed population	↓	After 1 and 3 years	
			Macroporosity	NS		
Silt loam	Chisel & disk	Soil compaction	Grain yield	↑	1st crop	Díaz-Zorita et al. (2004)
			Grain yield	↓	2nd & 3rd crop	
			SOC, TN, P (0–0.1 m)	NS	After 8 or 20 months	
			SW, SA, SHC (0–0.1 m)	↓		
			Macroporosity	↓		

(continued)

Table 10.1 (continued)

Study location and soil type/texture	Tillage implement	Reasons	Parameters measured	Response	Remarks	Reference
USA, silty clay loam (2)	Chisel or Disk or MT	Multiple	Grain yield, WA	NS	1st crop	Quincke et al. (2007a, b) and Wortmann et al. (2008, 2010)
			Grain yield, WA	↑	2nd crop	
			P runoff (0–0.025 m)	↓ (MT)	After 2 years	
			SOC, POC, AC (0–0.025 m)	↓	After 2 years	
			SOC, POC, AC (0.05–0.1 m)	↑	After 2 years	
			Yield, SA, SOC, P, VAM, MBC	NS	After 5 years	
USA, silt clay loam	Chisel or Disk or MT	Nutrient stratification	P, K, VAM (0–0.025 m)	↓ (MT)	After 1 year	Garcia et al. (2007)
			P, K, VAM (0.025–0.1 m)	↑ (MT)	After 1 year	
CA Chernozem fine-loam	Cultivator once or Cultivator twice or Cultivator twice, disk	Weeds	Grain yield	NS	1st, 2nd, 3rd crops	Baan et al. (2009)
		Nutrient stratification	SOC, POC, pH, SA (0–0.1 m)	NS	After 2 months	
			BD (0.05–0.1 m)	↓		
SP Eutric Leptosol (silty loam)	MT & disk	Soil compaction	Grain yield	NS	1st & 2nd crop	López-Garrido et al. (2011)
			Grain yield	↓	3rd crop	
			SOC, AC, β-glu (0–0.05 m)	↓	After 1 year	

Numbers in parenthesis are the number of sites; *MT* moldboard plow tillage, *SOC* soil organic C stocks, *POC* particulate organic C (53–250 µm), *WSA* water stable soil aggregates, *P* extractable phosphorus, *K* extractable potassium, *TN* total N, *SW* soil water, *SHC* saturated hydraulic conductivity, *BD* bulk density, *PR* penetration resistance, *AC* active C by $KMnO_4$ oxidation, *DHA* dehydrogenase activity, β-glucosidase activity (Glu), *VAM* vesicular arbuscular mycorrhizae, *SA* soil aggregates, *MBC* microbial biomass, *β-glu* β-glucosidase activity, *v* Vertosol, *s* Sodosol, *d* Dermosol, ↓ or ↑ indicate significant decrease or increase, respectively, at $p < 0.05$; *NS* non-significant

10.2.1 Soil Chemical Properties

Vertical stratification of immobile nutrients and SOC is commonly observed under NT, with high concentrations in the surface 0–0.05 m of the soil profile (Pierce et al. 1994; Garcia et al. 2007; Obour et al., 2018). Soil pH may also become stratified, although trends are less consistent and the extent of pH stratification is affected by N fertilizer management.

The effect of occasional ST on nutrient and SOC stratification has largely been found to depend on the type of ST tillage. More disruptive forms of tillage, such as inversion tillage with a moldboard plow, are often found to be most effective at reducing nutrient and SOC stratification ratios compared to less disruptive forms, such as with chisel or disk ST, which often have no effect on nutrient distribution (Garcia et al. 2007; Quincke et al. 2007a) (Table 10.1). Scanlan and Davies (2019) found that 80, 60, 60, and 10% of a sandy soil from the 0–0.1 m depth was moved deeper with ST by moldboard plow, disk plow, rotary spader, and off-set disk harrow with deep ripping, respectively. López-Garrido et al. 2011 and Melero et al. 2011 reported reduced SOC stratification with chisel plow ST, but others reported little ST effect on nutrient or SOC stratification (Crawford et al. 2015; Fidalski et al. 2015; Liu et al. 2016a, b; Dang et al. 2018; Celik et al. 2019).

Where NT has resulted in lowered surface soil pH, ST can increase surface soil pH (Kettler et al. 2000; Table 10.1). The redistribution of soil acidity in NT soil was greater with moldboard plow ST compared with chisel- and disk-ST (Garcia et al. 2007). Baan et al. (2009) and Díaz-Zorita et al. (2004) reported no effect of chisel- or disk-ST on soil pH stratification.

10.2.2 Soil Physical Properties

10.2.2.1 Compaction and Soil Aggregation

Strategic tillage of NT soil can fracture soil hardness and create increased soil macroporosity in the tilled zone, but results have varied (Table 10.1). Moldboard plow ST decreased bulk density and penetration resistance and increased macroporosity in some studies (Pierce et al. 1994; Celik et al. 2019) but increased bulk density in another study (Kettler et al. 2000). Bulk density was not affected by ST in other studies (Liu et al. 2016a; Dang et al. 2018). Surface soil aggregation was reduced by ST for a short time in other studies (Grandy et al. 2006; Dang et al. 2018; Conyers et al. 2019), but Quincke et al. (2007a) reported no effect.

10.2.2.2 Soil Hydrology

The practice of NT has inconsistently affected the rate of water infiltration, but it is commonly credited with reduced evaporation of soil water and increased soil water storage (Randall and Mulla 2001; Holland 2004). Soil compaction and reduced bulk density under NT (particularly in the absence of controlled traffic) can reduce water infiltration, saturated hydraulic conductivity, percolation, and soil water content, while the development of macropores may improve on these properties (Shipitalo et al. 2000; Uusitalo et al. 2018).

The effect of ST on water infiltration has been inconsistent. At 23–30 months after ST, sorptivity and infiltration rate were similar for ST and NT at one location in eastern Nebraska, but the rate of infiltration was 2.5 times higher for disk-ST and moldboard plow-ST compared with NT at the second location (Quincke et al. 2007a). Kettler et al. (2000) reported that at year 5 after ST, the water infiltration rate was similar for the first 25 mm applied, but the rate for NT was 46% of the rate for ST with the second 25 mm applied. Dang et al. (2018) found that the rate of water infiltration was reduced by ST for a Sodosol and a Dermosol but not affected by ST at five locations with Vertisols. The water infiltration rate was similar for NT and ST in other studies (DeLaune 2012; Conyers et al. 2019).

Soil water content was less at 3 months after ST for one site, but was not affected by ST for another 19 observations (Dang et al. 2018). Melland et al. (2017) found lower soil water content in the 0–0.075 m soil depth with NT compared to ST. The available soil water holding capacity was reduced by moldboard plow ST in the 0–0.2 m depth (Celik et al. 2019).

10.2.3 Soil Microbial Properties

Soil microbial biomass and activity can become stratified under NT, while tillage can disrupt mycelial networks, expose aggregate-protected microbes and enhance microbial activity (Doran 1987; Doran et al. 1998; Mozafar et al. 2000; Drijber et al. 2000).

Microbial biomass in the 0–0.05 m depth for year 1 and 2 following moldboard plow ST in eastern Nebraska was reduced by 35 and 28% for bacteria, 51 and 18% for saprophytic fungi, and 51 and 51% for arbuscular mycorrhiza (Wortmann et al. 2008). However, the biomass of bacteria and saprophytic fungi of the 0.05–0.2 m depth were consistently increased with ST, so that generally there was no loss in total microbial biomass for the 0–0.2 m depth. The biomass of arbuscular mycorrhiza was inconsistently affected at the 0.05–0.2 m depth, but root colonization by arbuscular mycorrhiza with ST was 53% of the NT level during the late reproductive stage of year 1 (Garcia et al. 2007). At 5 years after moldboard plow ST, mycorrhizal biomass was still reduced at one location, but unaffected at another location compared with NT (Wortmann et al. 2010). Biomass of bacteria was also less at 5 years after moldboard plow ST compared with NT.

Microbial biomass was inconsistently affected by moldboard plow ST, but microbial activity was decreased in the surface soil during year 1 (López-Garrido et al. 2011; Melero et al. 2011). Microbial biomass or activity were not affected by ST in other studies (Crawford et al. 2015; Dang et al. 2015b; Rincon-Florez et al. 2015, 2016; Liu et al. 2016a, b, c; Dang et al. 2018).

10.2.4 Environmental Consequences

10.2.4.1 Greenhouse Gas Flux

Tillage system effects on GHG emission have been inconsistent (Lu et al. 2016; Behnke et al. 2018). Emission of CO_2 can be much increased by ST during warm weather (Reicosky and Lindstrom 1993). The cumulative CO_2 emission at 6 and 30 days after ST was greater for chisel and disk ST compared with NT, but not for moldboard plow when ST was conducted at low soil temperatures (Quincke et al. 2007b). The SOC mass at 24–32 months and again at year 5 after ST was not affected by ST using the equivalent soil mass calculation (Wortmann et al. 2010). At 2 years after ST, SOC stock in the 0–0.3 m depth was similar for NT and all ST treatments (López-Garrido et al. 2011; Melero et al. 2011). Melland et al. (2017) reported reduced methane absorption for a Vertisol and more CO_2 emission for a Sodosol following ST. There was no ST effect on either greenhouse gas emission for a Dermosol or on N_2O emission for all soil types.

10.2.4.2 Runoff, Erosion and Nutrient Loss

No-till compared with conventional tillage reduces erosion and particulate P loss in runoff, but not dissolved P in runoff (Rhoton et al. 2002; Puustinen et al. 2005; Fu et al. 2006; Daryanto et al. 2017). The greater ground cover with NT compared with tilled gives protection against wind and water erosion (Blanco-Canqui and Wortmann 2017). Runoff volume has been inconsistently affected by NT as the effects of soil compaction and macroporosity have varied (Holland 2004). High P concentrations at the soil surface can contribute to high dissolved P concentrations in runoff. The effect of ST on runoff, erosion and nutrient loss has thus also varied.

Under simulated rainfall, runoff has been reported to be less with ST than with NT (Smith and Warnemuende-Pappas 2015; Dang et al. 2018), similar for NT and ST at 23–30 months after ST for one location, but higher with NT for another (Quincke et al. 2007a), and more with ST than with NT (DeLaune 2012; Melland et al. 2017). Sediment load was greater with ST than with NT in some studies (DeLaune 2012; Smith and Warnemuende-Pappas 2015; Dang et al. 2018) but ST did not affect sediment loss for a Vertisol (Dang et al. 2018).

Total N and P loss in runoff were generally greater with ST than with NT (DeLaune 2012; Smith and Warnemuende-Pappas 2015; Dang et al. 2018), but not for Vertisols (Dang et al. 2018) and Quincke et al. (2007a) reported inconsistent effects of moldboard plow ST on particulate P in runoff. The runoff concentration of soluble or dissolved P was higher with ST than NT (Smith and Warnemuende-Pappas 2015; Dang et al. 2018). Dissolved N and P loads of runoff were not affected by ST in other studies (Quincke et al. 2007a; DeLaune 2012; Smith and Warnemuende-Pappas 2015).

10.2.5 Weed, Disease and Insect Pest Control

Some weed species may be greatly reduced with continuous NT where a combination of herbicides, crop rotations, cover crops, and other practices (e.g. row spacing, seeding rate, crop planting time) can be used for crop suppression of weeds (Wicks et al. 2000). Some annual and perennial grassy weeds, however, have not been well-controlled in wheat without tillage (Kettler et al. 2000; Chauhan et al. 2012), and many weed species now have resistance to common herbicides such as glyphosate (Sarangi and Jhala 2018). The practice of ST may be used as an additional tool for the management of weeds that have growth and adaptation similar to the main crop, or that have natural or developed resistance to labeled herbicides (Dang et al. 2015a).

Some studies have found ST to be useful in weed control (Table 10.1). Weed numbers were reduced by ST for up to 5 years (Kettler et al. 2000), 2 years (Price et al. 2016), 1 year (Crawford et al. 2015), and 3–12 months (Dang et al. 2018). Douglas and Peltzer (2004) reported reduced weed density for herbicide-resistant annual rye grass following moldboard plow-ST and estimated that ST once in 8–10 years would be sufficient to off-set the development of resistance. Weed density at 7 and 14 weeks after chisel and disk ST were not reduced for a Vertisol (Liu et al. 2016a). The greatest reductions in weed density were with deep inversion ST (Kettler et al., 2000; Price et al. 2016).

In Australia, ST is sometimes practiced for "pupae busting after cotton" (Melland et al. 2017) and potential opportunities for disease and insect pest control have been discussed (Dang et al. 2015a). Effects on ST on disease and insect pests requires further research.

10.2.6 Grain Yield

The effect of ST on grain yield has been inconsistent and often varies with ST success or failure in alleviating problems associated with long-term NT (Table 10.1). Wheat grain yield was increased by 30, 9 to 0% for Year 1, 3 and 5 following moldboard plow ST compared with NT, with the yield increase attributed to improved weed control (Kettler et al. 2000). Dang et al. (2018) reported grain yield increases in two of 14 trials and no decreases for crop 1 following ST, with an overall 3% mean yield increase with single-pass ST. Soybean yield over 5 years following ST was 3.6% more with disk, chisel and moldboard plow ST, but 11% more with mini-moldboard plow ST, compared with continuous NT (Quincke et al. 2007a; Wortmann et al. 2010). The 2.6% mean yield increase with ST for maize and grain sorghum was not statistically significant. Other yield increases resulting from ST have been reported (Douglas and Peltzer 2004; Chastain et al. 2017). In other studies, ST did not result in increased crop yield (Crawford et al. 2015; Fidalski et al. 2015; Liu et al. 2016a, b; Conyers et al. 2019), or had inconsistent effects (West et al. 1996; Baan et al. 2009; López-Garrido et al. 2011; Dang et al. 2018; Celik et al. 2019).

10.3 The Place of Strategic Tillage in Crop Management

The above information indicates that ST can be conducted without long-term harm to soil properties and cropping system productivity provided runoff and erosion are adequately controlled, but that ST will often not be beneficial. In an interpretation of numerous ST studies, Dang et al. (2015b) suggested that the most likely effects of ST included: i) increased plant available water, P availability, water and dissolved nutrient runoff; and ii) reduced weeds, soil-borne diseases, soil biota, soil C and N, and profitability. However, all of these properties were affected inconsistently by ST, with mostly short-term small or no effects. Therefore, flexibility in NT management to allow for ST is justified providing there is adequate consideration of the problem or opportunity to be addressed and there is good choice of ST type, timing and frequency. Deep inversion ST, such as with a moldboard plow compared with shallow ST, requires more energy and cost and has more evaporative soil water loss, but may be required for effective ST with the exception of fracturing soil compaction.

The timing of ST may have implications for soil water availability during crop establishment, high CO_2 emission with warm soils, susceptibility to erosion, duration of ground cover loss, impact on weeds, and the value of improved water infiltration. Timing of ST needs to consider the crop rotation and how to best fit it into the cropping sequence. The soil water content at the time of ST is also important, with relatively low soil water required for effective fracturing of compacted soil and reduced evaporative loss. However, ST with low soil water may require excessive energy and result in clod production that may require a secondary tillage operation to restore soil tilth and reduce evaporative water loss. The risk of runoff and erosion following ST is a major consideration of timing. The practice of ST should be considered relative to alternative management solutions, such as crop rotation, strip tillage, injection of fertilizer, or cover crops. Often ST can address two or more problems.

10.3.1 Weed Control

Many ST studies were conducted for annual weed control while herbicide resistance in perennial weed species is of growing concern (Dang et al. 2015b). Burying weed seed that accumulated in surface soil with NT was effective with moldboard plow ST, while shallow non-inversion ST was of only short-term effectiveness. About 90% of the weed seeds in the 0–0.1 m depth are likely to remain in that depth following disk ST (Scanlan and Davies 2019). Other practices should accompany and follow the deep inversion ST for seed burial, such as crop rotation and weed suppression through competitive and allelopathic effects of cover crops (Weston 1994; Nichols et al. 2015; Price et al. 2016; Osipitan et al. 2019). The choice of ST type, timing and frequency will depend on the weed biology and the cropping system.

10.3.2 Soil Compaction and Improvement of Water Infiltration

Management of soil compaction has been well-addressed in review articles (Spoor et al. 2003; Batey 2009; Chaman et al. 2015). The ST needs to be deep enough to fracture the compaction while avoiding unnecessarily deep disturbance. The ST also has to be sufficiently aggressive for adequate fracturing, while avoiding excessive soil aggregate degradation. Sub-soiling with sweep or tine chisel implements that can cause fracturing without much disturbance of surface soil may be most appropriate. Most important to the timing of such ST is that the soil is dry enough to optimize fracturing of compacted soil. There may be an optimal stage of the crop rotation for ST to fracture compaction. Alternatives to ST may be strip tillage (Licht and Al-Kaisi 2005), planting of crops or cover crops with taproots that can break compaction and increase water infiltration (Chen and Weil 2010), and allowing time for wet-dry and freeze-thaw cycles to work. Once compaction is treated, management to avoid renewed compaction such as controlled traffic, avoiding traffic on wet soil, flotation tires, and reduced axle loads is essential.

10.3.3 SOC Sequestration

Inversion of high SOC soil in the surface 0.05–0.10 m with deeper soil may increase the capacity for SOC sequestration, although Quincke et al. (2007b) did not find such an increase even though ST reduced stratification of SOC. Moldboard plow ST may be most appropriate for increased SOC sequestration.

10.3.4 Stratification by Soil Depth of Soil Properties and Runoff Losses

This may be most effectively treated with moldboard plow-ST (Garcia et al. 2007; Quincke et al. 2007a; Scanlan and Davies 2019). Additional benefit can be gained by conducting ST after application of lime, manure or a heavy rate of fertilizer-P.

While runoff loss of sediment-bound nutrients often was increased with ST, runoff of dissolved nutrients was more often decreased, likely due partly to reduced nutrient levels in the surface soil following ST. Pesticide runoff may be reduced by ST incorporation as runoff loss is often relatively high with NT due to pesticide interception by crop residue and more runoff with NT compared with tillage (Gaynor et al. 1995; Mickelson et al. 2001). Alternatives to ST for reduced pesticide runoff, however, may include pesticide application when the high risk of runoff is relatively low (Devlin et al. 2009).

10.3.5 Disease, Nematode or Insect (Pest) Control

Field studies of ST have not addressed such pest management, but the topic was well discussed by Dang et al. (2015a, b). The biology of each disease or insect specific to the cropping system needs to be considered in the use of ST in integrated pest management.

10.4 Conclusions

Adoption of ST requires consideration of the costs of implementation and the likely positive and negative economic and environmental impacts. A negative is the added cost of practicing ST. Negative and positive impacts of ST tend to be small and short-term. The right type and time of ST for a given production situation and problem is important. Suggestions are given above for the use of ST for weed control, reduced soil compaction and improved water infiltration, SOC sequestration, vertical stratification of soil properties, and runoff losses. The potential for water and wind erosion is often increased with ST and precautions are needed to prevent increased erosion. Further research, including learning from farmer experiences, is needed to better design and target ST over a range of soil types and cropping systems, to optimize the frequency of ST, and to determine complementary practices to prolong the benefits of ST or minimize negative effects. Alternatives or complements to ST may include practices such as crop rotation changes, well-planned cover crop use, occasional strip tillage, rotation of the use of herbicide modes of action, and controlled traffic.

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Chapter 11
Developing Organic Minimum Tillage Farming Systems for Central and Northern European Conditions

Stephan M. Junge, Johannes Storch, Maria R. Finckh, and Jan H. Schmidt

Abstract Organic farming in temperate climatic conditions usually relies on intensive soil tillage to mineralize nutrients and suppress weeds in order to compensate for the lack of herbicides and synthetic fertilizers. In the long term, this may reduce soil organic carbon contents, and by this, soil fertility. Consequences are deterioration of soil structure and increased risks of water and wind erosion. For long-term sustainability, organic minimum tillage practices are needed that are based on strategies that circumvent problems with nutrient limitations and weed infestations. In three case studies, we demonstrate how the intensive use of cover crops, compost, and/or mulch help to improve soil structure and fertility and thus, enable the establishment of organic minimum tillage. This includes an example of practical research in a vegetable farm developing innovative, soil improving cultivation strategies. Traditional as well as participatory and on-farm research can be supported by a visual spade-based diagnostic method to determine the **Soil Structure Index** (SSI) that helps generate highly informative data. The success of organic minimum tillage hinges on (i) **Organic amendments** for balanced nutrient supply and increased crop performance while stimulating and enhancing the soil and rhizosphere microbiome; (ii) Effective **cover crop and crop residue management** for nutrition, weed suppression, prevention of pests and pathogens and climate resilience; (iii) **Technical solutions** and **professional support**, especially for direct planting and mulching. For organic farming, **soil fertility is not the result, but rather the prerequisite, for no- or minimum tillage.** Further research should focus on crop rotations, efficient cover crops, tillage strategies, and crop species adapted fertilization.

Keywords Soil fertility · Permanent soil cover · Cover crops · Transfer mulch · Soil structure index

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11.1 Introduction

Conventional no-till (NT) relies on the use of synthetic fertilizers and herbicides that are not permitted in organic farming. This leads to a number of very specific problems associated with no- or minimum tillage in organic farming. In Europe, organic NT and minimum tillage farming is predominantly practiced in the south, where soil degradation and water loss are more prevalent, and only rarely practiced in central and northern Europe (Peigné et al. 2015; Vincent-Caboud et al. 2017). Major obstacles are the reduced availability of nutrients in the top soil, unreliability in the termination of green manure crops, and (perennial) weed control (Stockdale et al. 2001; Berry et al. 2002).

Mulching of cover crops delays soil warming in spring and thereby often biological nitrogen (N) mineralization that is crucial for organic systems (Finckh and van Bruggen 2015). Especially in dense cover crop stands, their termination is often incomplete unless these are already in the generative phase. This restricts the choice (Peigné et al. 2007) and may delay the sowing of the subsequent cash crop (Mirsky et al. 2012; Carr et al. 2013). Consequently, reduced seedling germination and development (Peigné et al. 2007; Mirsky et al. 2012; Vincent-Caboud et al. 2017) and yield reductions of at least 10% under organic NT compared with inversion tillage have been reported (Cooper et al. 2016). Other factors impeding the adoption of NT in organic farming in Europe are high costs and low availability of NT equipment, additional costs for the more intensive use of high value cover or undersown crops such as vetches, specific clovers etc., the additional labor for weed management, and a lack of technical support (Casagrande et al. 2016).

It thus appears that in humid climates with slow soil warming in spring and optimum conditions for weed growth throughout the growing season, NT may not be the best solution for organic farmers (Vincent-Caboud et al. 2017). In contrast, in many cases shallow non-inversion tillage systems, not only have been shown to achieve similar yields than inversion tillage systems (Cooper et al. 2016) but also enable farmers to grow (vegetable) crops, such as potatoes, which depend on a minimum of soil tillage for optimum growth (Finckh et al. 2018).

Some of the problems with organic NT systems can be overcome by crop-livestock integration. Besides green manures, organic fertilizers can be obtained affordably through manure and composts produced on farm (Finckh and van Bruggen 2015). Livestock can serve for weed and seed destruction and enable farmers to grow perennial leys to improve the level of soil fertility without a financial burden. Consequently, the high proportion of specialized stockless crop farms that lack internally produced fertilizers depend on external resources to fill the nutrient gap and need solutions that allow for the minimization of tillage.

In recent years, a number of practitioners have developed innovative non-inversion tillage based organic growing systems especially for vegetable production. These integrate the shallow incorporation and mulching of cover crops and/or the use of cover crop and ley-based mulch materials that are transferred to neighboring fields. Our recent research concentrates on adapted non-inversion tillage methods combined with diligent residue and cover crop management in order to design locally adapted stockless minimum tillage systems.

In this chapter, we describe some of the alternative approaches that are being developed by us for organic non-inversion tillage in arable and vegetable cropping under central European conditions. These systems are also of great interest for conventional systems aiming to reduce inputs in view of the impending ban of glyphosate, and potentially many other herbicides, due to their effects on the environment (van Bruggen et al. 2018) and their role in the emergence of multiple antibiotic resistances worldwide due to their antibiotic properties (Kurenbach et al. 2015, 2018).

11.2 General Considerations

The most productive agro-ecosystem, independent of mineral nutrient input and soil tillage, is grassland. Compared to an arable field under NT or chisel ploughing, nitrogen mineralization in an undisturbed grassland is about 80–400% greater (Carpenter-Boggs et al. 2003). In such soils, the high plant diversity above-ground probably enhances microbial diversity and activity below-ground (Bartelt-Ryser et al. 2005) and the plant communities are the driving forces of mineralization in the absence of tillage (Yang et al. 2019). About 30–60% of the assimilated carbon is released in the form of organic acids to the soil by plant roots (Marschner 1995, p. 547). These help to make mineral nutrients available from the substrate directly and via the soil microbiome, enhancing soil life and plant nutrition.

Replacing the plough by surface composting and subsoiling results in less disturbance of the soil life (Roger-Estrade et al. 2010). The effect of plants and subsoiling on soil structure can be high (Fig. 11.1). A judicious combination of cover crops and reduced tillage enhances mycorrhizal networks (Bowles et al. 2017) that in turn will enhance nutrient uptake (Hallama et al. 2019) and protect plants from pathogens (Harrier and Watson 2004) and water stress (Evelin et al. 2009). A second very important group of organisms are free-living nematodes. Their trophic groups can serve as an indicator for the presence and abundance of fungal and bacterial decomposers and soil nutrient status, pH, and heavy metal contamination (Korthals et al. 1996; Bongers and Ferris 1999; Neher 2001). Their population size and composition are directly related to soil biodiversity and the stability of the soil food web (Yeates and Bongers 1999). In addition, they mineralize between 20 and 120 kg of N ha^{-1} year^{-1} through consumption and digestion of bacteria and fungi (Hallmann and Kiewnick 2015).

In addition to direct effects on soil nutrient contents, organic matter management is the basis for soil health and the suppression of soil borne plant pathogens. Outside their plant host, pathogens usually suffer severely from competition for nutrients and direct antagonism by free-living soil organisms. The latter are innately fitter in the soil environment (Cook and Baker 1983; van Bruggen and Semenov 2015). Disease suppression can be greatly enhanced through long-term minimum tillage due to effects on soil microbial communities (Schlatter et al. 2017). High plant

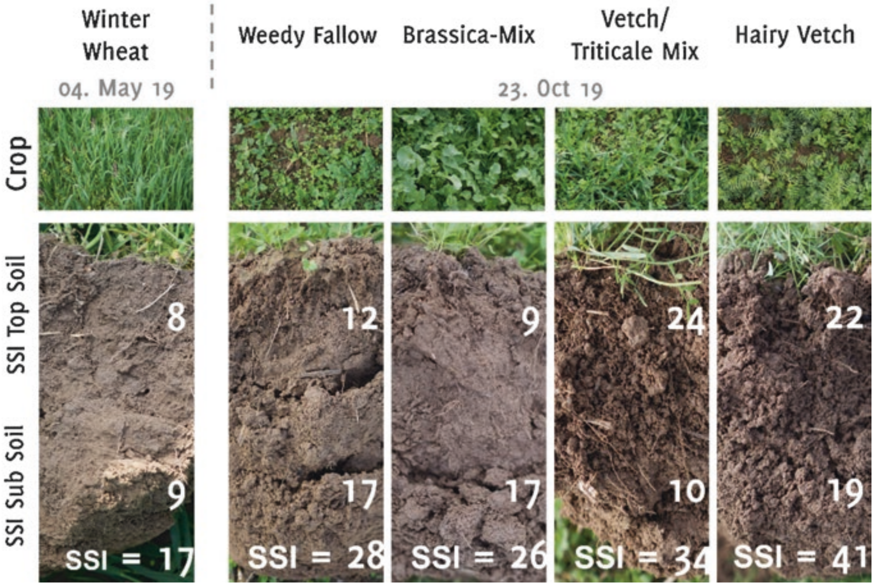

Fig. 11.1 Short term effects of cover crops on soil structure. The soil structure index (SSI) sums up the scores of the 0–0.15 m and 0.15–0.3 m soil layers. Scores range from 0 = poor to 100 = exceptional. Our experience indicates that SSI values for cultivated soils typically lie between 10 and 35 points; >40 points are the result of professional agricultural practices. The initial assessment was done on May 4 2019 (left) during a crop of winter wheat. After wheat harvest subsoiling was performed to about 0.3 m and soils rototilled to a depth of 0.05 m before sowing of cover crops on Sept. 17 2019. (Photos: Junge 2019)

diversity enhances soil microbial diversity (Bartelt-Ryser et al. 2005), this has led to greater suppression of *Rhizoctonia solani* AG-3 in grassland soils compared to long-term maize monoculture (Garbeva et al. 2006). Thus, diversification of arable farming systems through inclusion of more diverse crops in rotation, cover crops, and mixed cropping may contribute to disease suppression.

11.3 Case Study: Effects of Compost and Mulch Applications in Organic Minimum Tillage

Over the past 6 years, we have worked on the development of a ploughless cropping system with the aim of building soil fertility by systematically making use of cover crops on our experimental farm. The soil is a Haplic Luvisol (USDA: Typic Hapludalf) with 83% silt and 3% sand, and a measured pH often below 6. The field had been managed organically since 1989, but had not received substantial mineral fertilization or liming during that period. Despite organic management, C_{org} contents were rather low at about 0.9%. Deficiencies were apparent for S, P, K, and

B. Very high Mg contents led to low Ca availability requiring extensive Ca applications.

Thus, after 25 years of organic management, the rotation strategy without substantial (organic) fertilization had been unsustainable. An important reason was that cover crops were frequently sown too late due to management issues, resulting in poor crop stands before the onset of winter. Undersowing was not used and compost or manure rarely applied. The deficiencies of S and B also led to poor and patchy clover within the clover grass ley in the crop rotation.

We established two organic long-term trials in 2010–2011, comparing a ploughed system with non-inversion tillage. Superimposed was the use of nutrient rich mulch materials for potatoes and regular applications of a high value yard waste compost at a mean rate of 5 Mg DM ha^{-1} $year.^{-1}$. Mineral P and K at equivalent rates were supplied to plots that did not receive compost. After eight and 9 years in the top 0.15 m, C_{org} contents were 1.3% in the ploughed system without compost and mulch but 1.9% when mulch and compost had been applied under reduced tillage. Compost also increased N-, P-, K-availability by 10, 20 and 4%, respectively, while mulch combined with reduced tillage increased N-, P-, K-availability by 25, 48, and 147%, respectively compared to inversion tillage without mulch.

Free living nematodes were also significantly enhanced (Schmidt et al. 2017) and the effects persisted over time (Fig. 11.2a). After the use of two consecutive cover crops, nematode numbers were particularly high (Experiment 2, Fig. 11.2a). Also, potato yields correlated significantly with the number of free-living nematodes in that experiment (Fig. 11.2b).

Similar effects of cover crops and residue management on free-living nematodes have been reported under Mediterranean conditions. Leaving oat residues on the field followed by cover crops increased the number of bacterivorous nematodes. These nematodes correlated with mineral nitrogen in spring and, in turn, with increased tomato yields planted after the cover crops (Ferris et al. 2004). The driving forces for nitrogen mineralization, e.g. responsible species and decomposition pathways, in the two studies likely differed due to climatic conditions, nevertheless, the outcome was similar.

11.4 Case Study: Developing a Holistic Minimum Tillage Potato Cropping System

Ploughing, frequent hoeing, and hilling, are usually employed in organic potato production for mechanical weed control and enhanced mineralization of nutrients (Finckh et al. 2015; Döring and Lynch 2018). These methods reduce C_{org}, destroy the soil structure, and increase the risk of water and wind erosion. In the long-term trials on minimum tillage described above, potato yields were comparable under reduced and conventional tillage if a leguminous cover crop was combined with mulch application (Finckh et al. 2018). Since 2016, we have further experimented

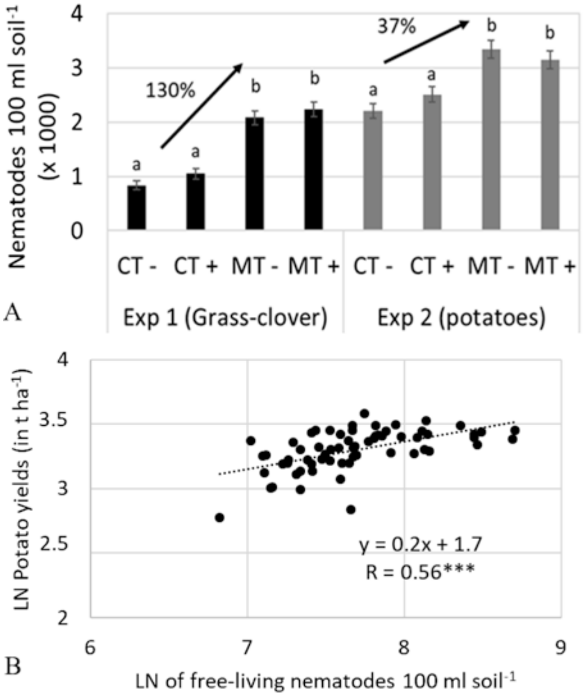

Fig. 11.2 (**a**) Total mean numbers (+ SE) of free-living nematodes 100 ml soil^{-1} in the first (black bars) and second (grey bars) field experiments with plough (CT) versus non-inversion (MT) tillage and mineral (−) versus organic compost (+) fertilizer treatments. Crop rotations were winter wheat-winter cover crop- potatoes- winter cover crop - grass clover (Exp 1) and winter wheat (terminated in summer) – summer cover crop – winter cover crop -potatoes (Exp 2). Arrows with percent values indicate the increase of free-living nematodes under MT compared to CT. Bars with no lower-case number in common are significantly different at $P < 0.05$; (**b**): Correlation between the natural logarithm (LN) of the number of free-living nematodes in 100 ml soil and potato yields under organic farming conditions in temperate European climates ($P < 0.001$). (Schmidt, Junge and Finckh, unpublished)

with surface composting of cover crops before potatoes through shallow rototilling at about 0.05–0.07 m depth followed by grubbing to 0.12–0.15 m depth with deep loosening chiselshares to reduce weed infestation and tillage. We adopted this approach in order to strive for a “regenerative” potato cropping system (Finckh et al. 2018), that aims at improving soil structure during intensive crop cultivation. To optimize the long-term trial, we set up a detailed experiment to evaluate the short-term effects of various cover crops and mulch types on the soil structure and performance of potatoes and a subsequent crop of triticale.

In 2017, a randomized split plot trial with four replicates was set up adjacent to the long-term trial in the same soil type as described above. Factor I was mulch type: (i) straw, (ii) hay, (iii) vetch/triticale-mix, (iv) clover grass, and (v) no mulch control applied in strips. Factor II were cover crops: (i) “Landsberger mix” (50%

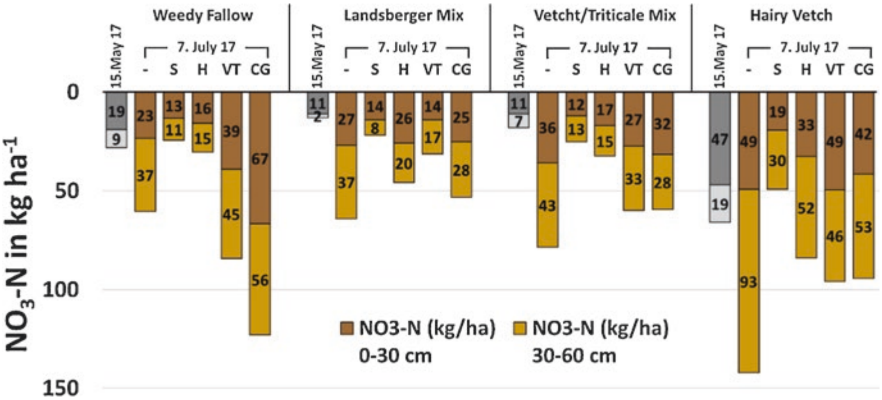

Fig. 11.3 Soil nitrate content about 3 weeks after the cover crops weedy fallow, Landsberger mix, hairy vetch/triticale mix, hairy vetch had been mulched and rototilled (15th May 2017, grey bars) and in response to different mulch materials at potato flowering on 7th July 2017. Mulch treatments were no-mulch control (–), straw (S), hay (H), hairy vetch/triticale-mix (VT), clover grass (CG)

Lolium multiflorum, 30% *Trifolium incarnatum,* 20% *Vicia villosa)*, (ii) hairy vetch, (iii) vetch/triticale-mix, and (iv) weedy fallow as control. The mulch quantity was approximately 50 Mg fresh matter ha^{-1}. Pre-germinated potatoes were planted on first May. Hilling was performed once and mulch applied before emergence on 16th May. Soils in mulched plots were tilled no more, un-mulched controls were once hilled and harrowed for weed control. No further fertilization was applied.

The preceding cover crops had different effects on the nitrogen supply in spring (Mid-May) (Fig. 11.3). The C:N ratios (above ground) were: “Landsberger mix” 22:1, hairy vetch/triticale mix 15:1 and hairy vetch 9:1 before being mulched and rototilled. They provided between 13 (weedy fallow) and 66 kg NO_3^- ha^{-1} (winter vetch) at a soil depth of 0–0.6 m (15th May, Fig. 11.3). In the absence of mulch, soil N at potato flowering on seventh July varied from 60 kg NO_3^- ha^{-1} (weedy fallow) to 142 kg NO_3^- ha^{-1} (vetch).

Mulch effects on N levels depended not only on the mulch materials but also on the pre-crop. Straw with a C:N ratio of 63 led to massive reductions in N-availability independent of pre-crop. With hay (C:N = 23), N-levels also stayed low except after vetch. After weedy fallow and “Landsberger” mix, clover/grass mulch (C:N = 14) was more effective than vetch/triticale (C:N = 20) in providing nutrients while the two types of mulch had similar effects after vetch and vetch/triticale cover crops. Late spring and early summer 2017 were very dry. As soils under mulch stay cooler, it is likely that mineralization of the hairy vetch and hairy vetch/triticale residues was reduced and nutrients released over a longer period. With the exception of straw mulch, canopy closure was only achieved when plots were mulched (Fig. 11.4). This was due to the additional nutrients due to mulching and water conservation under mulch.

Fig. 11.4 Comparison of un-mulched and mulched treatments. Mulch on the right reduced water stress allowing for canopy closure. Un-mulched plants stayed considerably smaller due to drought stress. Nutrient effects are also visible. The plot in the middle left marked by a frame is after the grass-dominated cover crop "Landsberger mix" that immobilized nitrogen early during the season. (Photo: Junge 2017)

Parallel to the nitrogen and water supply, cover crops in combination with the applied mulch materials influenced soil structure assessed before planting, during flowering, and before harvest with the spade diagnosis (Beste 2003). From this, the soil structure index (SSI) was calculated by relative means of the top- (0.15 m) and sub-soil (0.15–0.30 m) structure and aggregate stability assessments. Here, details are shown for weedy fallow, vetch/triticale and vetch cover crops combined with no mulch, straw, or vetch/triticale mulch (Fig. 11.5). Averaged across all factor combinations prior to potato planting (seventh April), SSI was lowest after the weedy fallow with 34 compared to 52 after vetch/triticale and after vetch cover crop. Therefore, the highest relative improvements of soil structure index were achieved under treatments with weedy fallow. In these treatments, straw mulch and vetch/triticale increased the soil structure index significantly by 74% and 82%, respectively. This can be explained by the poor structural condition on 7th of April in comparison to the treatments with cover crops. Straw mulch increased SSI after all three cover crops, however, except after vetch as cover crop, yields were as low as after weedy fallow without mulch. Vetch/triticale as mulch had the strongest impact on yield. However, if vetch/triticale was used as preceding crop and mulch, SSI greatly improved only until flowering. Before harvest, it had dropped to the lowest SSI among all treatments while it was associated with the highest yields (Fig. 11.5). The yield of the following triticale crop was 4.7 Mg ha^{-1} without mulch. Yields increased to 5.5–5.7 Mg ha^{-1} after all mulches except straw mulch, which resulted in no yield changes (4.5 Mg ha^{-1}). Thus, the effect of the high C:N ratio carried through. Practitioners have reported yield effects for up to 4 years.

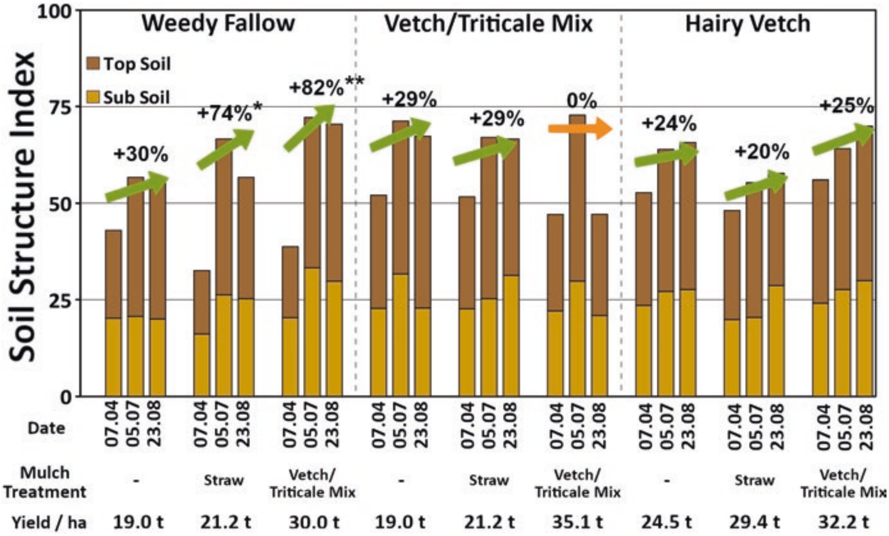

Fig. 11.5 Condition of the soil structure of selected treatment in top (dark brown bars) and sub soil (light brown bars) before killing of cover crops (Weedy Fallow, Hairy vetch/Triticale Mix, Hairy vetch) on 7th April and under different mulch types: without mulch (−), straw mulch (Straw), Vetch/Triticale Mix mulch at potato blossom on 5th July, and before harvest on 23th August. The change in the soil structure index in % and significant differences are marked by ∗ (linear contrasts)

Importantly, the results suggest that improvements of soil structure are possible with and without mulch, but that especially the use of a good cover crop can be a great advantage. Mulching is labor intensive and, particularly in larger operations, may not be practical. Nevertheless, it appears difficult to optimize soil structure and nutrient dynamics and thus yield at the same time. While the treatment of hairy vetch as cover crop without mulch appears encouraging and well feasible, it has to be ensured that the very high N-levels at flowering (Fig. 11.3) are successfully taken up by the crop and not lost. This will depend on the time and severity of damage by late blight (*Phytophthora infestans*) and/or Colorado potato beetles (*Leptinotarsa decemlineata*). If the crop is killed before the nutrients are taken up, nutrient leaching could occur.

In this context, it is important to mention that we observed repeatedly (Finckh et al. 2018) drastic reductions in infestation by Colorado potato beetles under mulch (Fig. 11.6). Similarly, potato late blight is consistently reduced in the mulched system. The mechanisms behind this likely include microclimatic effects as well as effects on beneficial insects (Zehnder and Hough-Goldstein 1990; Finckh et al. 2018). However, nutrition effects on plant attractiveness to the pests could also play a role (Schaerffenberg 1968; Zehnder and Hough-Goldstein 1990; Alyokhin et al. 2005). Thus, there may be a need for earlier planting without mulch than with mulch in order to escape late blight. Also, preventive and direct measures against potato beetles may be required (Finckh et al. 2015). No significant effects on tuber health and quality were observed. *Rhizoctonia* infestation, wireworm and mouse damage,

Fig. 11.6 Potato beetle damage on 9 July 2018. Larva and egg hatching were reduced in vetch/triticale mulched plots. In the picture canopy losses were 39% and 96% in the mulched and un-mulched plots, respectively. (Photo: Junge 2018)

and green tubers did not differ among treatments. The only exception was slug damage that was significantly higher in the clover grass mulch treatments ($P < 0.05$, Tukey HSD) than elsewhere. This is likely due to the slug's food preference for clover grass (Keiser et al. 2012).

Cover crops and mulch are used in this cultivation system to suppress weeds by competition (Kruidhof et al. 2008) and deprivation of light (Teasdale and Mohler 2000). Generally, closer C:N ratios enhanced crop growth, led to rapid canopy closure and thus to weed suppression through competition for light. Weed pressure after the different cover crops varied somewhat but not significantly: On July 19th, weed coverage was equally high (20%) after weedy fallow and "Landsberger" mix due to difficulties in termination of the grass in the "Landsberger" mix. The lowest weed cover occurred after hairy vetch cover crop with 12%. There were also no significant difference among mulch treatments for weed suppression. Under hairy vetch/triticale mulch, weed cover was lowest at 10%. The efficiency in weed suppression of hairy vetch is in part due to its high allelopathic effects (Fujii 2003). Seeds in the straw and hay mulch materials contributed to weed pressure, thus cover was 21 and 17%, respectively.

The cultivation system shows that high potato yields, soil fertility, and plant health are not contradictory under reduced tillage. While typically three to five hilling operations are performed for mechanical weed control and to enhance nutrient mineralization under German organic farming conditions, the mulch system requires no more hilling and cultivation during the season. It is important to harvest the potatoes as early as possible and to immediately establish a nitrogen demanding catch crop to maintain soil structure and prevent nutrient leakage. The basis for this is the skilled combination of cover cropping, tillage, and soil conservation methods to allow for the function of preventive agro-ecological mechanisms. The long-term effects can justify the high efforts and input required for mulch application. This type of cultivation is particularly interesting for intensive stockless cash crops on small fields, as the following practical example demonstrate.

11.5 Case Study: An Organic Minimum Till Mulch-Based Vegetable System

Vegetable farming is usually highly intense with much bare soil, leading to a decline in soil fertility (see Sect. 11.2). The cropping system of *live2give* developed for professional vegetable production aims at permanently active roots and soil cover. Since 2011, the farm "Bio-Gemüsehof Dickendorf" of *live2give* gGmbH is pioneering the use of mulch-direct-planting at field-scale organic vegetable production. Forty different crops are grown for direct marketing.

Precise driving and a level ground surface are important prerequisites. At the initiation of the system, mechanical soil-loosening in autumn to break up possible compaction and deal with perennial and root-spreading weeds is necessary. Right after that, a rapidly developing winter annual cover crop is sown to stabilize the mechanical tilth biologically (Fig. 11.7 left).

Bio-Gemüsehof Dickendorf (https://mulch-gemuesebau.de/)
4.6 ha vegetables incl. 2000 m² greenhouse
4 ha permanent grass land
350–450 m above sea level
Mean annual temp. 7.6 °C
Mean annual ppt: 700–1000 mm
Loamy soils on brown soil and pseudogley on basalt rock
C_{org} contents 1.6–2.6%

Typically, a high biomass cover crop of 60% triticale or rye, 30% hairy vetch, 10% winter peas that produces up to 10–12 Mg DM ha^{-1} by May/June is used. This is flail mown shortly before planting. Where the cover crop was not yet in full bloom, not producing enough biomass, or contained too many weeds, a subsequent covering of additional mulch material is necessary (total layer of 0.08 m is targeted).

Fig. 11.7 Soil structure 0–0.30 m of cover crop shortly before transplanting (left), transplanting leaks with the "MulchTec planter" (middle) and soil structure at harvest time (right)

Plantlets are transplanted into undisturbed, rooted, and covered soil and may use the mulch material itself for nutrition (Fig. 11.7 middle). This is the last step before harvest. The development of the "MulchTec planter" in 2012 was a breakthrough for economic realization of this system. Annual weeds, such as *Chenopodium album* and *Galinsoga*, are well controlled by the mulch layer and by avoiding soil disturbance. Perennial weed control, however, is limited and must be dealt with beforehand. By harvest time, soil cultivation was avoided for at least 1 year resulting in stable crumbs, no compaction zones, and a high density of roots and soil life (Fig. 11.7 right). This will allow for minimum tillage to the next winter annual cover crop thereby utilizing the residual mulch and crop residuals for soil cover and crop nutrition.

In order to provide enough material for a mulch layer of 12–15 Mg DM ha^{-1}, the crop rotation has been adapted for high biomass production (Table 11.1). This is provided by (i) 2 years of biomass producing mixtures of grains and legumes combined with undersown grass that are used as transferred mulch for the vegetable crops; and (ii) the yearly annual winter cover crops. The replacement of clover grass by high DM-yielding cover crops further improved DM-yields of the mulch material in the time of its highest demand (May/June). No problems with the repeated use of hairy vetch were observed over the last 10 years.

The estimated N-flows in the system result in an overall surplus of 21 kg N ha^{-1} year^{-1} (Fig. 11.8). Overall, 88 kg N ha^{-1} year^{-1} is exported from the system as vegetables, 77 kg N ha^{-1} year^{-1} are supplied by biological N-fixation, 66 kg N ha^{-1} year^{-1} is imported into the rotation by commercial organic fertilizers and 34 kg N ha^{-1} year^{-1} is lost by emissions of mulch materials. In year 1, 3, and 4 a surplus of up to 141 kg N ha^{-1} accumulates (Fig. 11.8). This surplus is bound in an organic form and should thus not be subject to leaching. The N-mineralization from organic material is mainly a function of the C:N ratio of the material itself. Neglectable N-absorbance by vegetables was observed at a C:N ratio > 35 in the first year after mulch application at the farm of *live2give*. Data from 2017/18 indicated that 10% of the applied N in the form of grass silage mulch in Brussels sprouts was found as mineralized N in the following year at a depth of 0–0.3 m. This enhanced the total yield of beet roots by 10% (53.4 Mg ha^{-1}) and the first quality yield by 30% compared to the un-mulched control.

Table 11.1 Rotation scheme and dry matter balances for self-sufficient mulch supply

Rotation		DM production (Mg ha^{-1})		
year	Crop	*insitu*	demand	balance
1	Brassicas	6.7	15.0	−8.3
2	Biomass (spring sown)	10.4	0.0	10.4
3	High/medium N-demanding crops	6.8	11.1	−4.3
4	Lettuce, herbs	5.9	12.4	−6.5
5	Onions	3.9	6.7	−2.8
6	Carrots	7.0	0.0	7.0
7	Biomass (autumn sown)	17.0	0.0	17.0

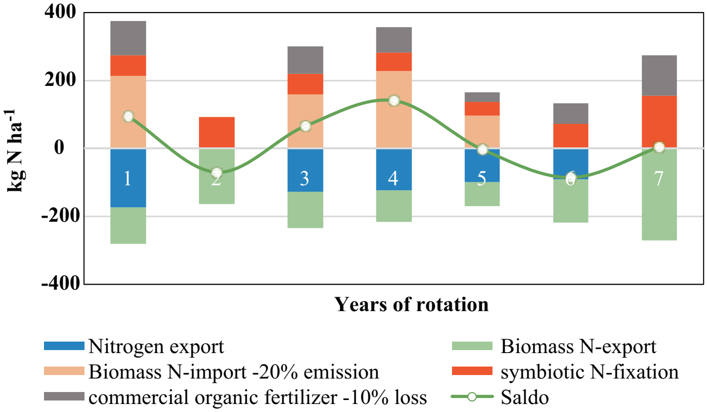

Fig. 11.8 N-flow in the seven-year crop rotation depicted in Table 11.1

As mulch is mineralizing more slowly than most commercial fertilizers, it is important to bridge the N-demand of the young plants with an underfoot dressing applied during the transplanting process. By an application of 95 kg N ha^{-1} in brussels sprouts the yield could be increased from 14–26 Mg ha^{-1}. Without "start-off fertilization" plants were weaker and could not utilize the estimated 151 kg N ha^{-1} provided by the mulch material.

The cropping system as described above has insignificantly lower production costs in comparison to common organic farming systems. The costs for human labor are lower, whereas costs for machinery are higher. However, yields and product qualities are generally higher in this system and can be raised to a conventional level. This may be attributed to higher resilience under extreme weather conditions, an overall better nutrition due to the innate soil fertility as well as low weed infestations (Fig. 11.9).

Permanently active roots and soil cover build up soil fertility in this usually highly intensive vegetable farming system. Foundations are laid for minimum tillage, because minimum tillage is not the condition, but the result of soil fertility.

11.6 Technological Adaptations in Organic Minimum Tillage Systems

The conversion to minimum tillage under organic conditions is particularly challenging with respect to weed and nutrient management. An important precondition for successful conversion is that the fields have been managed well before and overall weed pressure is not excessive (Reimer et al. 2019). Most important for successful organic minimum tillage systems is the diligent use and termination of subsidiary crops, such as cover crops or undersowings. The cover crop should be a mixture of winter-hardy legumes and grasses. We prefer a 4–6 ratio of hairy vetch and triticale

Fig. 11.9 From Top left: Cabbage, Brussels Sprouts, Zucchini, Kohlrabi, Endives, Fennel as well as Autumn and winter leaks at harvest time in mulch. Leeks yielded between 44.5–57 Mg ha^{-1}

as this results in high root and above ground biomass, fixes nitrogen, and suppresses weeds well. Winter peas may be used to substitute a proportion of vetches, unless peas are a main crop in the rotation. If crops are to be mulched, the mulch should have a C:N ratio < 20. This will accelerate plant growth through adequate nutrition and thus enhance weed suppression by the crop.

Roller crimpers seriously hurt the cover crops leading to strong leakage of fluids from the plants. In contrast to mowing, this often leads to plant death. In addition, by leaving most of the cover crop tissue intact, the decay of the residues on the surface is slowed down and weed suppression enhanced. The roller crimper works especially well if the cover crop is at the regenerative stage. Alternatively, mowing followed by incorporation with a high speed (1000 RPM) rotary cultivator with depth guidance at 0.05–0.07 m is very effective. The knives of the cultivator need to be skewed to avoid sealing moist soil. Surface composting will require about 2 weeks before a crop can be sown. An exception are potatoes, which can be planted almost immediately, but require the loosening of the soil by chisels down to about 0.12–0.15 m. The undisturbed capillary system below the tilling horizon on the one hand, and the water translocation by the roots of the dying cover crops on the other hand, enhance water availability.

Especially weakly textured sandy or silty loam soils are highly susceptible to subsoil compaction and may need deep ripping or subsoiling (Peigné et al. 2007), particularly during the transition to conservation tillage. Subsoiling at slow speed at a distance of 0.4–0.5 m the depth of compaction is recommended. The effects of this together with cover crops on soil structure can be seen in Fig. 11.1.

Perennial weeds need to be well managed. Using two short rotation cover crops can be very successful for weed control and building soil fertility as the highest amounts of root exudates are produced until the beginning of the generative stage (Sauerbeck and Johnen 1976). We have observed that thistles (*Cirsium arvense*) grow especially well if light reaches the soil. Others have experimented with variable success with rhizome fragmentation and mowing schemes against *Elymus repens* (Bergkvist et al. 2017; Kolberg et al. 2017).

Extension and support for farmers is crucial for successful transition to minimum tillage without the need for herbicides. A simple but highly effective and essential tool for farmers and extension workers is the spade diagnosis for assessing soil structure and quality for evaluation of tillage or crop rotation effects as shown in Fig. 11.2. Moebius-Clune et al. (2016) developed the first “Comprehensive Soil Assessment Framework” for farmers in the United States, with a focus on soil health. It describes improvement of soil health on field scale based on six steps: (1). Determination of farm management history and farming system; (2). Setting of goals and assessment of soil health status; (3). Identifying and prioritizing constraints; (4). Identifying management options; (5). Creating a short and long-term management plan; and (6). Implementation of soil health management, monitoring of results, and adaptation of soil health management (Moebius-Clune et al. 2016, p. 81). Although climatic conditions vary somewhat from those of North/central Europe, this framework may be a blueprint for a general framework, which can be adapted to climatic conditions.

11.7 Research Needs

In the previous sections, we highlighted the importance of a dense and continuous soil cover to protect soil and crops from biotic (e.g. weeds) and abiotic (e.g. water, nutrient limitations) stressors in temperate minimum tillage systems. To achieve this, precisely harmonized and likely farm specific combinations of (1) crop rotation; (2) cover crop species (and mixtures); (3) tillage; and (4) fertilization strategies are needed. Considering the interactions of these combinations, systemic research approaches based on mid- and long-term tillage trials are needed to find optimal management solutions for diverse soils and climates. The primary objective of such studies has to be the identification of the most suitable management combination at farm and/or field scale that fosters mineralization processes and the build-up of soil humus contents by enhancing soil microbial activity, finally leading to an optimum soil fertility and health status suitable for minimum or NT systems.

These research efforts should be assisted by (1) breeding for cover crop species and varieties that are suitable for mixed cropping and capable of producing large biomass stands under minimum tillage before the onset of winter, also when sown relatively late. Searching for new legume (cover crop) species with resistances to wide host range pathogens, such as *Fusarium*, *Didymella,* and *Peyronellaea spec.,* among others (Baçanoviç-Šišiç et al. 2018; Šišiç et al. 2018)*,* will also help reducing root necrosis of grain legumes in the rotation; (2) Breeding main crops for adaptation to mixed cropping, e.g. with cover crops undersown before harvest or with other cash crop species in order to increase above- and below ground diversity and by this, system health; (3) Developing new cover crop species mixtures consisting of several winter-hardy and frost-intolerant species to conserve water for spring-sown crops; (4) Technological developments to allow for the simultaneous removal of weed seeds during harvest and also direct sowing of cover crops before or at harvest to avoid bare soils; (5) Close collaboration with farmers that have been working on organic no- and minimum tillage systems in order to spread their knowledge (participative research); (6) Research for new (soil) indicators that can help to evaluate the success of management strategies/ combinations to achieve a self-regulatory system in terms of nutrition and nutrient cycling as well as weed, pest and pathogen tolerance (see Sect. 11.2).

11.8 Concluding Remarks

Organic rotations in temperate conditions are generally accompanied by heavy soil tillage and typically include clover grass leys for fertility building and as a means to control especially perennial weeds (Finckh and van Bruggen 2015). For stockless organic operations, the latter practice is very expensive as without cooperation with other farms the material produced cannot be made use of. Furthermore, clover grass leys alone do not necessarily result in sustainable plant nutrition (see Sect. 11.3), and soil inversion through ploughing excessively disturbs soil life and thus reduces soil fertility over time. Agricultural systems that do not rely on the import of synthetic fertilizers thus have to aim at supporting soil life by maximizing plant growth and their recycling at all times.

Constant nutrient supply through decaying roots, root exudates, organic fertilizer (manures, compost), surface composting, and organic mulches (cover crops, living and dead mulches), should keep the soil life strong and active across the whole vegetation period. In the long term, an improvement of soil quality due to increased soil organic matter and microbial biomass, as well as an increased baseline level of mineralization should be achieved (Carpenter-Boggs et al. 2003). Thus, agronomic practices in organic farming have to be thought within the system as nutrient limitations are the main drivers of the overall dynamics: Less plants mean less root exudates mean less soil fertility mean less plants. Consequences arise from this for weed, pest and disease dynamics. However, improving soil fertility is a long-lasting process that needs to be adapted to site-specific conditions, such as soil texture, rainfall, and livestock. The basis for improving soil fertility is a dense and continuous soil cover, preferably by living plants, all over the season expressed by high frequencies of diverse (leguminous) cover crops in the rotation. In such systems, weed pressure is generally low and nutrient mineralization processes are sped up enabling the farmer to reduce the tillage intensity. Indeed, **"Soil fertility is not the result, but rather the prerequisite for no- or minimum tillage"**. There is no sequence of principles by which conservation agriculture can be achieved but all stand side by side and are inseparable as defined by Hobbs (2007), namely (1) Permanent soil cover; (2) Crop rotations; and (3) Minimum of soil disturbance. Thus, permanent soil cover and crop rotation systems must be optimized in order for minimum tillage to be successful in organic farming.

However, we are still lacking deep knowledge of soil (microbial) processes and how to steer soil fertility in agricultural systems, for example through the use of plant communities to foster a general soil disease suppression (Mazzola 2004; Kinkel et al. 2012; Schlatter et al. 2017). Furthermore, there is a high demand for cheap and simple methods, preferably applicable by farmers, that allow assessment of the effects of farming system adaptations. The spade diagnosis as described in Fig. 11.1 is one such easily applicable method. The identification of free-living nematode densities and communities, while requiring a laboratory, could also be helpful to help the farmer judge whether a soil is ready for minimum tillage.

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Part II
Soil Management

Chapter 12
Controlling Soil Erosion Using No-Till Farming Systems

Steffen Seitz, Volker Prasuhn, and Thomas Scholten

Abstract Soil erosion is a natural phenomenon that has been thrown off balance by human activity and particularly by agriculture. It is associated with severe environmental impacts, high economic costs, reduced productivity and thus influences food security as well as social and economic development. Agriculture affects erosion rates in two ways (1) by the removal of soil-protecting vegetation and (2) by the mechanical processing of topsoils through tillage. In this regard, erosion is not only caused by tillage operations, but acts together with the atmospheric influences of water and wind, and all three agents reinforce each other. Individual erosion events can cause erosion rates of more than 100 Mg ha^{-1} $year^{-1}$ on agricultural land. This is where no-till (NT) farming comes in to play. No-till actively maintains soil surface cover by vegetation and reduces soil disturbances to the very moment of planting. Therefore, it effectively mitigates all forms of soil erosion caused by machinery use, water, and wind and is thus considered to be a major improvement regarding soil erosion control. The further acceptance of NT practices by farmers is one of the most important measures to successfully tackle the threat of soil erosion globally.

Keywords Tillage erosion · Water erosion · Wind erosion · Soil loss · Erosion control

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12.1 Soil Erosion and the Influence of Water and Wind

Erosion is one of the oldest and largest threats to soils globally, which are in turn one of the most valuable resources on our planet (Bennett and Chapline 1928; Stallings 1957; Pimentel et al. 1995; Poesen 2018). Accordingly, soil erosion has been recognised as the greatest challenge for sustainable soil management with approximately 75 billion tonnes (Mg) of soil eroded every year on arable land, leading to an estimated financial loss of 400 billion $US (Borrelli et al. 2017). Along with the enormous economic costs, e.g. from reduced productivity, the effects of translocated sediments outside eroded areas affect human safety, food security and social development (Lal 1998; Boardman et al. 2003; Pimentel 2006).

For centuries, humans have worked the earth's surface for agriculture, leading to unprotected and destabilized soils exposed to the influences of the atmosphere (Lal 2001). However, erosion is neither a process that is limited to cultivation, nor is it caused solely by water and wind. Generally, erosion is a natural phenomenon that can also be observed without human influence. As such, it is of central importance for the formation of the earth's surface. Under undisturbed conditions mostly minor soil erosion takes place, which can be compensated for by weathering and soil formation, establishing a natural and dynamic equilibrium (Richter 1998; Montgomery 2007). However, if the vegetation cover is disturbed by human intervention, this natural balance undergoes a fundamental shift. Today, overgrazing, construction activities, and mainly agricultural land use have tremendously accelerated erosion rates (Blanco-Canqui and Lal 2010).

As long as sediment removal on agricultural land does not exceed new soil formation, the extent of damage remains limited. If, however, soil erosion becomes more prevalent than new soil formation, the soil degrades. In this context, the most developed and most fertile top soil layers are removed first, causing significant soil degradation and loss of nutrients in situ ("on-site effects"). In addition, this eroded material is then removed and transported to other areas, where it may cause further damage ("off-site effects") (Lal 2001) due to the burial of fertile soils, crops or infrastructure, and/or due to the translocation of nutrients and pollutants such as pesticides or heavy metals. The balance resulting from erosion, deposition and new formation of soil is therefore critical. The rate of global soil regeneration under arable use can generally be set between 0.1 and 1.4 Mg ha^{-1} $year^{-1}$, depending on the region, agricultural practices and site conditions, which corresponds to a mean increase in soil profile thickness of 0.02–0.2 mm^{-1} $year^{-1}$ (Auerswald et al. 1991; Verheijen et al. 2009; Guo et al. 2015). Even with only slightly increased erosion rates by agricultural practices, these formation rates are not sufficient to compensate for soil loss (Montgomery 2007). Whereas natural erosion rates range between 0.01 to a maximum of. 2 Mg ha^{-1} $year^{-1}$ on flat land with grass or forest cover (Pimentel 2006), the average rate of soil erosion on arable land is well above that of new formation in many regions, e.g. 2.7 Mg ha^{-1} $year^{-1}$ for the European Union (Panagos et al. 2015b), 11.0 Mg ha^{-1} $year^{-1}$ for Australia (Lu et al. 2003), or 28.5 Mg ha^{-1} $year^{-1}$ for China (Guo et al. 2015).

12.1.1 Water Erosion

Soil erosion initiated by water can be divided into two sub-processes (Richter 1998). First the impact of raindrops apply energy to the soil surface leading to the destruction of aggregates and a mechanical detachment of particles ("splash effect", Fig. 12.1). At the same time, beginning infiltration leads to a rapid moistening of the soil surface, dispersion of clay particles and organic colloids, and aggregate break down under the pressure of trapped air bubbles (Auerswald 1995). This destructive effect increases with increasing speed and mass of the impacting raindrops and thus their kinetic energy (Goebes et al. 2014), which can be up to 10^6 hPa (Ghadiri and Payne 1981). Due to the splash effect, water droplets, together with sediment particles, can be moved up to 1.5 m vertically and > 5 m horizontally (Fernández-Raga et al. 2017). Fine material can accordingly be transported through surface runoff. However, especially at the beginning of an erosion event, the transport capacity is not yet sufficient to move important quantities of fine material. Thus, it accumulates in a thin layer on the soil surface and silts up the pores, causing the infiltration to drop rapidly (Morgan 2006).

Subsequently, the transport capacity of surface runoff increases, leading to the second sub-process: the transport of loosened soil particles on the soil surface (Fig. 12.1). Surface runoff occurs when the intensity of rainfall exceeds the infiltration capacity of the soil surface, or when the soil is saturated to such an extent that it cannot absorb and infiltrate any more water (Toy et al. 2002). The proportion of runoff, as well as the flow velocity, then increase, as does the particle size of the transportable sediment. During high-intensity rainfall events, the transport capacity

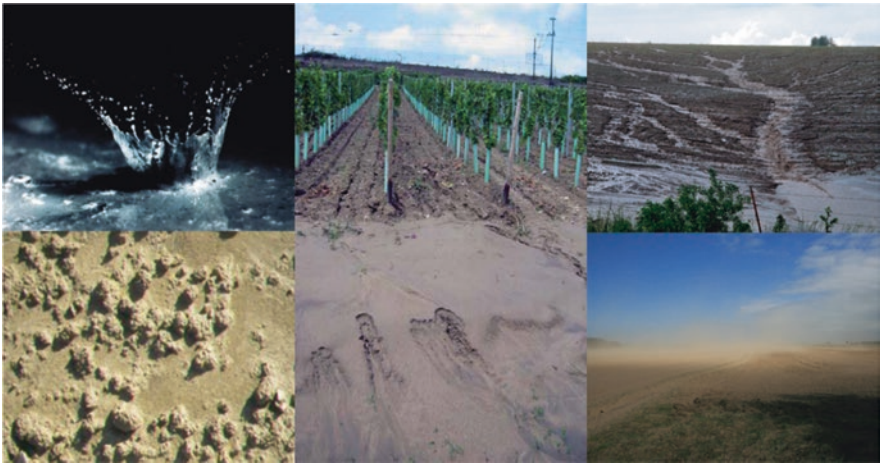

Fig. 12.1 Forms of water, wind and tillage erosion on agricultural lands: splash impact and clogging of the soil surface (left), colluvial deposits after heavy rainfalls in a vineyard (middle), inter-rill and rill erosion (top right) and combined tillage and wind erosion on a freshly ploughed field (bottom right). (Source: USDA, Steffen Seitz and Roger Funk)

of runoff rises further and detaches soil material by incising and forming channels on the soil surface (Morgan 2006). The size of such linear forms of water erosion varies greatly, from micro-rills and rills to meter-deep gullies (Fig. 12.1). Globally, single recorded soil losses by water erosion of up to 400 Mg ha^{-1} $year^{-1}$ have been measured (Pimentel and Kounang 1998). Exemplary average water erosion rates on agricultural land range between 6.7 Mg ha^{-1} $year^{-1}$ (USA) to 14.9 Mg ha^{-1} $year^{-1}$ (West Africa) to 24.6 Mg ha^{-1} $year^{-1}$ (China), depending on the region (based on plot measurements and modelling approaches after Guo et al. 2015). Away from the place of origin of sediments, off-site colluvial and alluvial deposits importantly affect ecosystems (Lal 2001) and cover large areas (e.g. Fuchs et al. 2010; Stolz et al. 2012). Thus, water erosion not only alters soil properties of eroding soils, but also affects neighboring landscapes.

12.1.2 Wind Erosion

Erosion caused by wind can reach dimensions comparable to or even higher than water erosion (Blanco-Canqui and Lal 2010). In contrast to water erosion, important slope inclinations are not required to obtain high erosion rates. Wind erosion occurs when wind forces exceed resistance thresholds of soil surfaces and is typical, but not exclusive, to arid and semi-arid regions. Three sub-processes can be distinguished to explain wind erosion: creep close to the ground, saltation and suspension (Bagnold 1941). Creep is caused by impacts of particles already in motion directly on the surface, which are pushed by other particles and thus start rolling. This process mainly affects larger particles with a diameter of 0.5–2 mm. Saltation refers to a jumping movement of particles with diameters of 0.5–0.07 mm and represents the largest share of transport by wind. Particles whirled up experience an acceleration and hit the soil surface again with higher kinetic energy than when they were detached. This impulse sets further particles in motion, so that the number of transported particles increases very rapidly. Whereas creeping and saltating particles move limited distances, the travel distances of particles in suspension are importantly higher (Toy et al. 2002). Wind erosion typically shows a distinct sorting effect of the moving particles according to their size, density and shape. A consequence of this sorting is thus a depletion of the topsoil from clay and silt particles as well as a loss of organic matter (Sterk 2003). During saltation and suspension, transported particles abrade and soil aggregates are destroyed by their impact leading to a "sandblast effect". Tilled soils with low organic matter are the most vulnerable to wind erosion (Blanco-Canqui and Lal 2010) (Fig. 12.1).

Globally, sediment transport rates by wind up to 200 Mg ha^{-1} $year^{-1}$ have been recorded on unprotected arid and semi-arid soils (Michelena and Irurtia 1995; Sterk 2003), whereas Bielders et al. (2002) reported erosion rates up to 50 Mg ha^{-1} $year^{-1}$ on intensively used agricultural land. At the same time, depositions of material carried by wind are prominent in many regions, such as northeast China or central and eastern Europe, and form the basis for successful agriculture on highly fertile soils (Zhang et al. 2004).

12.1.3 Protection from Soil Erosion

It is obvious that the best protection against both water and wind erosion is provided by a closed vegetation cover (Thornes 1990). Thus, living plants, but also plant residues, are key to mitigate soil erosion and a soil surface cover between 30–40% can be considered effective for protection in many cases (Prasuhn 2012; Hösl and Strauss 2016). Furthermore, the stabilization of the soil structure is a recognized means of preventing erosion (Six et al. 2000b). This stabilizing effect can be achieved by the promotion of biological activity in the soil. Common measures include humus-enrichment together with a reduced use of pesticides, liming, and a general avoidance of negative C and nutrient balances (Six et al. 2002; Lutzow et al. 2006). Those measures also lead to an increase in cementing substances, which in turn increase aggregate sizes and stability (Six et al. 2000b). Water erosion-inducing surface runoff can be minimized by an interruption of long flow paths (e.g. with hedges) and slope parallel processing (Toy et al. 2002). Landscape-structuring measures, such as windbreak hedges and strip cultivation, can also counteract wind erosion by enhancing the wind resistance of the soil surface and a reduction of the wind speed close to the ground (van Oost et al. 2000). A reduction of slope inclination can be achieved by land consolidation and terracing. In this context, artificial sediment traps such as hedge buffer strips can intercept transported sediments and create colluvial deposits before eroding material leaves the affected area. Most importantly, an increase in the infiltration capacity through the promotion of low bulk soil density and soil drainage e.g. through secondary pores or deep roots, are of high relevance. This is again fostered by higher biological activity. These measures can also help to mitigate a third erosion-inducing process: tillage.

12.2 Erosion in Conventional Agriculture

12.2.1 Tillage Erosion on Agricultural Lands

The intensive and continuous use of ploughs, especially since the advent of mechanization in agriculture, has increased sediment transport. In this respect, tillage erosion is defined as a gravitational net displacement of soil and soil constitutes, where particles are lifted by ploughing and then fall back on average further down the slope than up the slope (Fiener et al. 2018). Even though this process can represent up to 70% of the total soil loss of a given area, it has only received attention by researchers in recent decades (Lindstrom et al. 1992; Lobb et al. 1999). Depending on the inclination and the direction of cultivation, the extent of the shift varies. In contrast to water erosion, which has the strongest effect downslopes, tillage erosion has the same effect at all slope positions (Govers and Poesen 1988). Tillage operations further lead to underlying soil compaction and soil structure degradation as well as a loss of soil organic matter (Hartge et al. 2016). The resulting reduction in infiltration and water storage capacity leads to increased surface runoff and further increases the risk of erosion. It has to be noted that erosion processes caused by water, wind, and tillage operations generally do not occur separately, but act together and generally foster each other. Whereas tillage operations mostly do not transport soil particles off agricultural land, but redistribute them within the area, they prepare the soil surface for further removal and transport by water and wind. Thus, all these forces should be considered together to get a comprehensive understanding of the whole system of soil erosion in agriculture (Quine et al. 1999; Li et al. 2007).

12.2.2 Extent of Soil Erosion in Conventional Agriculture

Although soil erosion control has been studied for many decades (Lal 1998; Wischmeier and Smith 1978; Montgomery 2007), erosion is still high on arable land worldwide (Smith et al. 2016; Poesen 2018). This also includes regions e.g. in the US or Europe, where significant progress in erosion control have been made (Panagos et al. 2016; Nearing et al. 2017). One main reason is a lack of vegetation cover throughout the year, which acts as a physical barrier against impacting raindrops and modifies surface water flows, particularly in periods of strong weather events (Thornes 1990; Blanco-Canqui and Lal 2010). Another development greatly affecting soil erosion on agricultural land is the increasing weight of machinery and the pressure of time during seedbed preparation or harvest, which is often carried out by subcontractors. Soil compaction and degradation of the soil structure when driving on agricultural fields at high soil moisture can importantly increase erosion rates (Hartge et al. 2016). Long-term field measurements of soil erosion in Germany (Steinhoff-Knopp and Burkhard 2018), England (Boardman and Evans 2019) and Switzerland (Prasuhn 2012) demonstrated that soil erosion on arable land is often caused by human-made flow pathways such as plough furrows. Furthermore, a worldwide trend to enlarge and consolidate farmland by removing erosion-inhibiting barriers such as hedges to simplify machining has to be stated (Morgan 2006). As a result, erosive slope lengths are increasing and leading to higher erosion rates (Lal 1998; Montgomery 2007).

Increasing demand for food also puts farmers under pressure to cultivate land that is less suitable for agriculture. Land consumption by construction activity on terrain well suited for agriculture reinforces this trend and leads to a shift into marginal areas with often steeper slopes (e.g. Jayne et al. 2014). Furthermore, an increase in open arable land can be observed due to the conversion of permanent grassland into crop rotation areas for forage cultivation (particularly maize). Indeed, maize is an example of the expansion of cultivation of particularly erosion-inducing crops. The architecture of the maize plant leads to the formation of large drops at the tip of the leaves during rainfall events, which then fall into an uncovered intermediate row and there regularly cause high erosion rates (Seitz et al. 2019). Together with other plants such as colza, maize plays an important role in the production of biofuels (Spiertz and Ewert 2009) and thus their cultivation area is expanding. At the same time there has been a decrease in the proportion of perennial arable fodder cultivation and a narrowing of crop rotations down to monocultures in many areas. In some parts of the world, e.g. the Amazonian basin, shifting cultivation regularly worsens erosion when the duration of fallow phases is reduced (Jakovac et al. 2017).

Examples of the variation in rates of erosion recorded worldwide depending on region and land use can be found in Table 12.1. In Brazil, for example, erosion rates under CT with sugarcane were nearly 10-times higher than under managed forest in 2009 (Table 12.1, cf. Merten and Minella 2013). In Australia, soil erosion rates on cropping lands are on average 5–30 times higher than under a predicted natural vegetation cover for the same location (Lu et al. 2003). It becomes clear that different climatic, topographic, soil and management conditions lead to a high variation of soil loss rates (García-Ruiz et al. 2015) and there are strong regional differences between, as well as within, countries. For China, Guo et al. (2015) states that whereas soil loss rates from forests, shrub, and grassland do not show considerable

Table 12.1 Comparison of soil erosion rates under no-till (NT), conventional tillage (CT) and an erosion-preventing land use for different countries and the European Union

Region	Land use type	Range of soil loss [Mg ha^{-1} year^{-1}]	Mean soil loss [Mg ha^{-1} year^{-1}]	Reference
Australia	Forest and shrub land	0–5.2	1.0	Lu et al. (2003)
	Farmland, CT	0.1–100.5	16.1	
	Farmland, NT	–	2.6	So et al. (2009)
Brazil	Forest, cultivated	–	1.4	Merten and Minella (2013)
	Sugarcane, CT	–	13.0	
	Farmland, NT	–	<1.0	
China	Forest	0–1.9	0.7	Guo et al. (2015)
	Farmland, CT	7.7–49.4	24.6	
	Farmland, NT	–	1.9	
EU	Forest	–	<0.1	Panagos et al. (2015b)
	Permanent crops, CT	–	9.5	
	Farmland, NT	–	<1.5	Personal Com.
USA	Native grassland	–	<0.1	Zhang and Garbrecht (2007)
	CT	–	5.7	
	NT	–	0.3	

Land use types refer to the original classification within the respective study. Erosion rates are in part mean values of different regions within a country. Data are based on plot measurements and modelling approaches differences to neighboring areas, the rates from farmland under CT are still much higher than in most other countries. Some regions experienced considerable declines in soil erosion rates in agriculture (e.g. United States of America: from 9.3 Mg ha^{-1} year^{-1} in 1982 to 6.7 Mg ha^{-1} year^{-1} in 2012 on cultivated cropland; Nearing et al. 2017) and today show importantly lower sediment transport rates than a few decades ago (e.g. Europe: 2.5 Mg ha^{-1} year^{-1} for potentially erosion-prone land cover; Panagos et al. 2015b). Nevertheless, these values still exceed sustainable limits. Large differences can also be found on an even smaller scale, e.g. at the level of single EU member states. In Germany for example, about one third of the arable land has a medium to high risk of erosion, but with very high risk being found only in four highland regions in Lower Saxony, Saxony, and Bavaria, whereas large intensively farmed regions in the north and northeast of the country show only very low erosion due to the natural conditions (Bug et al. 2014). Comparable findings were reported from Switzerland, where Prasuhn et al. (2013) classified 43% of the agricultural area as high erosion risk, but qualified this finding by stating that most of this area is located in erosion-mitigating grasslands.

A major difficulty in dealing with soil erosion on agricultural lands is that the available empirical data on its extent are largely based on case studies. These are often not comparable with each other as various parameters, such as the erodibility of recorded soils or rainfall characteristics, differ between studies (Auerswald et al. 2009). In a global meta-analysis of soil erosion rates, García-Ruiz et al. (2015) identified an extraordinarily high variability of erosion rates and concluded that their significance from short-term studies is limited. Soil erosion is not only caused by a continuous ablation of an entire surface, but often strongly depends on randomly occurring major events (Prasuhn 2011; Evans 2017). Thus, gathered data rarely refer to the same temporal and spatial scales, which equally complicates comparability. Furthermore, there are a variety of measurement and modelling approaches, all of which have different advantages and shortcomings (Alewell et al. 2019; Parsons 2019). Field measurements are mostly conducted with different types and sizes of sediment traps or erosion pins, capturing processes from the point scale (<1 m^2) to the watershed scale (Stroosnijder 2005). In this context a reliable upscaling of rates is usually not possible. Field measurements can be conducted under natural rainfall and wind, but also with simulators to obtain homogenous experimental conditions (Seitz et al. 2015; Marzen et al. 2017). Furthermore, mapping techniques are commonly used and especially useful to investigate rill erosion (Prasuhn 2011; Steinhoff-Knopp and Burkhard 2018). Tillage erosion in particular can be investigated with different tracer methods (Guzmán et al. 2013) and the current progress in remote sensing opens up new possibilities for in situ measurements (Eltner et al. 2015; Smith and Vericat 2015). Additionally, various empirical and physically-based soil erosion models are available and widely used to calculate soil losses (Pandey et al. 2016). They need reliable field-measured input variables to predict erosion rates (Nearing et al. 1990). In every case, measurement variability (both human and natural) can be high and reflects the complexity of the involved processes (Stroosnijder 2005).

12.2.3 Consequences of Soil Erosion in Conventional Agriculture

Soil erosion in conventional agriculture not only has an obvious impact on farmers through reduced yields, but also has a negative long-term impact on soil characteristics and functions. Declining yields and a reduction in soil fertility are mainly caused by a loss of the topsoil layer and thus organic matter and nutrients (Morgan 2006). Underlying soil horizons usually contain less organic matter and are more densely packed (Toy et al. 2002). With changing topsoil layers, infiltration, water capacity, and runoff properties also substantially change, e.g. if pores are clogged by detached fine material. This silting and incrustation also leads to reduced soil aeration, reduced nutrient retention, and impedes plant growth (Richter 1998). A disturbed aggregate structure with smaller aggregate sizes offers less resistance to splash erosion and is further affected by reduced organic matter contents (Six et al. 2000b). In addition, damage to agricultural areas, e.g. due to large rills or gullies and thus a greater heterogeneity of the soil surface, generally makes machining more difficult (Toy et al. 2002).

Negative impacts not only influence the actual erosion areas on-site, but can also affect deposition areas off-site (Morgan 2006). This impact often has its beginning at the foot slope of the affected farmland as fertile topsoil, young plants, and infrastructure are covered by sediments, leading to crop failures and e.g. road damage. Furthermore, the input of sediments, nutrients and pollutants into water bodies within the discharge area can affect water quality and burden ecosystems far from the actual erosion area (Pimentel 2006). Most of the negative impacts mentioned above can be effectively mitigated by reducing the number of tillage operations, or introducing NT.

12.3 Effects of No-Till Farming on Erosion Control

In NT farming, seedlings are sown directly into the topsoil without tillage and the usage of any further soil breaking tools is reduced to a minimum. Furthermore, plant residues after harvest are left at the soil surface, which remains covered, preferably all year round. As such, NT appears as the ultimate form of conservation tillage without any soil disturbance except for the very moment of planting. Therefore, it effectively reduces all forms of erosion caused by water, wind, and machinery use and is thus considered to be a major improvement regarding soil erosion control (Lal 1998; Montgomery 2007; Blanco-Canqui and Lal 2010).

Today, reduced erosion rates are widely observed after adoption of NT (Table 12.1 and Fig. 12.2). Evans (2006) reviewed a high number of erosion studies and reported that soil erosion can be strongly mitigated by NT. This finding was confirmed by Montgomery (2007), who summarized results from 39 experiments in which CT and NT were directly compared. It was found that NT practices reduced soil erosion

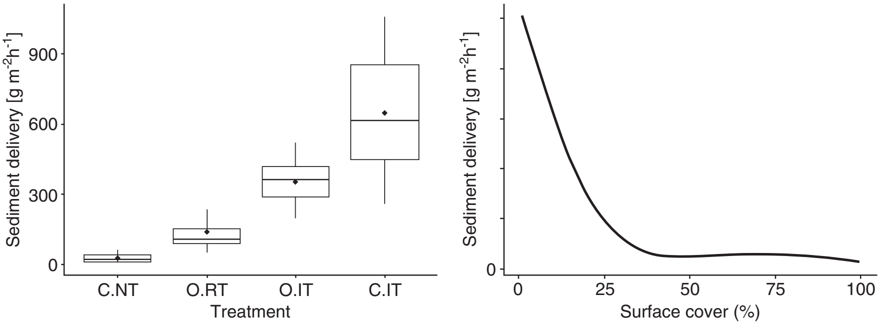

Fig. 12.2 Sediment delivery for different management treatments (left) and soil surface cover (right) in a Swiss Farming and Tillage Trial (Agroscope FAST, cf. Seitz et al. 2019). Data are based on small-scale plot measurements. *C* conventional agriculture, *O* organic agriculture, *IT* intensive tillage, *RT* reduced tillage, *NT* no-till

by 2.5 to >1000 times. Mhazo et al. (2016) analyzed data from 282 runoff plots and reported that soil losses were 60% lower under NT than under CT. Furthermore, the influence of NT on erosion-affecting soil properties was investigated. In this context, Li et al. (2019) conducted a global meta-analysis and highlighted that NT practices have many beneficial effects on such properties compared to CT. A number of case studies further confirmed the erosion reducing effect of NT (e.g. Puustinen et al. 2005; So et al. 2009; Ulén et al. 2010; Seitz et al. 2019). Long-term monitoring by Steinhoff-Knopp and Burkhard (2018) in Germany and Prasuhn (2012) in Switzerland strongly underpinned the erosion-reducing effect of NT. In the Swiss study for example, the average soil loss during 10 years of monitoring was one order of magnitude lower with NT (0.12 Mg ha^{-1} $year^{-1}$) than on ploughed land (1.24 Mg ha^{-1} $year^{-1}$).

Whereas significant data are available from meta-analyses and case studies, reports on erosion rates under NT for whole countries or regions are scarce (Table 12.1). Merten and Minella (2013) expect soil losses under NT in Brazil to be less than 1 Mg ha^{-1} $year^{-1}$. Guo et al. (2015) stated that NT is not widely adopted in China, but data from two Chinese water erosion regions clearly show lower mean soil losses (<2.0 Mg ha^{-1} $year^{-1}$) in NT systems. Also in Europe, NT is less common (<4% of the arable land in the EU; Panagos et al. 2015a) and thus comprehensive data for the entire region are rare. In the USA, where NT systems are most prevalent, Zhang and Garbrecht (2007) demonstrated very low erosion rates under NT - close to native grasslands. In this context, it is noticeable that NT systems are mainly used in wealthier countries, but not widespread in South and Southeast Asian, African, or Central American countries. This is all the more remarkable since many of these countries have erosion-prone soils together with high annual rainfall. In this context, Lal (2007) points to a lack of access to herbicides, adequate seeding machinery, and most importantly, an absence of crop residues mulch and other biomass on the soil surface as reasons for not implementing NT.

The benefits of NT farming for erosion control occur due to improvements in soil functioning (Li et al. 2019). Avoiding intensive soil cultivation stabilizes the soil structure with improved soil aggregation, macroporosity and thus water characteristics. The energy required to destroy aggregates and detach particles during splash erosion strongly depends on the cohesion between soil particles. This is determined, among other things, by soil organic matter, soil rooting and the activity of soil organisms, all three of which are normally elevated in NT systems (Arshad et al. 1990; Kladivko 2001; Kemper et al. 2011). Thus, the mean weight diameter of aggregates in NT soils is generally higher and aggregates are more water stable (Six et al. 2000a). Furthermore, a slight hydrophobicity of the soil aggregates is caused by enhanced humus contents, and this water repellency has been shown to enhance aggregate stability in NT (Behrends Kraemer et al. 2019). Residues from soil organisms and root exudates also enmesh soil particles and enhance the formation of macro-aggregates. Higher soil water infiltration rate and hydraulic conductivity are commonly found in NT and are mostly due to the abundance of macropores (Azooz and Arshad 1996; Li et al. 2019). Without the use of ploughs these are preserved, and especially the work of secondary pore-forming soil animals such as earthworms is less disturbed. The extent of such soil improvement increases with the duration of NT, but also depends essentially on natural soil characteristics and the type of management (Li et al. 2019). At the same time, it has to be stated that many beneficial aspects of NT are not only due to improvement of soil characteristics, but directly related to a remaining soil surface cover (Fig. 12.2). Plant residues on the soil surface intercept raindrop impacts, prevent pore clogging and retain surface runoff (Fernández-Raga et al. 2017). No-till systems in which no crop residues are left after harvest lose many of these advantages (Blanco-Canqui and Lal 2010).

Thus, NT has a whole series of beneficial influences on erosion control and provides a dual protecting function as it reduces both the erodibility of soil and the erosivity of rainfall (Blanco-Canqui and Lal 2010). However, it should be noted that when NT systems are first adopted, increased soil compaction is sometimes reported, which can increase surface runoff and thus sediment transport (Blanco-Canqui and Lal 2007). Nevertheless, this increased compaction is compensated by a multitude of improved soil properties. For example, while increased soil bulk density is usually found in the first years of the transition from tillage to NT, this tends to decrease over time as soil organic matter contents and the activity of soil organisms increase (Beare et al. 1994; Jiang et al. 2018).

It should also be noted that many studies on the effects of NT practices on soil erosion additionally compare methods of reduced or conservation tillage to the application of a long-term NT. This occurs because even though NT is the best technique to avoid erosion, it causes problems for other aspects of farm management, which can encourage farmers to periodically use tillage. These problems are mainly related to weed control, as weed abundance in NT systems can be higher than in plough-based systems (Armengot et al. 2015). Thus, herbicides are used in larger quantities to compensate for the lack of tillage operations (Reimer et al. 2019). They are especially needed in the transition phase from tillage to complete NT, making the implementation of NT in organic farming, where herbicide use is generally not permitted (Wittwer et al. 2017), more challenging (Singh et al. 2015). Seitz et al. (2019) demonstrated that the implementation of NT to conventional farming leads to lower erosion rates compared to tilled organic farming, but also showed that reduced tillage temporarily led to even lower erosion rates in organic management due to weed infestation. A major concern to farmers is that crop yields decline with higher weed infestation in organic farming (Peigné et al. 2007). Pittelkow et al. (2015) showed that in NT systems yields are reduced by 5.1% compared to CT, but results on crop yields in organic farming differ: whereas Armengot et al. (2015) stated that yields from reduced and CT systems are similar, several studies show declining yields in organic NT systems (e.g. Wittwer et al. 2017). In summary, a consistent implementation of NT in organic, but also conventional agriculture, depends on the respective farmer, whose decision does not only consider erosion control.

12.4 Conclusion

Two major environmental issues of the twenty-first century reflected in the Sustainable Development Goals of the FAO are food security and soil degradation. In this context, combating soil erosion remains one of the most important measures worldwide. An essential means to reduce sediment losses is the use of conservation tillage, or complete NT, which has beyond controversy the most beneficial effect on soil erosion control. There is great potential to introduce NT, particularly in regions that currently have low adoption rates, such as China. However, in order to implement NT across the board, certain barriers to adoption, such as partly reduced crop yields, must be overcome. In a global meta-analysis, Pittelkow et al. (2015) showed that NT systems perform best under rain fed conditions in dry climates, matching CT yields on average and Knapp and van der Heijden (2018) stated that a transition to NT does not affect yield stability. There is also great potential for reducing tillage operations in organic farming, despite challenges such as weed control. One way to go might be to increase the use of subsidiary crops, which can at least partly compensate for reduced weed control in the transition phase to NT (Reimer et al. 2019). Indeed, further development of the existing techniques to alleviate shortcomings in conservation and NT systems (such as the use of glyphosate) appears to be crucial to success. Moreover, it can be stated that the interplay between soil erosion and socio-economic as well as political behaviour and the general perception of a soil erosion problem in society are a major factor to support adaption of NT practices to mitigate sediment losses in agriculture (Boardman et al. 2003; Fullen et al. 2006). Finally, more reliable, and above all comparable, measurements are necessary in order to substantiate the findings with robust data and to better understand basic processes.

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Chapter 13
No-Till Farming Systems for Enhancing Soil Water Storage

Samuel I. Haruna and Stephen H. Anderson

Abstract No-till (NT) management has been a successful soil management practice for many decades due to its ability to increase sustainable agricultural production practices through reduced soil erosion. Utilizing this NT conservation practice helps enhance the sustainability of crop production systems. No-till management practices can also improve soil water storage, which optimizes the use of this critical water resource for plant production. No-till management has been found to improve soil organic carbon, soil water retention, plant available water capacity, soil hydraulic conductivity, and water infiltration in soils, resulting in major improvements with water use efficiency. These improvements in soil properties and processes can translate into a more efficient system for sustainable food, fiber and biofuel production for future generations.

Keywords No-till · Soil water storage · Soil conservation · Soil organic carbon

13.1 Introduction

Conserving and efficiently utilizing soil and water resources is critical for sustaining the world's current growing population. Minimizing soil erosion has been one of the main reasons to utilize NT conservation management systems. No-till systems allow the soil to remain undisturbed, reducing soil detachment and transport, two of the principal mechanisms of erosion (Williams et al. 2009). Efforts over the past 50 years in applying NT have been instrumental in reducing soil erosion and improving the long-term sustainability of agricultural management systems (Islam and Reeder 2014). Since NT management systems have been found to reduce runoff

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(Williams et al. 2009), these management systems also efficiently utilize water in rain-fed agricultural areas.

The hunting and gathering lifestyle of humans gave way to a more sedentary style about 10–13 millennia ago and this led to the beginning of settled agriculture (Manning 2004). Settled agriculture led to the development of simple tools to bury the seed in the soil by the Sumerians about 10 millennia ago (Lal et al. 2007a). Thus, the method of seedbed preparation and mechanical weed control, tillage, was born. This method developed and was widely adopted until environmental challenges (e.g. the Dust Bowl), the invention of 2,4-D, and the development of paraquat in U.K. began the NT movement (Hood et al. 1963; Hood et al. 1964). The fundamental principles of NT include growing crops without using traditional tillage; using special planting equipment that cuts through the residue mulch; retaining surface residue to reduce soil erosion, water evaporation and weed growth; and sowing directly into the soil covered by residue mulch (Lal et al. 2007a). These principles often lead to the build-up of soil organic carbon (SOC), improvement in soil aggregation and stability, and water storage under NT compared with conventional tillage (CT) (Lal et al. 2007a). This chapter illustrates the benefits of NT management for improved soil carbon and soil water storage and discusses the effects of this management system on available water capacity, soil hydraulic properties and soil water infiltration.

13.2 No-Till Management Effects on Soil Carbon

Soil carbon has long been identified as an important component of soil quality and productivity (Arshad and Coen 1992; Granatstein and Bezdicek 1992). In most mineral soils, soil carbon is associated with nutrient mineralization and immobilization, soil particle aggregation and aggregate stability, and porosity. Soil management and microbial abundance can affect soil carbon (Kladivko et al. 1997).

Conservation tillage with which NT is associated, requires that at least 30% of the residue from the previous crop be left behind on the soil surface. The retention of this organic material, combined with reduced soil disturbance under NT, has the potential to increase SOC and the activity of soil organisms. Furthermore, these residues also have soil conservation and quality benefits, such as reduced soil erodibility (Williams et al. 2009), and improved soil aggregation (Kremer and Li 2003; Udawatta et al. 2008; Helgason et al. 2010; Veum et al. 2012).

13.2.1 Macro- and Micro-Organisms

Various tillage management systems affect soil physical and chemical properties, and this management may affect the abundance and diversity of several macro- and micro-organisms within the soil. The physical agitation of the soil and inversion of plant and animal residues during tillage can significantly reduce the diversity of the ecosystem (Briones and Schmidt 2017). Residues left behind in NT management, on the other hand, can increase the activity of surface dwellers (e.g. epigeic earthworms, dung beetles) by serving as a habitat and nutrient source. Furthermore, these residues can protect the soil microclimate, further increasing the abundance and diversity of these organisms (Kladivko 2001). These ecosystem engineers can increase organic carbon through their metabolic activities and secretions (Nieminen et al. 2015). Some deep-dwellers, like endogeic earthworms, can also bury organic carbon deep within the soil and this can reduce its breakdown (Kladivko et al. 1997) and increase its mixing with soil minerals. Zhu et al. (2019) reported a higher proportion of carbon, especially in the rhizosphere, in treatments with earthworms than those without earthworms, and the difference was more pronounced in NT soils. Furthermore, earthworms have been reported to activate and sequester carbon through greater carbon stabilization, and this can improve microbial activity (Zhang et al. 2013). This carbon has a significant impact on the more accessible carbon released into the rhizosphere (Zhu et al. 2019).

The activity of soil microorganisms is also influenced by tillage practices. For example, protozoa move easily in water films on and between soil aggregates and thus are very sensitive to soil moisture gradients (Adl 2007). Since NT tends to conserve more soil moisture (less water evaporation), the abundance of soil protozoa tend to be higher under NT management compared with CT (Adl 2007). Protozoa play a significant role in nutrient cycling (Griffiths 1990) and can lead to increased organic carbon.

In a 31-year study of various tillage systems, cover crops and different nitrogen fertilizer rates on continuous cotton (*Gossypium hirsutum* L.) production in Tennessee, Mbuthia et al. (2015) found that NT resulted in a significantly greater abundance of Gram positive bacteria, actinomycetes, and mycorrhizae fungi fatty acid methyl ester biomarkers compared to disk tillage. They also reported that important enzymes linked with C cycling (β-glucosidase) had greater rates under NT management as compared with tillage, and this corresponded with greater soil C. Furthermore, these researchers concluded that long-term NT can result in significant shifts in microbial community and activity that favor C cycling compared with tillage practices.

Different organisms respond differently to soil management, however, most organisms are more abundant and diverse in NT compared with CT systems (Kladivko 2001). The relative abundance and diversity of these organisms is important for soil health and resilience. Ecosystem engineers usually ingest both mineral and organic soil components. Digestion is accomplished through the relationships with the microorganisms in their guts. Their casts are a mixture of partially decomposed organic materials and soil minerals and these casts can help improve soil structure and aggregation and may last longer than the organism that produced them (Tomlin et al. 1995; Kladivko and Clapperton 2011). For example, Blanchart et al. (1999) reported that casts were still observed several months after earthworm eradication. Thus, these authors concluded that the effects of earthworms on soil physical properties may last for 2–3 years after their removal from the soil. Furthermore, ecosystem engineers build nests and dig burrows. These activities can increase soil porosity, which can increase root growth, gaseous interchange, water infiltration, and nutrient transport (Kladivko et al. 1986; Trojan and Linden 1992; Shipitalo and LeBayon 2004).

13.2.2 Soil Organic Carbon

Studies from different parts of the world suggest that intensive tillage can contribute to SOC loss (Bronson et al. 1998; Lal et al. 2007b; Ghimire et al. 2015). Furthermore, conservation practices like NT have been linked with crop residue management that affects SOC accrual (McVay et al. 2006; Ladha et al. 2011; Bhattacharyya et al. 2012a; Ghimire et al. 2012). For example, Robertson et al. (2000) reported a 32% greater SOC under NT management compared with CT at a 0.075 m depth in Michigan. Similarly, Lal et al. (2007b) estimated that CT results in as much as 75% loss of SOC in native lands. Furthermore, in an analysis of 67 long-term studies across tropical and temperate regions, West and Post (2002) showed that transitioning from CT to NT could result in 0.57 ± 0.14 Mg C ha^{-1} year^{-1} of SOC sequestration.

In a comparative analysis of studies conducted in the US corn belt (Minnesota, Kentucky, and Indiana), Elliot et al. (1994) reported that SOC (particulate organic matter C and mineralizable C) was greater in NT management compared to CT. They concluded that this might lead to increases in the potential availability of soil C to heterotrophs. Ghimire et al. (2012) reported significantly greater SOC in the top 0.50 m of NT compared with CT soils on a plain in Nepal under a rice (*Oryza sativa*)-wheat (*Triticum aestivum*) system. In the top 0.05 m of the soil, these researchers reported 28.3% greater SOC under NT management compared with CT. In addition, Pandey et al. (2014) reported that NT before sowing of rice and wheat could increase SOC by 0.59 Mg C ha^{-1} year^{-1}. In a study on the impact of long-term CT and NT management practices on the SOC of a silty clay loam soil in Indiana, Gal et al. (2007) reported that in the 0–0.05 m and 0.05–0.15 m soil depths, NT resulted in 33% and 9% more SOC as compared with a Fall moldboard plow. The reason for the higher SOC in the NT management system may be attributed to less annual soil aeration, especially in the upper soil layers (Holanda et al. 1998). Root derived C may also be important for soil C storage (Gregorich et al. 2001; Tresder et al. 2005) and increased water retention.

The greater microbial activity and corresponding SOC under NT management results largely from greater soil aggregation and conservation of micro- and macroaggregates (Bhattacharrya et al. 2012b) due to less soil disturbance. This can benefit available water content, water infiltration and soil conservation by lowering soil erodibility.

13.3 Available Water Capacity

Water is usually considered the most limiting factor in crop production, and agriculture is responsible for about 80% of global human water consumption. Good water management is thus imperative for improved and sustained crop productivity. Not all water in the soil is available for plant uptake. Some water drains rapidly under gravity, and some is held too tightly for plant use. Plant available soil water can be measured by determining the soil water retained, often using pressure chambers in the laboratory (although tensiometers and psychrometers have been used for *in situ* measurements). Thus, plant available water capacity can be determined as the difference between the lower (permanent wilting point) and upper (field capacity) limits of soil water content in the vadoze zone (Cassel and Nielsen 1986). These limits are often based on soil water equilibrating with forces exerting various degrees of tension on the soil water (Bauer and Black 1992).

Soil water availability is influenced by several factors, including climate, soil texture and structure, landscape position and management. Humid regions with higher precipitation levels usually have more available water compared with arid and semi-arid regions with lower precipitation levels and high soil water evaporation rates. The shapes and mineralogy of the various soil particles can also influence available water. The largely spherically shaped, primary minerals of sandy soil textures allow water to drain out quickly under gravity due to the higher proportion of macropores (> 1000 μm effective diameter). Conversely, the mainly platey-shaped, secondary minerals of finer textures retain water longer due to the higher proportion of micropores (< 10 μm effective diameter). Various land management practices can also affect available water capacity by altering pore size distribution and structure. These practices include NT, CT, cover crops, crop rotations, perennial grasses and buffer strip systems. The following subsections discuss the influence of NT management practices on plant available water capacity.

13.3.1 No-Till Management Effects on Soil Field Capacity

Generally, field capacity (FC) is defined as the water content of the soil after all the macropores and mesopores (10–1000 μm effective diameter) have drained under gravity. Field capacity is the water content of the soil 2 days after the soil has been thoroughly wetted.

No-till management practices can affect FC by influencing SOC levels and reducing soil disturbance. Soil organic C improves soil aggregation and increases the proportion of larger pores (Kladivko et al. 1986). Furthermore, as a soil colloid, SOC can also retain more water due to a higher surface area than most soil minerals (Haruna et al. 2017). Consequently, Bescansa et al. (2006) reported that water retention at FC was 11% higher in NT management compared with moldboard plow management.

Soil disturbance and aeration can lead to rapid depletion of SOC which can reduce soil aggregation and influence soil pore size distributions. Furthermore, minimal disturbance can reduce soil pore tortuosity factors (Haruna and Nkongolo 2015) and increase soil pore connectivity. This can further improve water retention and available water at FC.

13.3.2 No-Till Management Effects on Soil Permanent Wilting Point

The permanent wilting point (PWP) is the point at which soil water is under very high tension, so high that most plants are unable to extract soil water. As such, plants begin to permanently wilt. Once this condition has been reached, it may be difficult for plants to survive. With the exception of xerophytes, the PWP of most upland crops is −1500 kPa (Cassel and Nielsen 1986).

Generally, water retention at matric potentials less than −100 kPa are influenced by particle size distribution rather than by management, with clay-sized particles retaining more water (Bauer and Black 1992; Jiang et al. 2007). However, some researchers have reported that at −1500 kPa soil water pressures, water retention was higher under NT management compared with CT (Hill et al. 1985; Bescansa et al. 2006). This suggests that the influence of SOC on water retention may extend to lower soil water pressures. This influence may result from the colloidal properties of SOC (Haruna et al. 2017). Due to the increased surface area of soil colloids, SOC can help retain more water at lower soil water pressure.

13.3.3 No-Till Management Effects on Plant Available Water Capacity

The influence of NT on plant available water capacity (AWC) can result from the influence of this management practice on soil organic carbon (SOC), minimal soil disturbance, and improved biopores due to enhanced microbial activity. Bascansa et al. (2006) reported that NT management had 11% higher AWC compared with moldboard plow tillage. They attributed this to the higher percentage of smaller pores due to minimal disturbance. Salem et al. (2015) also reported that with higher precipitation, NT management had higher available water content compared with minimum and reservoir tillage. These studies show that minimal soil disturbance can improve available soil water capacity.

Various researchers have reported increased microbial activity under NT management compared with tillage (e.g. Feng et al. 2003; Carpenter-Boggs et al. 2003; Helgason et al. 2010). Increased microbial activity can increase SOC content, soil aggregation, pore size distribution, and this can increase AWC. Tillage, on the other hand, while it can be advantageous in extremely water-logged situations (Tisdall and Hodgson 1990), has the potential to increase water evaporation from soil. Furthermore, the increased heterogeneity and tortuosity of pores caused by mechanical disturbance can lead to less water storage and AWC compared with NT management (Haruna and Nkongolo 2015).

Crop residues can reduce radiant energy reaching the soil surface by shading the soil, causing lower surface temperature and reducing wind effects (van Donk et al. 2010). Researchers have reported annual irrigation savings of as much as 0.13 m from both irrigated and rain-fed regions of the U.S under NT management (Klocke et al. 2009). Pryor (2006) contends that converting from CT to NT can reduce irrigation water because of reduced evaporation. These researchers demonstrated that tillage operations can dry-out the soil before planting to the tillage depth layer and cause the loss of about 0.8–1.9 cm of soil moisture per tillage pass. Thus, NT systems can further increase AWC through reduced soil moisture evaporation.

13.4 No-Till Management Effects on Saturated Hydraulic Conductivity and Water Retention Curves

Saturated hydraulic conductivity is the flow rate through a saturated soil horizon under a unit hydraulic gradient. It is an important parameter for soil water infiltration, soil water retention, and water movement through a porous material. The saturated hydraulic conductivity is a very sensitive measurement that varies spatially and temporally and is influenced by pedogenic and anthropogenic factors. This soil property can be determined *in situ*, as well as in the laboratory. Methods of determination are beyond the scope of this presentation and readers are directed to consult Hillel (1998), Lal and Shukla (2004), Radcliffe and Simunek (2010), and Shukla (2014).

The following sub-sections will discuss the influence of NT management on *in situ* and laboratory determined saturated hydraulic conductivity and water retention curves. To differentiate between laboratory and field measured saturated hydraulic conductivity, laboratory measured saturated hydraulic conductivity will be denoted as K_{sat} while field measured saturated hydraulic conductivity will be denoted as K_{fs}.

13.4.1 No-Till Management Effects on In Situ *Measured Saturated Hydraulic Conductivity*

Saturated hydraulic conductivity is influenced by soil bulk density, porosity, and aggregate stability. Field methods have shown tillage to have different effects on K_{fs}. Researchers have reported either a greater K_{fs} in CT compared with NT (Gregorich et al. 1993), or a greater K_{fs} in NT (Culley et al. 1987) and strip till (Jabro et al.

2009) compared with CT. This can be attributed to the temporal variability of parameters and soil properties that influence K_{fs} since most of these studies were conducted right after soil tillage.

In fact, Gregorich et al. (1993) concluded that tillage resulted in smaller aggregates and that these aggregates may become subject to destruction over time, which can negatively influence the water flow rate. Furthermore, Akhtar and Qureshi (1999) reported that water puddling after deep tillage significantly reduced K_{fs}. This confirms that, over time, tillage may reduce K_{fs} compared with NT. Further studies are needed to investigate the temporal variability of K_{fs} under various tillage management systems.

13.4.2 *No-Till Management Effects on Laboratory Measured Saturated Hydraulic Conductivity*

Hydraulic conductivity is affected by soil structure and texture, which varies in space and time, with temporal variability being caused by the growth and decay of plant roots (Meek et al. 1992), soil organism activity (Willoughby et al. 1996), surface crusts that can form from precipitation (Messing and Jarvis 1993), shrinking and swelling (Bagerello et al. 1999), and management practices such as tillage and wheel-traffic compaction (Ankeny et al. 1990; Logsdon and Jaynes 1996).

Soil agitation through tillage can affect hydraulic conductivities in contrasting ways. Plowing can create macropores that can increase saturated and near-saturated hydraulic conductivity values significantly, but this management can also increase the soil pore tortuosity factor, which can reduce hydraulic conductivity (Bouma 1991). Several researchers have reported that right after tillage, saturated and near-saturated hydraulic conductivity values in the topsoil are usually large but decrease over time due to soil particle reconsolidation (Cassel and Nelson 1985; Messing and Jarvis 1993; Feng et al. 2011; Haruna et al. 2018a [Fig. 13.1]). In general, less soil disturbance can increase soil pore connectivity and this can positively influence K_{sat}. In a long-term study (>27 years.) of the effects of tillage management practices on saturated and near-saturated hydraulic conductivities of soils in the Pacific Northwest of the US, Fuentes et al. (2004) reported that the K_{sat} of the top 0.05 m of the soil was significantly greater in NT than in moldboard plow tillage. Similarly, Benjamin (1993) reported as much as 180% greater K_{sat} values in NT compared with moldboard and chisel plowing.

In their study on a silt-loam soil, Haruna et al. (2018a) reported that right after tillage in the top 0.2 m of soil, moldboard plow significantly increased the proportion of coarse mesopores and K_{sat} values compared with NT. However, approximately 1 year post tillage, these researchers reported greater K_{sat} values under NT compared with moldboard plow tillage. They also found that lower bulk density values do not always translate to higher K_{sat} values for similar soil management

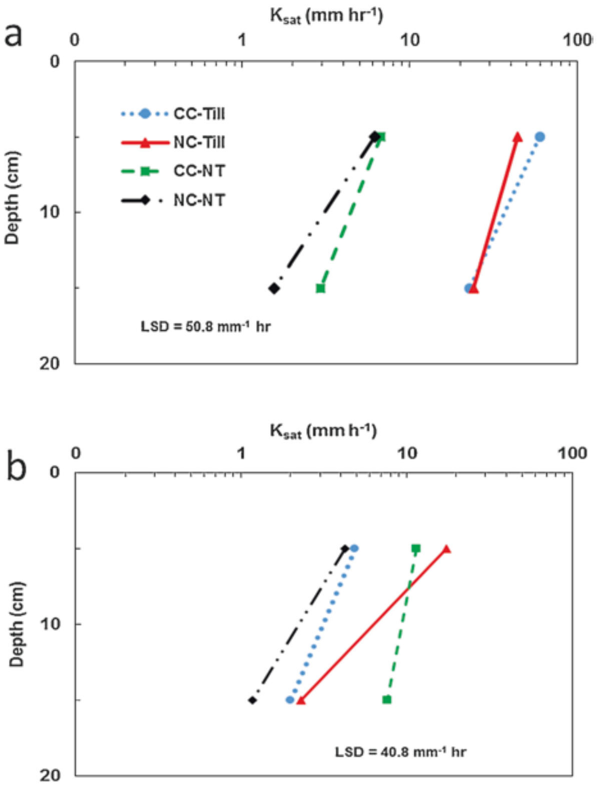

Fig. 13.1 Temporal variability in saturated hydraulic conductivity between no-till and conventional tillage (**a**) right after tillage, (**b**) 1 year after tillage. CC-Till = cover crop with tillage, NC-Till = no cover crop with tillage, CC-NT = cover crop with no-till, and NC-NT = no cover crop with no-till. (Redrawn from Haruna et al. 2018a)

practices for two reasons. First, soil bulk density is a less sensitive property compared to K_{sat}. Second, bulk density does not show soil pore continuity.

The influence of compaction on hydraulic conductivity is also dependent on soil management practices. Under NT management, wheel-traffic induced compaction can result in the reduction of K_{sat}, but biological effects (such as earthworm burrows and root channels) can counteract the compaction-induced reduction of K_{sat} (Gantzer and Blake 1978; Ankeny et al. 1990).

13.4.3 No-Till Management Effects on Soil Water Retention Curves

Soil water retention curves, or soil water characteristics, describe the relationship between soil water content and soil water pressures. This measurement can be used to predict water storage and is strongly influenced by management practices that influence soil porosity. Compared to moldboard plow, NT generally leads to a reduction in porosity (Gantzer and Blake 1978). In addition, NT has been observed to influence pore size distribution, with an increase in the proportion of finer pores and a decrease in larger pores (van Ouwerkerk and Boone 1970; Tollner et al. 1984).

No-tillage has been reported to increase volumetric water content (Mitchell et al. 2012; Haruna and Nkongolo 2015; Chawala and Kahlon 2018) due to reduced water evaporation resulting in greater water reserves compared to CT. The increased water storage ability may also be attributed to less pore tortuosity due to less soil disturbance (Haruna and Nkongolo 2015). For example, Eynard et al. (2004) reported that NT increased soil porosity between 0.05–0.3 m soil depth and increased pore connectivity due to increased biological activity compared with tilled plots and this led to increased infiltration and water content.

Hill et al. (1985) conducted a study on the effects of tillage on soil water retention and pore size distribution of two Mollisols (Site 1: Typic Haplaquolls; Site 2: Aquic Hapludolls) in Iowa. They measured soil water retained between 0 and –39 kPa soil water pressures. These researchers (Hill et al. 1985) reported that CT had a greater proportion of pores >15 μm radii, while conservation tillage (reduced and NT) had a larger proportion of pores between 15–0.1 μm pore radii. Consequently, they reported that at Site 1, besides 0 kPa, NT plots retained more water compared with CT, while NT retained more water than CT plots at all soil water pressures measured in Site 2. They concluded that because CT soils have a greater proportion of large pores right after tillage, these soils may be more susceptible to densification over time as compared to soils under NT management systems. Haruna et al. (2018a) reported similar findings on soils in central Missouri.

Brandt (1992) carried out a 12-year study of NT v CT on 36 sites and reported that NT resulted in greater volumetric soil water content and water use efficiency on 9 sites with no significant differences among the rest. In fact, these researchers reported between 0.56–0.81 kg ha^{-1} mm^{-1} greater water use efficiency between NT and CT. They attributed this to biopores developed by soil microorganisms as a result of less soil disturbance. Azooz and Arshad (2001) reported that between −5 and −160 kPa soil water pressures, NT management had higher water retention compared with CT. They also found that in the top 0.30 m the rate of soil drying was greater for CT compared with NT, while the rate of wetting was greater for NT compared with CT management.

13.5 No-Till Management Effects on Water Infiltration

Water infiltration is important for soil water storage and environmental sustainability. The rate of water infiltration and the cumulative infiltration can be influenced by soil management practices such as tillage. Tillage can affect infiltration by influencing soil pore integrity and connectivity, soil organic carbon, K_{sat}, and antecedent soil moisture content.

Mechanical agitation of the soil breaks up soil clods and this action may temporarily improve water infiltration. For example, Blanco-Canqui et al. (2017) reported that cumulative infiltration after 3 h was significantly higher under moldboard plow tillage (after 1 year of tillage) compared with NT. These researchers also reported that total porosity, K_{sat}, and water retention were similar between both tillage management treatments. Haruna et al. (2018b) reported similar findings after 3 months of tillage. This was probably due to the lower antecedent water content induced by higher evaporation rates due to tillage. Similarly, Jones et al. (1994) reported that cumulative infiltration after 2 h of simulated rainfall was 90% greater on stubble-mulch tillage compared to NT in Texas. They suggested tillage destroyed the consolidated surface crust, reduced bulk density, and increased surface roughness and depression storage capacity. However, their research was carried out right after tillage.

The sustainability of soil management practices depends on their performance beyond a few years. Due to possible tillage-induced compaction, water infiltration might be inhibited over time. For example, Capowiez et al. (2009) reported that moldboard plow tillage did not significantly influence water infiltration measured between 1 and 24 months after tillage due to the reconsolidation in soil bulk density that occurred after mechanical soil agitation. Conversely, Azooz and Arshad (1996) reported that for antecedent soil moisture conditions ranging from dry to field capacity, the ponded infiltration rate values were greater by 0.24–3.01 cm h^{-1} in NT compared to those in CT for a silt loam soil, and by 3.30–4.13 cm h^{-1} for a sandy loam soil. Similarly, Shukla et al. (2003) reported that steady state infiltration rate after 3 h and field capacity water content 24 h after infiltration were higher under NT compared with CT. These researchers also reported much higher bulk density under CT compared with NT.

In a more recent study, Blanco-Canqui and Ruis (2018) reported that NT increased wet aggregate stability by as much 97% and water infiltration by as much as 86% compared with CT. This led to about 44% higher available water in NT compared with CT. Stone and Schlegel (2010) studied the influence of tillage and crop rotation on soil physical properties in the West-Central Great Plains of the US and reported that steady-state infiltration rate was 63% higher under NT management compared with CT (Fig. 13.2). They concluded that NT management may be the most appropriate management in this region due to its benefits (significantly better aggregate stability, higher infiltration rate and lack of reconsolidation during the growing season) as compared with CT.

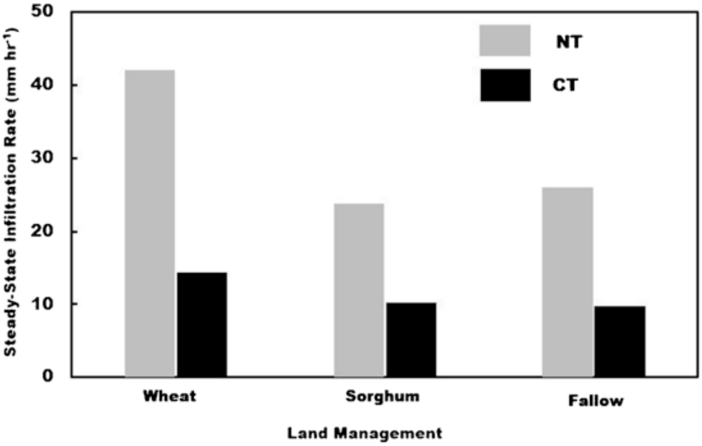

Fig. 13.2 Ponded, steady-state infiltration rate grouped by land management for no-till (NT) and conventional tillage (CT). (Redrawn from Stone and Schlegel 2010)

13.6 No-Till Management Effects on Water Repellency and Soil Behavior

Soil water repellency (SWR) is an important soil hydrological property that refers to the ability of the soil to resist wetting. It is an intrinsic and dynamic soil property that can be influenced by soil management. The following section will explore the effect of tillage on SWR and how this can affect soil behavior.

13.6.1 No-Till and Soil Water Repellency

No-till management can result in SWR due to the accumulation of hydrophobic organic C from crop residues, microbial activity, and less soil disturbance (Blanco-Canqui 2011). The magnitude of this effect can vary temporally during the growing season. For example, Chan (1992) reported that SWR was about 40 times greater under NT compared with CT in summer but was only 2 times greater in during the fall season.

In a study conducted by Simon et al. (2009), NT soils were reported to have 20% greater SWR compared with CT. They also reported that this result was consistent whether or not the NT management was mulched. Bottinelli et al. (2010) studied the influence of belowground earthworm casts on SWR in France. These researchers found that between the 0.12–0.17 m soil depth, SWR was 2 times greater under NT management compared with CT. However, no significant differences were found between tillage types at depths above 0.07 m. Blanco-Canqui et al. (2009) reported similar findings and found that in the 0–0.02 m depth, SWR was consistently greater in NT management compared with CT.

13.6.2 Influence of No-Till Induced Water Repellency on Soil Behavior

Excessive SWR can increase runoff volume, rill erosion, loss of sediments and nutrients, preferential flow, and interflow. However, slight NT induced SWR can lead to some important positive benefits on soil behavior. Slight increases in SWR can slow down water penetration into NT soil aggregates and this can help preserve soil macropore integrity and connectivity and improve aggregate stabilization (Eynard et al. 2006). By contrast, rapid water penetration can lead to air entrapment and slaking and this can compromise the integrity of soil structure. For example, Blanco-Canqui and Lal (2009) reported a strong positive correlation between SWR and wet aggregate stability for NT soils in the top 0.05 m of soil depth. This suggests that SWR can increase wet aggregate stability and possibly reduce soil erosion.

Furthermore, due to the improved soil structure stabilization as a result of slightly greater SWR in NT soils, C in soil aggregates will also be stabilized (Lamparter et al. 2009). These stable aggregates can protect the organic C from rapid decomposition by reducing microbial access and controlling water, air, and nutrient fluxes (Bachmann et al. 2008). This can lead to enhanced soil C sequestration. Researchers have reported strong positive correlation between SWR and the labile components of SOC (Simon et al. 2009) and between SWR and SOC (Blanco-Canqui and Lal 2009).

In summary, NT induced SWR can enhance soil water storage by reducing soil erodibility, crusting, and aggregate slaking, and improving soil aggregation, soil water distribution, and pore connectivity and integrity.

13.7 Water-Logging Issues and Climate Change with No-Till Management

No-till management adds more residue to the soil surface, which can reduce water evaporation. Due to this slightly lower evaporation under NT management with increased surface residues, soil surface conditions often result in slightly higher soil water content and this will occur during the early crop growth periods (Mitchell et al. 2012). The net result of NT management may cause excess soil water at the soil surface which, under high rainfall, may result in water logging conditions. To handle these situations, managers may utilize surface and subsurface water drainage in combination with NT to improve these conditions.

Climate change issues include concerns about future agriculture production. These climate issues include more intensive rainstorms and potentially more severe drought for some regions of the world (Zaibon et al. 2017). No-till management can assist in mitigating these issues through better infiltration, allowing more rainfall to infiltrate during more intense storms and also protecting the soil from the erosive energy of these storms. Furthermore, NT management practices can slow the rapid decomposition of organic carbon, thus keeping sequestered carbon within the soil longer, although some studies indicate these effects may be smaller than originally expected (Powlson et al. 2014). By enhancing residue cover under NT management, less evaporation will occur allowing better plant production in regions experiencing increased drought.

13.8 Conclusions

The sustainability of crop production systems is highly dependent on the adoption of conservative agricultural practices. No-till management practices can improve soil water storage by improving soil organic carbon, soil water retention, plant available water capacity, hydraulic conductivity, water infiltration, and increasing water repellency. These benefits can translate into a more efficient system for sustainable food and biofuel production, cleaner bodies of water and a more enduring environment for future generations.

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Chapter 14
Enhancing Soil Aggregation in No-Till Farming Systems

Humberto Blanco-Canqui

Abstract Improving soil physical properties, such as aggregate stability, is essential to reducing soil erodibility, stabilizing C and nutrients, improving water, air, and heat fluxes, and supporting root growth. No-till (NT) farming generally improves soil aggregate stability near the soil surface, but the extent of this improvement can depend on the companion practices used with NT, including crop residues, cover crops, crop rotations, organic amendments (i.e., manure, biochar), inorganic fertilization, or one-time or strategic tillage. The objective of this paper is to discuss how companion practices to NT affect soil aggregate stability (a sensitive indicator of changes in soil structure), as compared to NT without such companion practices. Research indicates that companion practices can differently affect aggregate stability in NT soils relative to NT without companion practices. For example, inorganic fertilization does not affect aggregate stability in 70% of cases, but animal manure can increase aggregate stability in 60% of cases. Crop residue baling at high rates can reduce near-surface aggregate stability by 7–64%, particularly in the long term (> 3 years). This reduction can be especially large at low rates of inorganic fertilization. Practices such as strategic tillage and moderate crop residue grazing (<30% residue removal) do not generally affect aggregate stability. Conversely, cover crops, animal manure, biochar, and intensified crop rotations can increase the ability of NT soils to improve aggregate stability in the long term (> 5 years), particularly in low organic matter (<2.5%). While the latter practices offer much promise to enhance aggregate stability, challenges associated with cover crop management, biochar production, and others should be addressed. *In sum, adding* cover crops, animal manure, biochar, and using intensified crop rotations can enhance the potential of no-till to further enhance soil aggregation, especially when such practices are targeted to low organic matter, eroded or degraded NT soils.

Keywords No-till · Soil structure · Soil aggregate stability · Cover crops · Inorganic fertilization · Crop residue removal · Crop residue grazing · Crop rotations · Biochar · Animal manure

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14.1 Introduction

Maintaining or improving soil aggregation is critical to reduce water and wind erosion, filter runoff, retain and recycle nutrients and water, protect and sequester organic C, mediate soil microbial processes, and support root development and crop production. For example, the stability, size, and distribution of soil aggregates determine the volume of pore space for the movement of water, air, and heat. Large pores favor rapid movement of water, air, and heat, while small pores are important to retention of available soil water and protection of C and nutrients. An increase in organic matter, root biomass, and biological activity promotes soil aggregation (Blanco-Canqui and Lal 2004; Rosenzweig et al. 2018).

No-till farming generally increases surface soil aggregate stability relative to tilled soils, but the extent of such increase can vary. A review by Blanco-Canqui and Ruis (2018) concluded that NT-induced increase in near-surface wet soil aggregate stability ranged from 1 to 97% compared with tilled soils. This high variability in NT effects can be partly attributed to the differences in companion practices used with NT but also to initial soil properties such as soil organic matter content (Fig. 14.1). The magnitude to which each companion practice changes aggregate stability in NT soils is, however, unclear. For example, strategic tillage, the one-time or strategic tillage of long-term NT soils, is used in some cases to manage herbicide-resistant weeds, excessive soil compaction, C and nutrient stratification, and other challenges with continuous NT farming, but its impact on aggregate stability is not widely discussed. Thus, the objective of this paper is to discuss how companion practices to NT affect soil aggregate stability as compared to NT without such companion practices. This paper focuses on wet aggregate stability, hereafter referred to as aggregate stability, as the most sensitive indicator of changes in soil structure.

14.2 Does Inorganic Fertilization Increase Aggregate Stability?

Inorganic fertilization is a common companion practice in NT systems for supplying nutrients, which leads to the question: How does inorganic fertilizer affect soil aggregate stability? The summary of research findings in Table 14.1 indicates that

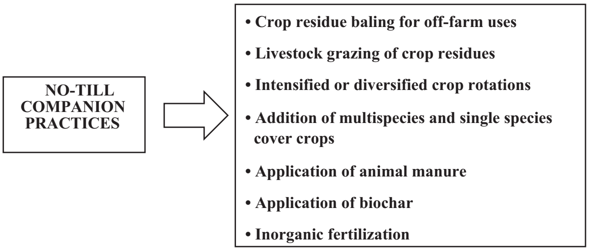

Fig. 14.1 Depending on farmer's preferences, accessibility, needs, and goals, a number of practices are used as companion to no-till farming

Table 14.1 Impacts of inorganic fertilization on soil aggregate stability indexes in no-till (NT) systems

Location	Soil	Crop	Years in NT	Fertilization rate per year	Fertilization impact on aggregate stability	References
Nebraska, USA	Silty clay loam	Corn	28	0, 80, and 160 kg N ha^{-1}	Increased MWD by 43% in the upper 0.075 m depth	Blanco-Canqui et al. (2014a)
					Reduced MWD by 47% in the 0.15–0.6 m depth	
Kansas, USA	Silt loam	Grain sorghum	26	0 and 135 kg N ha^{-1}	Increased MWD by about 24% in the upper 0.15 m depth	Presley et al. (2012)
Kansas, USA	Silt loam	Corn	50	0, 45, 90, 134, 179, and 224 kg N ha^{-1}; 20 and 40 kg P ha^{-1}	No effect in the upper 0.075 m depth	Blanco-Canqui and Schlegel (2013)
					Reduced MWD by 30–160% in the 0.075–0.3 m depth at high N and P rates	
Mississippi, USA	Silt loam	Cotton	3	0 and 112 N kg^{-}ha^{-1}	No effect on WAS	Adeli et al. (2019)
South Africa	Clay loam	Corn	13	0, 100, and 200 kg^{-1} N ha^{-1}	No effect on MWD	Sithole et al. (2019)
Argentina	Loam	Corn-soybean-wheat	7	0, 120, and 150 kg N ha^{-1}; 30 kg P ha^{-1}	No effect on MWD	Wyngaard et al. (2012)

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

the use of N and P fertilizers does not alter aggregate stability in most NT soils (70% of cases). Table 14.1 also indicates that, in a few cases, N and P fertilization can either increase aggregate stability by 24–43% or reduce it by 30–160%. The reduction appears to occur in the 0–075-0.30 m depth. The increased aggregate stability with fertilization can be due to increased biomass production and biomass C input, whereas the reduced aggregate stability can be due to a fertilization-induced release of NH_4^+ and decrease in soil pH (Haynes and Naidu, 1998). An increase in NH_4^+ in the soil solution can disperse soil colloids and deflocculate aggregates. Also, Blanco-Canqui and Schlegel (2013) found that the decrease in aggregate stability was larger when both N and P fertilizers were applied at >100 kg N ha^{-1} year^{-1} and > 40 kg P ha^{-1} year^{-1} than when N or P was applied alone or when both were applied at lower rates. Overall, inorganic fertilization does not increase aggregate stability in most cases in spite of increased crop biomass production with fertilization. This finding appears to corroborate that the main value of adding inorganic fertilizers to crops is to increase crop yields and not to improve soil properties such as aggregate stability.

14.3 Does Animal Manure Application Increase Aggregate Stability?

The summary in Table 14.2 indicates that, in about 60% of cases, animal manure application to NT fields increases surface soil aggregate stability by 8–75% relative to NT systems without manure. It is well recognized that manure application can improve soil aggregation by increasing soil organic C concentration, microbial biomass and activity, and plant growth, and inducing slight hydrophobic properties to soil. The manure-induced slight water repellency reduces aggregate slaking. Manure also contains organic matter at different stages of decomposition, which can differently impact soil aggregation. Manure-derived particulate organic matter promotes aggregation in the short term, whereas, in the long term, manure transformation into mineral-associated organic matter can promote formation of stable microaggregates (Aoyama et al. 1999). In some cases, animal manure may have a high concentration of monovalents (Na^+, NH_4^+, and K^+), which can cause dispersion of colloids, thereby reducing soil aggregation (Whalen and Chang 2002).

Table 14.2 also suggests the following trends. First, composted manure can increase aggregate stability more than raw manure as the former provides decomposed organic materials and encourages biological activity to bind soil particles and form aggregates (Jiao et al. (2006)). Second, large amounts of manure may be needed to significantly increase aggregate stability. Jiao et al. (2006) applied beef manure at 0, 15, 30, and 45 Mg ha^{-1} year^{-1} and found that only 30 and 45 Mg ha^{-1} year^{-1} increased aggregate stability, suggesting that only high rates

Table 14.2 Impacts of animal manure application on aggregate stability indexes in no-till (NT) soils

Location	Soil texture	Crop	Years of manure application	Manure type	Manure rate (Mg ha^{-1} year^{-1})	Soil depth (m)	Manure effect on aggregate stability	References
Ohio, USA	Silt loam	Corn	41	Beef	15	0.10	Increased kinetic energy of raindrops needed to break aggregates by 39%	Blanco-Canqui et al. (2007)
Canada	Sandy loam	Corn and corn-soybean	4	Composted beef manure	0, 15, 30, and 45	0.10	30 and 40 Mg/ha of manure increased WSA (> 2 mm) by about 25%	Jiao et al. (2006)
Mississippi, USA	Silt loam	Cotton	3	Poultry litter	6.7	0.15	Increased WAS by 8%	Adeli et al. (2019)
Nebraska, USA	Site 1 (two silt loams)	Corn	30 days	Manure	50	0.025	Manure increased aggregate size (> 2 mm) by 67%	Wortmann and Shapiro (2008)
				Composted manure			Composted manure increased aggregate size (> 2 mm) by 75%	
	Site 2 (silt loam and loam)	Not available	4	Beef feedlot and swine slurry manure	46 (beef manure) for silt loam		Beef feedlot had no effect	
					2.7 (swine manure) for loam		Swine slurry increased aggregate size (> 0.25 mm) by 21%	
	Site 3 (silt loam)	Corn-soybean	4	Composted beef manure with low and high P	66.7 low P		No effect	
					66.7 high P			
Nebraska, USA	Silt loam	Corn	3	Sheep and beef	17.3 (sheep manure in year 1)	0–0.025	No effect on MWD	Blanco-Canqui et al. (2014b)
					19 (beef manure in year 2)			

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

($>$15 Mg ha^{-1} year^{-1}) of manure application can induce changes in aggregate stability. In general, animal manure application generally increases aggregate stability.

14.4 Does Baling Crop Residues Reduce Aggregate Stability?

Crop residues from NT fields are often baled, particularly in the US Midwest such as for livestock feeding and biofuel production. Thus, the question is: How does baling crop residues affect aggregate stability? Table 14.3 indicates that corn residue removal commonly reduces aggregate stability by 12–64%. Several findings emerge from Table 14.3 as follows:

- In corn producing systems of the US Midwest, > 5.5 Mg ha^{-1} year^{-1} of crop residues should be retained to maintain aggregate stability with greater retention for highly erodible soils (Wortmann et al. 2012; Johnson et al. 2014).
- Corn residue removal reduces aggregate stability more at low than at high rates of N fertilizer application, although few studies have assessed the interactions of different levels of residue removal and N fertilization. High rates of N application appear to offset the adverse effects of residue removal on aggregate stability. This is possibly due to the greater residue production and C input under high N rates.
- Continuous crop residue removal for >3 years is more detrimental to aggregate stability than short-term or infrequent removal.
- Decrease in aggregate stability due to crop residue removal is often confined to the upper 0.05 or 0.10 m of the soil surface especially in the short term (<3 years). Continued residue removal in the long term can, however, reduce aggregate stability at deeper depths (Stewart et al. 2019).

No-till performance is a function of crop residue retained in the field (Table 14.3). Residues protect the soil from raindrops and other erosive forces, stabilize soil, reduce aggregate detachment, increase soil organic C concentration, and provide C and energy sources to soil microorganisms (Johnson et al. 2014). Low residue retention also rapidly alters surface soil water content and soil temperature, inducing abrupt fluctuations in drying-wetting, freezing-thawing, and swelling-shrinking cycles, particularly in winter and spring. These abrupt cycles degrade the inter- and intra-aggregate bonds (Blanco-Canqui et al. 2016). For example, intra-aggregate pores expand during freezing, increasing the total aggregate volume. In contrast, rapid drying of the soil decreases aggregate size and reduces intra-aggregate macroporosity. In summary, leaving sufficient crop residue retention in NT fields is important to maintain or improve aggregate stability because NT fields with limited or no residues can be equally or more prone to degradation than tilled fields.

Table 14.3 Impacts of corn residue removal on soil aggregate stability in no-till (NT) systems

Location	Crop	Soil	Years after residue removal	Amount of residue removal (Mg ha^{-1})	Amount of residue left (Mg ha^{-1})	Removal rate (%)	Soil depth (m)	Residue removal effect on aggregate stability	References
Nebraska, USA	Irrigated continuous corn	Silt loam	6	5.6	4.4	56	0–0.05	Reduced MWD by 23%	Sindelar et al. (2019)
Kansas, USA	Irrigated continuous corn	Silt loam	3	1.67	5.00	25	0–0.05	No effect on MWD	Kenney et al. (2015)
				3.45	3.47	50			
				5.03	1.68	75			
				6.24	0	100			
	Irrigated continuous corn	Loam	3	1.80	5.41	25		No effect on MWD	
				3.58	3.59	50			
				5.22	1.74	75			
				6.45	0	100			
	Rainfed continuous corn	Loam	3	0.85	2.53	25		No effect on MWD	
				1.57	1.59	50			
				2.37	0.79	75			
				4.33	0	100		Reduced MWD by 64%	
Nebraska, USA	Irrigated continuous corn	Sandy loam	3	8.14	3.32	71	0–0.05	No effect on MWD	Blanco-Canqui et al. (2017)
Nebraska, USA	Rainfed continuous corn	Silt loam	12	2.7 to 3.3	2.21 to 1.6	55	0–0.05	Reduced WSA (>0.5 mm) by about 23% at 60 kg N ha^{-1} $year^{-1}$	Jin et al. (2015)
								No effect at 120 and 180 kg N ha^{-1} $year^{-1}$	

(continued)

Table 14.3 (continued)

Location	Crop	Soil	Years after residue removal	Amount of residue removal (Mg ha^{-1})	Amount of residue left (Mg ha^{-1})	Removal rate (%)	Soil depth (m)	Residue removal effect on aggregate stability	References
Minnesota, USA	Rainfed continuous corn	Silt loam	12	NA	NA	90	0–0.05	Reduced amount of macroaggregates (>0.25 mm) by 59%	Laird and Chang (2013)
Nebraska, USA (3 sites)	Irrigated continuous corn	Silt loam	3	5.4	4.2	56	0–0.05	No effect on MWD	Rakkar et al. (2019)
Nebraska, USA	Irrigated continuous corn	Silt loam	3	9.7	5.0	64	0–0.05	Reduced MWD by 64%	Ruis et al. (2018)
Illinois, USA (4 sites)	Rainfed continuous corn	Silt loams	8	3.4	4.2	45	0–0.15	Both removal rates reduced WSA by about 9% at 134 kg N ha^{-1} year^{-1}	Villamil et al. (2015)
				6.8	0.8	89		No effect of removal on WSA at 268 kg N ha^{-1} year^{-1}	

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

14.5 Does Grazing Crop Residues Reduce Aggregate Stability?

Livestock grazing of crop residues is a common component of synergistic crop-livestock integration. This leads to the question: How does grazing of crop residues affect aggregate stability? While research data are relatively few, a review found that moderate grazing of crop residues has small and mixed effects on aggregate stability (Rakkar and Blanco-Canqui 2018). Moderate crop residue grazing often removes <30% of residues and has much smaller effects on aggregate stability than high rates of residue baling. The reasons for the small or no effects of crop residue grazing effects on aggregate stability deserve further discussion. On one hand, residue grazing may reduce aggregate stability by (1) reducing organic material return to the soil, (2) exposing the soil surface to erosive forces such as raindrops, and (3) inducing abrupt fluctuations in wet-dry and freeze-thaw cycles (Layton et al. 1993). On the other hand, grazing livestock adds manure to grazed fields. Manure input may not only offset the potential adverse effects of residue grazing but may also improve aggregate stability (Rakkar and Blanco-Canqui 2018). Additionally, hoof action during grazing can compress soil aggregates and potentially increase soil aggregate strength or stability relative to non-grazed soils. Overall, moderate grazing of crop residues in NT cropping systems has small or no effects on aggregate stability and can be valuable to crop-livestock integration.

14.6 How Do Cropping Systems Affect Aggregate Stability?

The cropping system effects on soil aggregation depend on the amount of residue produced and returned to the soil. High-biomass producing crops in the rotation can improve aggregate stability over rotations with low biomass production. High-biomass producing crops such as continuous corn increases aggregate stability over low-biomass producing crops such as corn-soybean rotation, continuous soybean, and continuous tobacco (Table 14.4) (Zuber et al. 2015).

In water limited environments, such as in the semiarid US Great Plains, reducing the frequency of one-year fallow periods can improve aggregate stability (Table 14.4). Note that fallow in this paper refers to fallowing where all vegetative growth is prevented by using chemicals to store water. No-till with fallow periods every 3 or 4 year generally increases aggregate stability relative to fallow periods every other year. As the frequency of fallow periods decreases, mean annual biomass input can increase. One strategy to reduce fallow periods in crop-fallow systems is by growing grain, forage or cover crops that are terminated early enough for some water accumulation before sowing of the primary crop. The precipitation pattern is important to such cropping system choices.

In general, an increase in cropping frequency is positively correlated with an increase in aggregate stability (Table 14.4). Also, diversified rotations with high-biomass producing crops can be effective for enhancing microbial activity and

Table 14.4 Impacts of intensified no-till cropping systems on soil aggregate stability from studies published in the past 5 year

Location	Crop rotation	Years of intensification	Impacts of intensified cropping systems on aggregate stability	References
Kansas, USA	Sorghum-fallow Continuous sorghum Winter wheat-sorghum-fallow Winter wheat–fallow Continuous winter wheat	33	Continuous wheat increased MWD by 67% compared with sorghum-fallow and wheat-sorghum-fallow in the upper 0.025 m depth	Blanco-Canqui et al. (2010)
Montana, USA†	Winter wheat-fallow Pea-winter wheat Continuous wheat	8	Pea-wheat and continuous wheat increased WSA (> 1 mm) by 49% compared with wheat-fallow	O'Dea et al. (2015)
Colorado, USA‡	Winter wheat-fallow Rotations with fallow every 3 or 4 year Continuous rotations	0–30	Continuous rotations increased MWD by about 45% in the upper 0.10 m depth	Rosenzweig et al. (2018)
Nebraska, USA	Corn-soybean Continuous corn	28	Continuous corn increased MWD by 32% compared with corn soybean in the upper 0.075 m depth	Blanco-Canqui et al. (2014a)
Illinois, USA	Continuous corn Corn-soybean Corn-soybean-winter wheat Continuous soybean	15	No effect in the upper 0.10 m depth	Zuber et al. (2015)

† Soil depth sampling was not specified
‡ Soil was sampled from 96 NT fields in the semi-arid Great Plains, USA

aggregate stability. For instance, in the semiarid US Great Plains, Rosenzweig et al. (2018) reported that adopting NT crop rotations increased fungal biomass in the surface soil by about three times compared with NT crop-fallow systems. Overall, NT continuous cropping or intensified crop rotations with high biomass production can increase aggregate stability relative to NT systems with low biomass production.

14.7 Does Adding Cover Crops to No-Till Soils Improve Aggregate Stability?

Adding cover crops to existing NT cropping systems can be one innovative strategy to enhance aggregate stability. Cover crops provide additional biomass input to NT cropping systems. A review by Blanco-Canqui et al. (2015) found that cover crops can increase aggregate stability by 0–100%, depending on site- and management-specific conditions. Some of the factors that affect cover crop impacts on aggregate stability include:

- Initial soil organic matter
- Cover crop biomass production
- Length of growing season
- Cover crop species
- Fertilization and irrigation
- Time after adoption
- Tillage system
- Seeding rate
- Climate

The amount of biomass produced is one of the most important factors that dictate cover crop benefits. An increase in both aboveground and belowground cover crop biomass typically improves soil C levels and biological activity to improve aggregate stability (Blanco-Canqui et al. 2015). Also, the aboveground biomass protects the soil surface, while the belowground biomass (roots) interact with the soil matrix. High-biomass producing cover crops combined with reduced soil disturbance can improve aggregate stability (Ruis et al. 2019).

The amount of biomass produced by a cover crop is a function of the available growing degree day for cover crop growth. Early planting and late termination can increase cover crop biomass production relative to late-planted and early-terminated cover crops (Ruis et al. 2019). Cover crops planted in summer and terminated in late fall produce more biomass due to favorable temperature and soil moisture conditions than those planted in late fall and terminated in spring, even though the number of days of cover crops in the field for the latter is longer (Blanco-Canqui et al. 2015).

The amount of biomass production also depends on cover crop species. Grass cover crops, such as cereal rye, can be one of the highest biomass producing winter cover crops in temperate regions due to its winter hardiness and rapid establishment (Ruis et al. 2019). Cover crop effectiveness to improve aggregate stability can also increase with time after cover crop adoption. Significant cover crop effect on soil aggregation may require >5 years (Blanco-Canqui et al. 2015). Cover crop biomass production could also increase with increasing seeding rate, fertilization, and irrigation, which can result in improved aggregate stability, although the economics of increased farm input should be considered.

14.8 Does Adding Biochar to No-Till Soils Increase Aggregate Stability?

Applying biochar, a C-enriched material produced from pyrolysis of organic materials, to NT soils can enhance aggregate stability. Biochar application can increase aggregate stability by 3–226% (Blanco-Canqui 2017). Some of the mechanisms by which biochar improves aggregate stability include (Blanco-Canqui 2017; Zhang et al. 2020):

- Biochar contains between 60 and 90% of C, which can enhance aggregation particularly in the long term. The C content in biochar will vary depending on the feedstock and pyrolysis temperature.
- Biochar can improve soil aggregation by adding polyvalent cations and increasing cation exchange capacity. However, if biochar has a high concentration of monovalent cations such as Na^+, it may have limited potential to increase aggregate stability.
- Biochar addition can increase soil biological activity as fungi and bacteria feed on labile C and other organic substances in biochar although biochar commonly contains more stable than labile C. Soil organisms release organic binding agents to increase aggregate stability.
- Biochar can reduce the mineralization of native soil organic matter or C, a process known as negative priming effect. Thus, biochar could increase aggregate stability not only by adding C to soil but also by reducing decomposition of native C. Reduced mineralization of native C can also protect aggregates and reduce their turnover.
- Biochar application can induce a slight water repellency to soil if it has hydrophobic properties. The slow water entry into aggregates can reduce slaking of aggregates.

The effectiveness of biochar to improve aggregate stability can depend on a number of factors including initial soil organic matter, biochar amount, feedstock, pyrolysis temperature, and others. Biochar material with small particle size and high C concentration can more readily and rapidly interact and bind inorganic soil particles than coarse biochar material (Blanco-Canqui 2017). Biochar is also expected to improve aggregate stability more in the long than in short term as biochar particles age and interact with soil matrix (Zhang et al. 2020). Surface application of biochar to NT soils may not allow rapid interaction of biochar particles with soil. Thus, incorporation of biochar through one-time or occasional tillage of NT can be strategy to incorporate biochar into the root zone in NT systems.

14.9 Does Strategic Tillage of No-Till Reduce Aggregate Stability?

In this paper, strategic tillage refers to the one-time tillage of long-term NT soils to manage some of the challenges with NT management, including control of herbicide-resistant weeds, excessive soil compaction, C and nutrient stratification, and acidification. In general, tillage of long-term NT soils once in 5 or 10 years is considered strategic tillage (Wortmann et al. 2010). The few published studies indicate that strategic tillage may or may not reduce aggregate stability (Table 14.5). In cases where strategic tillage reduces aggregate stability, the reduction is short lived

Table 14.5 Effects of one-time or strategic tillage (ST) of otherwise continuous no-till (NT) on soil aggregate stability

Location	Soil	Years under NT	Tillage method	Tillage Depth (m)	Sampling time after ST (years)	Effect of ST on aggregate stability	References
Australia	Three soils	10, 14, and 16	Scarifier or offset discs	0.1	<1	Reduced amount of aggregates (>0.25 mm) by 0–14% in the 0.05 m depth, but returned to initial levels after 1–2 year	Conyers et al. (2019)
Turkey	Clayey	9	Moldboard plow (MP)	0.3–0.33	0	Reduced MWD by 7.2% in the upper 0.1 m depth	Celik et al. (2019)
						Increased MWD by 78% in the 0.1–0.2 m and by 104% in the 0.2–3 m depth	
USA	Two silty clay loams	7–12	MP, miniMP, and chisel or disk	0.1–0.3	<1, 2, and 5	No effect on WSA	Quincke et al. (2007) and Wortmann et al. (2010)

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

and disappears 1 or 2 years after tillage (Wortmann et al. 2010). In other cases where strategic tillage **r**educes aggregate stability near the soil surface, it increases aggregate stability in the subsoil due to inversion or mixing of surface with subsurface layers. Thus, the sum of changes in aggregate stability for the soil profile due to strategic tillage of NT is generally minimal.

It is important to clarify that while strategic tillage, every 5 or more years, does not generally reduce aggregate stability, more frequent tillage may reduce aggregate stability. For example, Stavi et al. (2011) found that disk plowing of NT every 3 years reduced aggregate stability in a temperate region; however, in the same region, one-time tillage had no effect on aggregate stability when NT soil was tilled once in 10 years (Wortmann et al. 2010). In summary, strategic tillage of long-term NT soils does not appear to have large negative effects on soil aggregate stability, but short-term tillage (<5 years) may reduce aggregate stability.

14.10 Opportunities and Challenges

Opportunities exist to enhance aggregate stability in NT soils through the adoption of cover crops, crop residue management, addition of animal manure and biochar, and intensification of cropping systems with extended rotations or high-biomass producing crops. However, challenges can exist with the use of some companion practices. For instance, cover crop effectiveness depends on the amount of cover crop biomass produced. Cover crops that are planted late or terminated early often produce too little biomass to be of measureable benefit. Also, in water-limited or semiarid regions, cover crops may reduce available water needed for the next crop. A potential opportunity is to use cover crops in low organic matter or degraded NT soils where they can provide more benefits than in high organic matter and productive soils. Targeting low organic matter soils with cover crops can be a better strategy to improve soil properties such as aggregate stability. It is also important to design site-specific cover crop management strategies (i.e., timely planting or termination) to increase cover crop biomass production.

Another opportunity to increase soil C concentration, and thus aggregate stability, is the use of biochar. However, at present, biochar material can be costly and not readily accessible, which limits its use at larger scales. The cost of biochar can be significant when high rates (>10 Mg ha^{-1}) of biochar are often needed to significantly improve aggregate stability and other properties. Also, biochar effects on crop yields have been inconsistent depending on biochar properties, management, and initial soil properties. Similar to cover crop benefits, low organic matter and degraded NT soils may benefit more from biochar application than highly productive NT soils (El-Naggar et al. 2019). Also, identifying the optimum application rates of biochar for different soil types, cropping systems, and climate is a research priority.

Retention of sufficient crop residue is needed to maintain or improve aggregate stability of NT soils. For example, research from the US Midwest shows that excessive crop residue removal can reduce aggregate stability. Indeed, crop residue removal from NT soils could reduce aggregate stability more than residue removal from tilled soils. For example, Laird and Chang (2013) reported that corn residue removal reduced the amount of macroaggregates by 59.5% in NT but only by 13.6% in chisel plow and 30.3% in plow till. Some have suggested that NT soils with limited residue cover, or after complete residue removal, may be equally or more erodible than tilled soils due to reduced aggregate stability (Layton et al. 1993). Estimates from the Midwestern US suggest that about 5 Mg ha^{-1} year^{-1} of crop residues is needed to maintain soil properties in NT fields (Johnson et al. 2014). Additional research is needed to establish threshold levels of residue removal for different soils and climates to manage soil erosion. This means that low-biomass producing NT cropping systems or NT systems where residues are baled should be redesigned to include high-biomass producing crops or cover crops for enhancing aggregate stability.

Furthermore, strategic tillage is proposed as a strategy to address some of the challenges with NT. However, strategic tillage disturbs soil, which could increase risks of water and wind erosion immediately after tillage. Thus, timing of strategic tillage and targeting specific problems will be critical to reduce any potential negative effects. Strategic tillage every 5 or 10 years may not be detrimental to soil properties, but more frequent tillage such as short-term tillage may degrade aggregate stability and other soil structural properties (Quincke et al. 2007; Wortmann et al. 2010; Conyers et al. 2019).

14.11 Conclusions

No-till companion practices differently affect soil aggregate stability. Some companion practices such as inorganic fertilization and strategic tillage do not generally affect soil aggregate stability. Inorganic fertilization increases crop yields, while strategic tillage addresses some of the challenges in long-term NT farming, but these practices do not appear to improve soil aggregate stability. Potential opportunities to increase soil aggregate stability include adoption of cover crops, application of animal manure and biochar, and diversification or intensification of cropping systems. These practices may not come without some challenges, which include the need for redesigning current cropping systems, developing strategies to grow forage or cover crops in water-limited regions, and producing biochar for use at large scales. Also, managing crop residues in NT farming is an essential component. Excessive removal of crop residues through baling or grazing can reduce the ability of NT soils to maintain or improve aggregate stability. In conclusion, maintaining abundant residue cover, growing cover crops, intensifying crop rotations with high-biomass producing crops, and adding animal manure or biochar are some of the potential strategies to enhance structural properties of NT soils, although challenges with adoption of these practices need consideration on a site-specific basis.

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Chapter 15
Resilient and Dynamic Soil Biology

Alwyn Williams, Frederik van der Bom, and Anthony J. Young

Abstract Agricultural intensification has delivered great gains in terms of food production but has come at great environmental cost. Consequently, there is growing societal demand for more sustainable farming systems, i.e., sustainable intensification. Within this, there is increasing recognition of the ecosystem services provided by soil organisms that contribute both to agricultural production and environmental sustainability. Conventional tillage-based farming systems experience frequent and significant soil disturbance, which negatively impacts many key soil organism groups, e.g., fungi and earthworms. Loss of these soil organisms results in loss of critical soil ecosystem services, including those related to soil nutrient cycling, crop nutrient uptake, and soil water management. Conversion of farming systems from conventional tillage to no-till can allow recovery of soil biology and restoration of soil ecosystem services. Thus, no-till farming systems can contribute positively towards sustainable intensification. However, important knowledge gaps and challenges remain. Greater knowledge of what soil organisms are present in soil and what services they provide is urgently needed. The ultimate goal is to understand how soil biology can be manipulated through management to provide desirable ecosystem services in space and time.

Keywords Crop nutrient uptake · Soil ecosystem services · Soil fauna · Soil microbial community · Soil organic matter · Soil nutrient cycling · Tillage

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15.1 Introduction

Agricultural intensification has been highly successful in terms of increasing global food production and consequently lifting millions of people out of hunger (Godfray et al. 2010). However, the success of agricultural intensification has come at great environmental cost, including widespread soil degradation, loss of biodiversity, greenhouse gas emissions, and polluted waterways (Foley et al. 2011). This has led to greater societal awareness and demand for sustainable intensification; that is, more environmentally sustainable farming systems that are still highly productive (Tilman et al. 2011; Kremen and Miles 2012). Within this, there is increasing recognition of the ecosystem services provided by soil organisms that contribute both to agricultural production and environmental sustainability (Bommarco et al. 2013; Bender et al. 2016). This includes contributions to regulating ecosystem services, such as maintaining and improving soil structure, soil water holding capacity, and soil carbon (C) storage; as well as to supporting ecosystem services, including soil nutrient cycling and crop nutrient uptake (Millenium Ecosystem Assessment 2005). No-till (NT) farming systems are recognized as improving the supply of soil ecosystem services compared with conventional tillage-based (CT) farming systems, driven primarily by a drastic reduction in soil disturbance combined with crop residue retention that fosters improved soil biology (Hobbs et al. 2008; Williams et al. 2016b). Consequently, NT farming systems can contribute positively towards efforts to sustainable intensification. In this chapter we introduce key organism groups present in agricultural soils and provide an overview of the ecosystem services they provide. We then discuss the impacts of CT on soil biology and the capacity of NT to restore soil biota and soil ecosystem services. Finally, focussing on soil nutrient cycling, we outline key knowledge gaps that inhibit our ability to actively manage soil biology to generate dynamic ecosystem services in space and time within NT farming systems.

15.2 Soil Biology

Soils are among the most complex of biological ecosystems. Although often considered simply the substrate for plant growth, soils represent living, breathing entities comprising myriad interacting organisms. Charles Darwin, the preeminent figure in the evolution of the study of life sciences, dedicated his latter life to examining the role of earthworms in soil formation and was consistently struck by the complexity involved (Darwin 1881). The development of sophisticated molecular biology platforms has facilitated insights into soil biology that were unimaginable in Darwin's time. For example, it is estimated that a single teaspoon of soil from a fertile agricultural field contains tens of millions of bacterial cells, tens of kilometres of fungal hyphae, as well as a diverse array of micro-, meso- and macro-fauna (Stirling et al. 2016). Each of these organisms is connected by complex food web interactions, and together they provide a multitude of ecosystem services critical for sustainable crop production. This section will briefly introduce some of the key soil organism groups found in agricultural soils and outline the vital processes and services they provide. It should be noted that many soil organisms can also generate ecosystem disservices, most visibly in the form of crop pests and diseases. Crop pests and diseases within NT farming systems typically stem from poor crop rotation management, and are covered extensively in Chaps. 8 and 9.

15.2.1 Soil Microbes

Soil microbial communities are strongly impacted by the soil environment. In particular, they are responsive to temperature, moisture, pH, soil organic carbon (SOC) content, and nutrient availability (Rousk et al. 2010; van der Bom et al. 2018). Changes in these components can alter the structure and function of the microbial consortia. Bacteria, oomycetes, and fungi are the key soil microbial groups and have a major impact on crop productivity and the generation of soil ecosystem services. Archaea are also soil microbes but their role in agriculture is currently poorly defined (Di et al. 2009; Ouyang et al. 2016). Soil microbes impact on crop productivity both directly, via mutualistic or pathogenic relationships with plants, and indirectly, via their role in soil processes that influence crop uptake of nutrients and water. As the primary decomposers in the soil system, the activities of this diverse assemblage of organisms drives the cycling of nutrients between organic and inorganic pools. This means that despite being microscopic, soil microbes play an oversized role in fundamental processes relating to soil fertility.

15.2.1.1 Indirect Impacts

Microbes influence crop productivity indirectly via their role in soil organic matter (SOM) decomposition and nutrient cycling. Filamentous, saprophytic fungi are the dominant decomposers, producing large quantities of degradative enzymes, e.g., cellobiohydrolases and lignin peroxidases, that decompose complex organic matter such as crop residues (Treseder and Lennon 2015). These organisms are metabolically efficient and can effectively immobilize nutrients within fungal biomass (de Vries and Bardgett 2012). The nutrient immobilization generated by saprophytic fungi can compete with and limit crop nutrient uptake in the short term (de Vries and Bardgett 2012); but can also conserve nutrients that can be mineralized at a later date, thus helping to limit potential nutrient losses (Robertson and Vitousek 2009; de Vries and Bardgett 2012). In contrast, bacteria have a relatively fast turnover rate and respond rapidly to take advantage of liberated nutrients. The fast turnover rate of bacteria promotes gross mineralization rather than immobilization (Schimel and Bennett 2004), which provides short-term benefits in terms of promoting crop nutrient uptake. However, if the timing of mineralization does not coincide with periods of crop uptake, e.g., during fallow periods, there is high risk of soil nutrient loss and depletion of SOM in the longer term (Robertson and Vitousek 2009).

Soil bacteria and fungi have contrasting influences on the accumulation and turnover of SOM. This is a result of differences in their metabolism, the recalcitrance of mineralized products, and interactions with soil physical properties (Six et al. 2006). Current evidence indicates that a significant fraction of stable SOM is of microbial, and particularly fungal, origin (Cotrufo et al. 2013; Kallenbach et al. 2016). Moreover, the hyphal networks developed by arbuscular mycorrhizal fungi (AMF) and saprophytic fungi play a primary role in soil aggregation, by physically enmeshing soil particles and by fungal secretions (Wilson et al. 2009; Peng et al. 2013; Lehmann and Rillig 2015). The development of soil macroaggregates can slow the decomposition of SOM through physical protection of organic material within macroaggregates (Grandy and Robertson 2007; Plaza et al. 2013). Fungal-dominated systems may therefore have higher C retention than bacterial dominated systems (Six et al. 2006). The improvement of soil structure generated by aggregate formation can also enhance the ability of soils to regulate water flows by improving rainfall infiltration and increasing soil water holding capacity (Franzluebbers 2002; Zibilske and Bradford 2007).

Soil microbes can also indirectly assist plant growth by regulating pests and pathogens. This suppression can be general or specific, depending on the microbes involved. Among the best-known examples of general suppression are the nematode trapping fungi, which have evolved a range of traps to capture nematodes (Li et al. 2005). Nematode trapping fungi are usually associated with high C:N ratio leaf litter and use the digested nematodes as a nitrogen (N) source (Barron 2003). These fungi trap a range of nematodes from different trophic groups; thus, if more plant-parasitic nematodes (PPN) are present, the fungi will consume more of them. Specific suppression occurs when a microbe attacks a specific entity, such as the endospore-forming bacterium *Pasteuria,* which adheres to and then infects passing nematodes. This has been shown to suppress populations of agriculturally important PPN, such as root-knot nematode (Bhuiyan et al. 2018). While there exist many commercial formulations of beneficial microbes, such as *Metarhizium*, *Trichoderma* and *Bacillus amyloliquefaciens*, equivalent microbes adapted to local conditions are found throughout agricultural soils.

15.2.1.2 Direct Impacts

Although a wide array of soil microbes form direct associations with plants, we only briefly mention two here that have direct relevance to agricultural crops: N-fixing bacteria and AMF. Nitrogen-fixing bacteria (e.g., *Rhizobium*) can develop symbioses with a wide range of legume crop hosts. The host plant provides photoassimilated C to the bacteria located within root nodules. The bacteria utilize this C to transform atmospheric N into ammonia-N that is readily available for assimilation by the host plant. Legumes can derive up to 90% of their N from atmospheric N fixation through this process (Franche et al. 2009). As a result, symbiotically fixed N is a major source of N in agriculture, estimated at between 50 and 70 Tg of N per year in agricultural systems worldwide (Herridge et al. 2008). Arbuscular mycorrhizal fungi are symbiotic organisms that colonize the roots of the vast majority of plant species, effectively extending the plant root system. By producing extracellular phosphatases that mineralize soil phosphorus (P) (Treseder and Lennon 2015), AMF are able to efficiently mine soil P and transport it into plant roots. Plants are then able to access a proportion of this P in exchange for photoassimilated C (Smith and Read 2008). Root colonization by AMF has been shown to enhance P nutrition in a range of economically important crops (Jakobsen 1986; McGonigle and Miller 1993; e.g., Bagayoko et al. 2000), and can be particularly important in soils with low nutrient status (Menge 1983; Hetrick 1991). In addition to P, AMF can enhance crop uptake of other immobile nutrients, including ammonium and zinc (Frey and Schüepp 1993; Cavagnaro 2008).

15.2.2 Micro- and Meso-Fauna

Soil fauna can be conveniently categorized according to body size, giving micro-, meso- and macro-fauna (Table 15.1). Here we will consider micro- and meso-fauna together. The major organism groups in the microfauna include protozoans, tardigrades, and nematodes. Major organism groups in the mesofauna include collembolans (springtails) and mites as well as larger nematodes (Coleman et al. 2018). Microfauna occur exclusively in water films and feed primarily on bacteria and fungi. This close trophic relationship with the soil microbial community, and with bacteria in particular, means microfauna can exert a strong positive influence on soil nutrient availability through their excreta (Stirling et al. 2016). Similarly, changes in the microbial constitution of soils is reflected in the diversity and abundance of micro- and meso-fauna that consume them. Among these, nematodes represent the best studied and most informative of the microfauna when assessing changes in soil health.

Although PPN are most commonly associated with agriculture, the full soil trophic array is exhibited across nematode groups. In addition to PPN, different nematode species can be bacterivorous, fungivorous, omnivorous, and predatory. The numbers and proportions of each group fluctuate depending on food source availability. Food source availability in-turn varies depending on soil management, making nematodes an excellent indicator of soil microbial community structure.

Table 15.1 Size range classification of micro-, meso-, and macro-fauna by body length and width

Size classification	Microfauna	Mesofauna	Macrofauna
Body length	<0.20 mm	0.20–10.4 mm	>10.4 mm
Body width	<100 μm	100 μm – 2 mm	>2 mm

Adapted from Coleman et al. (2018)

Plant-parasitic nematodes can exert economically damaging losses in agricultural systems, with notable examples including cyst-forming and root-lesion nematodes (Stirling et al. 2016). Omnivorous and predatory nematodes can help regulate populations of PPN; however, they are sensitive to soil disturbance and their populations can be slow to recover due to their relatively long generation times (Stirling et al. 2016).

Collembolans and mites are microarthropods closely associated with the litter layer. As such, they predominantly occur in the topsoil where crop residues are abundant and soil pores are large enough to facilitate easy movement. Collembolans are primarily fungivorous, and it is through consumption and digestion of fungal hyphae that they play a role in decomposition processes, soil nutrient cycling and soil respiration (Coleman et al. 2018). Mites account for a diverse group of organisms. Like Collembolans, many mites are fungal as well as bacterial feeders. However, the mites also include predatory species as well as plant feeders and parasites (Coleman et al. 2018).

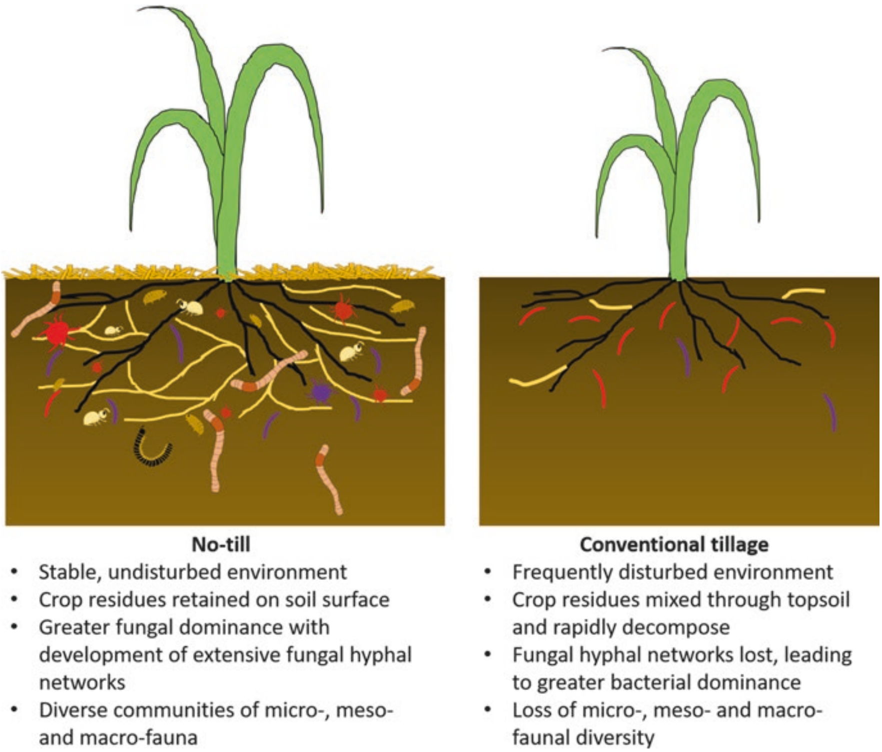
15.2.3 Macrofauna

The soil macrofauna comprises many well-known organisms that are visible with the naked eye. These include ants, termites, dung beetles, centipedes, millipedes, isopods, and earthworms. The macrofauna differ importantly from the micro- and meso-fauna in that many of them are considered ecosystem engineers; that is, through their activities, they can directly alter soil structure (Coleman et al. 2018). Arguably the best-known example of such ecosystem engineers is earthworms.

There are over 3000 formally described species of earthworms, with many more yet to be discovered (Csuzdi 2012). They vary in length from centimetres to metres and exhibit a range of feeding and tunnelling behaviours that impact the overall biology of the soils they inhabit (Lavelle et al. 1997). Earthworms can be categorized as epigeic, which feed in the uppermost soil and litter layers; endogeic, which feed within the topsoil; or anecic, which form deep borrows but feed on surface litter (Bouché 1975). These different feeding habits can have a profound impact on the soil environment. Through their burrowing behaviours, earthworms relocate substantial quantities of soil to the surface. This process creates macropores that are important for rainfall (or irrigation) infiltration, can aid drainage in more waterlogging-prone soils, and improve soil aeration (Stirling et al. 2016). Macropores can also assist plant root growth and movement of beneficial organisms, such as predatory mites, throughout the soil (Stirling et al. 2016). Additionally, anecic earthworms pull crop residues from the surface down into the soil profile. This brings crop residues into greater contact with bacteria and fungi thereby facilitating decomposition processes. Also, the downward transfer of residue serves to redistribute SOM (Stirling et al. 2016). Beyond the positive physical contributions to soil structure, earthworms can also stimulate efficient soil nutrient cycling via their consumption of crop residues and subsequent production of nutrient-rich casts (Coleman et al. 2018).

15.3 Impacts of Conventional Tillage v No-Till on Soil Biology and Soil Ecosystem Services

The repeated and frequent disturbance of soil via CT has many impacts on soil biology (Fig. 15.1). In general, CT systems tend to support lesser abundances and diversity of soil biota compared with NT systems, and display an overall community shift to dominance by organisms with *r*-selected life history strategies, i.e., those that favour rapid reproduction and dispersal (Pianka 1970; Wardle 1995; Verbruggen and Kiers 2010). Larger-bodied organisms with longer generation times (*K*-selected organisms) are more susceptible to disturbance events and suffer depressed populations in tilled systems (Postma-Blaauw et al. 2010; Briones and Schmidt 2017).



No-till

- Stable, undisturbed environment
- Crop residues retained on soil surface
- Greater fungal dominance with development of extensive fungal hyphal networks
- Diverse communities of micro-, meso- and macro-fauna

Conventional tillage

- Frequently disturbed environment
- Crop residues mixed through topsoil and rapidly decompose
- Fungal hyphal networks lost, leading to greater bacterial dominance
- Loss of micro-, meso- and macro-faunal diversity

Fig. 15.1 No-till soil management leads to greater complexity and diversity of soil biology compared with conventional tillage. These changes lead to significant changes in the delivery of soil ecosystem services. Note, figure not drawn to scale

These community shifts can have profound impacts on the provisioning of soil ecosystem services and sustainable crop production.

Compared with NT, CT agricultural soils have been found to support lower overall microbial biomass with a shift in the fungal:bacterial ratio in favor of bacterial dominance (Frey et al. 1999; Helgason et al. 2010; Cavigelli et al. 2012). The relative decrease of fungi in conventionally tilled soils is related to the effects of increased soil disturbance, reduced soil moisture content, and to the incorporation of crop residues (Beare et al. 1992; Frey et al. 1999). Soil fungi are highly sensitive to soil disturbance, particularly those that develop extensive hyphal networks, e.g., filamentous saprophytic fungi and AMF. The destruction of hyphal networks wrought by CT leads to loss of fungal biomass and diversity (Helgason et al. 1998; Jansa et al. 2002; Kabir 2005; Alguacil et al. 2008). Increasing soil moisture can have a positive effect on fungal biomass but does not affect bacterial biomass; subsequently, increased moisture under NT can lead to a shift towards greater fungal dominance (Frey et al. 1999). Similarly, fungi are more efficient than bacteria at taking advantage of crop residues at the soil surface, hence, greater surface residue retention in NT leads to a more fungal dominated community (Frey et al. 1999). This microbial shift results in differing functional attributes under CT relative to NT, with reductions in soil enzyme activities and subsequent nutrient cycling rates (Kladivko 2001; Balota et al. 2014; Mbuthia et al. 2015).

The physical action of tillage also leads to the breakdown of soil aggregates, which liberates and exposes previously protected labile SOM (Grandy and Robertson 2006, 2007). This newly exposed SOM is rapidly mineralized by soil bacteria resulting in SOM depletion (Grandy and Robertson 2006; Panettieri et al. 2015). Due to the strong dependence of soil aggregate stability on fungal hyphae (Caesar-TonThat and Cochran 2000; Rillig and Mummey 2006), those aggregates not immediately destroyed by CT are rendered susceptible to further breakdown with subsequent exposure of SOM. These outcomes have important consequences for long-term soil fertility and the ability of soils to store C. Stabilized SOM is not only of microbial origin but is also N-rich (Cotrufo et al. 2013; Kopittke et al. 2018). Consequently, the reduction in fungal biomass in conventionally tilled soils results in greater soil N losses and reduced capacity for microbial N immobilization (de Vries et al. 2011; de Vries and Bardgett 2012). This suggests reduced production of N-rich microbial biomass and subsequently lower production of stabilized, nutrient-rich SOM. Thus, rather than building long term soil fertility, CT-based systems run-down and deplete soil fertility (Karlen et al. 2013).

This picture is echoed in terms of soil C. Firstly, reduced aggregate turnover under NT results in increased formation of stable macroaggregates that can stabilize and sequester SOC (Six et al. 2000). Secondly, the generation of new, microbially-derived SOM is in large part dependent on the C-use efficiency of the soil microbial community, i.e., if microbial C-use efficiency is high, proportionally more substrate-C is used to generate new microbial biomass rather than produce CO_2 (Kallenbach et al. 2015). Fungi tend to exhibit higher C-use efficiency than bacteria, and both C-use efficiency and fungal abundance are highly correlated with SOC concentration (Kallenbach et al. 2016). Therefore, the increase of fungal biomass under NT leads to more efficient incorporation of soil C into microbial biomass. This microbial biomass and subsequent necromass then contribute positively to stabilized SOM (Cotrufo et al. 2013; Ludwig et al. 2015). Consequently, the recovery of fungal biomass observed in agricultural soils when tillage is halted (Williams and Hedlund 2014) points to the potential for NT farming systems to reduce the global C footprint of agriculture. Indeed, this is reflected in the numerous studies that demonstrate increases in topsoil C in NT farming systems compared with CT systems (e.g., Grandy and Robertson 2007; Varvel and Wilhelm 2011; Shi et al. 2012; Panettieri et al. 2015).

The loss of soil aggregates combined with reductions in SOM also has follow-on effects for soil hydrological properties. The improvements to soil structure promoted by aggregate formation enhance rainfall infiltration and soil water holding capacity (Franzluebbers 2002; Zibilske and Bradford 2007). In fact, with their greater capacity to conserve soil moisture relative to CT-based systems, NT has been advanced as a potential drought management farming system (Lal 2004; Powlson et al. 2014). Thus, the consequences of microbial community shifts resulting from CT or conversion to NT are pervasive and impact across a wide range of soil ecosystem services, including soil nutrient cycling, soil C storage, and soil water management.

Long term NT management increases the abundance of micro-, meso- and macrofauna, and influences their community structures. That said, implementation of NT often results in a short-term increase in the impact of soil-borne pathogens followed by a decline as suppressive factors become established. For example, Stirling and White (1982) reported a reduction in root-knot nematodes associated with grapevines in older relative to newly established vineyards. This was attributed to the establishment of the bacterial parasite *Pasteuria*. The same effect has been identified for *Rhizoctonia,* where NT systems have developed suppressive communities (Roget 1995; Schillinger and Paulitz 2014). These suppressive soils can increase yields by decreasing the impacts of soil-borne pathogens (Peters et al. 2003). Similarly, there is an increase in the proportion of fungal-feeding nematodes in reduced and NT systems due to minimal disruption of fungal hyphal networks (Ferris et al. 2006; Zhong et al. 2017). There is also an increase in predatory nematodes that, being larger, are more sensitive to tillage and have longer generation times. The number of plant-feeding nematodes also declines under NT (Zhong et al. 2017). This indicates more self-regulating nematode communities under NT farming that may prevent or contribute to minimising economically damaging PPN outbreaks. In contrast, while NT was found to foster greater numbers of collembolan species compared with CT, it did not result in greater overall collembolan diversity (Brennan et al. 2006).

In a recent global meta-analysis, NT systems were found to support substantially greater earthworm abundance and biomass than CT systems (Briones and Schmidt 2017). Within this, the depth of tillage was found to be an important factor, with shallow tillage (<0.2 m depth) having much weaker negative effects than deeper tillage (>0.2 m depth). The benefits to earthworms of NT likely also stem from crop residue retention on the soil surface, which serves as a food resource for earthworms and also helps to maintain adequate soil moisture for earthworm activity (Curry 2004; Briones and Schmidt 2017). Promoting the activities of these primary soil engineers is a major advantage for reduced and NT systems.

Reducing tillage has significant, measurable impacts on soil biology. No-till increases the abundance and diversity of soil organisms, which facilitates improved nutrient and water management, and leads to the establishment of a balanced ecosystem where pest and pathogen populations are naturally managed. These effects do not occur immediately upon implementation of reduced tillage as it takes time for natural communities to recover, particularly for macro- and meso-fauna such as earthworms and predatory nematodes. However, once established, these diverse communities offer biological buffering against a range of physical and biological impacts. While there is a significant need to improve the biology of many agricultural soils, if left alone they will often repair themselves.

15.4 Outlook and Conclusions

The adoption of NT farming has led to significant improvements in soil health compared with CT-based farming. This is evidenced by increases in the abundance, biomass, and diversity of soil organisms as well as the ecosystem services they generate. Despite this, challenges remain, and additional progress must be made to further improve and enhance the environmental sustainability and long-term productivity of cropping systems worldwide.

From a soil biology context, a major challenge facing NT systems is reconciling conflicts between opposing soil ecosystem services. The management of SOM and soil nutrient cycling provides an instructive example. As put forth by Janzen (2006), sustainable soil management in agriculture faces a dilemma: should SOM be hoarded or should it be used? No-till farming can build SOM stocks through its positive effects on soil microbial biomass, and especially soil fungal biomass. The accrued SOM serves as a reservoir of nutrients that, once mineralized, can support crop growth and production. However, in the absence of soil disturbance, the cycling of soil nutrients held within SOM occurs on a timescale unsuitable for highly productive crop production systems. The accumulation of crop residues on the soil surface can also lead to nutrient immobilization, reducing the quantity of mineral nutrients available for crop uptake (Martens 2001). Such immobilization is particularly pronounced following cereal crops, which tend to produce large quantities of residues with high C:N ratios (Martens 2001; Ichir and Ismaili 2002). Under such conditions, sufficient fertilizer must be applied to ensure crop nutrient deficiencies and yield penalties are avoided (Martens 2001). Conversely, if soils undergo frequent CT that breaks down soil aggregates and exposes SOM to microbial decomposition, soil management will return to the environmentally unsustainable days prior to the advent of NT.

This SOM-nutrient cycling dilemma highlights the limitations of NT farming systems. Under NT, the soil is managed in a uniform way that creates an homogenous environment of minimal or no soil disturbance and high quantities of crop residues (Williams et al. 2016b). In this environment, the predominance of nutrient immobilization and SOM-building processes can constrain crop yields (Martens 2001; Williams et al. 2016b) and subsequently hinder progress towards sustainable intensification. To prevent this, a more adaptive system of soil management that recognizes the role of soil organisms in generating ecosystem services is needed. Such a system requires interventions that allow for a dynamic soil biology that delivers desirable soil ecosystem services at the appropriate place and time, i.e., is spatiotemporally optimized. The recently proposed concept of soil functional zone management (SFZM) is an example of such an adaptive system.

Soil functional zone management is a strategy for row-crop production that creates spatial heterogeneity over decimetre scales by managing crop rows and inter-rows as distinct functional zones (Williams et al. 2016b). In doing so, the goal of SFZM is to promote both soil building and nutrient provisioning processes within the same field, rather than one process at the expense of the other, as is the case in NT and CT systems, respectively. Real-world examples of SFZM include the reduced tillage systems of ridge and strip till. In ridge till, crop rows (ridges) are lightly tilled prior to planting to create a favourable seedbed. This light tillage intervention moves topsoil and crop residues away from crop rows and onto the surface of inter-rows. The decomposing residues are moved back to the crop row later in the season, when the crop is more developed and entering its peak N demand phase (Hatfield et al. 1998; Williams et al. 2016b). This redistribution of labile SOM to the crop row stimulates microbial activity and biomass (Müller et al. 2009; Zhang et al. 2013), resulting in elevated soil mineral N concentrations in close proximity to the majority of crop roots in synchrony with crop physiological N demand (Williams et al. 2016a, 2017). Moreover, this change in the location and availability of soil mineral N corresponds with increased crop N uptake relative to CT (Kane et al. 2015). In generating these improved N outcomes, SFZM also delivers significant increases in a highly labile, microbially processed soil C fraction (permanganate oxidizable C) compared with CT (Culman et al. 2012; Williams et al. 2017). Thus, by applying targeted soil disturbances that align with soil biological processes, SFZM is able to reconcile the opposing soil ecosystem services of SOM-building with rapid nutrient mineralization for crop uptake. Furthermore, the resilience of soils to provide multiple ecosystem services, i.e., multifunctionality, under repeated dry-wet cycles, has been shown to be greater under ridge till than NT (Zhang et al. 2019). Such resilience is likely to be of increasing importance with climate change.

While SFZM is presented as a hitherto successful example of an adaptive soil management strategy, it is not intended to be interpreted as the sole path forwards. Certainly, further research is required to elucidate the long-term impacts of a SFZM approach on soil biology and soil ecosystem services. What the SFZM example demonstrates is that limited and targeted soil disturbance is not necessarily detrimental to soil biology and soil ecosystem services and can even enhance soil multifunctionality and resilience. This has been similarly documented in the case of strategic tillage to control herbicide resistant weed populations and outbreaks of stubble-borne diseases in NT farming systems (Liu et al. 2016; Rincon-Florez et al.

2016). Consequently, NT farming cannot be viewed as a panacea to the problems of global crop production. Indeed, for NT farming to be successful, it typically needs to be implemented alongside the two other principles of conservation agriculture: maintaining soil cover by retaining crop residues or planting cover crops, and diverse crop rotations (Hobbs et al. 2008). Failure to do so can result in depletion of SOM, build-up of deleterious organisms, and reductions in crop yields (Pittelkow et al. 2015; Williams et al. 2018). Furthermore, conservation agriculture approaches need to be regionally-adapted to ecological and socio-economic contexts to maximize yield potential and to minimize trade-offs between competing demands for limited resources (Giller et al. 2009; Rusinamhodzi et al. 2011; Williams et al. 2018).

Advances in soil management can be achieved through an understanding of soil biology and ecosystem services, combined with knowledge of how soil organisms respond to interventions. Such advances are critical for efforts towards the sustainable intensification of agriculture. A pragmatic approach to soil management that promotes a resilient and dynamic soil biology and minimizes the limitations of NT will lead to greater sustained benefits than a dogmatic adherence to NT.

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Chapter 16
Earthworms in No-Till: The Key to Soil Biological Farming

Jacqueline L. Stroud

Abstract No-tillage is a habitat manipulation tactic resulting in an undisturbed soil habitat and an overlying plant litter layer. This creates a specific micro-climate, with the litter layer providing shelter, nesting materials, and food for litter-feeding animals. Plant litter is often laborious to manage and has competing uses, such as fodder or fuel, but the changes to the soil habitat are assumed to be aligned with a sustainable agriculture agenda. However, plant litter also fosters pests and diseases that jeopardizes crop yields and quality. There are currently knowledge gaps in how to best configure and monitor habitat management practices to achieve agro-ecosystem benefits. There is a global community of farmer-led initiatives adopting conservation agriculture, engaged in social learning, connected through digital communications, and experimenting with habitat manipulation. This is an exciting development that offers the potential for farmer-scientific partnerships to co-create knowledge and improve the sustainability of agriculture together. This chapter focuses on an ecosystem engineers that is found globally, and whose populations are controlled by tillage and plant litter that are suited for co-learning about biodiversity, nutrient cycling and bio-control in agro-ecosystems: earthworms.

Keywords Co-learning · Participatory science · Earthworms · Ecosystem services

16.1 Managing Biodiversity and Functions

Sustainable agriculture is inhibited by a widespread lack of biodiversity knowledge. For example, it is estimated that the natural control of crop pests by insects is worth $4.5 billion in the USA alone (Losey and Vaughan 2006). However, 70% of farmers

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are unaware of natural enemies or biological control and this lack of knowledge is linked to pesticide dependency (Wyckhuys et al. 2019). There are beliefs that all insects are pests and must be killed (Heong et al. 2002), similarly all birds are perceived as pests by some farmers in both Europe (Herzon and Mikk 2007) and China (Zhang et al. 2015).

The biodiversity disconnection is widespread across society. For example, where scientists and conservationists have positive attitudes towards invertebrates, the public and farmers have negative attitudes ranging from dislike to aversion (Kellert 1993). Asking Americans to rate different animals reveals invertebrates are widely disliked (especially bees, earthworms, spiders, and beetles), where leopards, elephants and chimpanzees are well liked, linked to anthropomorphism (Batt 2009). The problem with the biodiversity disconnection is societal ambivalence towards e.g. soil ecosystems, resulting in neglect by policy-makers (Baveye et al. 2016). One pathway to improve this situation is to directly build connections between soils and people (Ball et al. 2018). For example, earthworms have global cultural significance; in some countries earthworms have symbolic meanings connecting people to soils (Pauli et al. 2016).

There is a widespread belief that biodiversity and soil functioning are positively correlated, but this Linnean infinite biodiversity assumption has long been questioned, particularly at microbial scales (Andrén and Balandreau 1999). The problems caused by overlooking co-evolutionary processes in the real world is the role of ecosystem engineers. Ecosystem engineers have disproportionate effects on soil functions, and include organisms such as earthworms, ants, and termites (Lavelle et al. 2016). Earthworms are ecosystem engineers that both enhance plant productivity (van Groenigen et al. 2014), create microbe-lined chimneys in the soil (Nieminen et al. 2015), and concentrate biodiversity into hotspots that are visually obvious (Stroud et al. 2016). Recognizing and improving our understanding of the role of co-evolutionary processes creates opportunities to improve sustainable agriculture.

In agroecosystems, earthworms influence pests and disease pressures that impact crop yields and quality. For example, earthworm activities influence the nitrogen cycle, which influences plant defensive chemistry, which influences the susceptibility of plants to above-ground pests. This can mean that the presence of earthworms increases the susceptibility of plants to aphids but also increases plant resistance by 81% against thrips (Xiao et al. 2018). Therefore, a contextual understanding of the earthworm population and pest pressure is needed in practice. Earthworms also play an important role in recycling plant litter (Edwards and Bohlen 1996). Laboratory studies have shown that anecic earthworms preferentially feed on litter infected with *Fusarium* spp., a major soil-borne pathogen detrimental to cereal crop production around the world (Goncharov et al. 2020). Therefore, a contextual understanding of the earthworm ecological groups and appropriate plant litter loading is also needed. Logically, sustainable agriculture requires a close relationship between farming and transdisciplinary science. However, there are currently weak links between science and practice to bridge knowledge gaps and optimize the role of ecosystem engineers in agro-ecosystems.

The principle challenges of NT are linked to plant litter management. For example, in China, corn is sown directly into wheat stubble and leading to outbreaks of thrips and thus different neonicotinoid pesticides are being tested to protect corn production (Ding et al. 2018). No-till and straw management influences the abundance of *Fusarium* spp. that cause yield loss and quality in cereals in Europe, with researchers recommending ploughing and straw removal to manage the infection risk (Hofgaard et al. 2016). The rates of straw application under NT change the microbial community and infection risks to crops in China (Wang et al. 2020). The presence, abundance, and ecological groups of earthworms in farmlands is largely unknown. Sustainable agriculture is inhibited by a widespread lack of biodiversity knowledge.

The development of Information and Communication Technologies and their use by farmers opens pathways for novel participatory research to co-learn about habitat manipulation in agroecosystems. This is an exciting development that offers the potential to tackle the contextual challenge of the roles of soil biology in agroecosystems. This chapter focusses on the easily observed ecosystem engineers, earthworms.

16.2 Earthworms in Agriculture

Earthworms are segmented soft bodied tube shaped animals, that are principally (80% biomass) composed of water (Edwards and Bohlen 1996). The lifespan of an earthworm is years, and some species that are commonly found in farmland soils can live for over a decade (Edwards and Bohlen 1996). Earthworms have been grouped by their feeding and burrowing behaviors, with epigeic earthworms surface dwelling, plant litter feeding earthworms; endogeic earthworms topsoil burrowing, geophagous earthworms, and anecic earthworms, deep vertical burrowing earthworms that feed on microbes, plants (seeds, seedlings and plant litter) and animals (Fig. 16.1). Earthworm activities have a broad influence on agro-ecosystems including water, gas, and root movement in soils, predator populations, nutrient cycling, disease persistence, and plant productivity (Edwards and Bohlen 1996).

Conventional tillage (CT) changes earthworm community structure, and is detrimental to the litter-feeding epigeic and anecic earthworm populations (Chan 2001; Briones and Schmidt 2017). Tillage can increase topsoil dwelling endogeic earthworm populations by increasing their food supply through soil mixing (Chan 2001), but can lead to local extinctions of anecic earthworms (Kladivko et al. 1997). Below we discuss a number of case studies that illustrate the state of knowledge regarding earthworm populations in different regions worldwide, and the myriad of functions that earthworms provide.

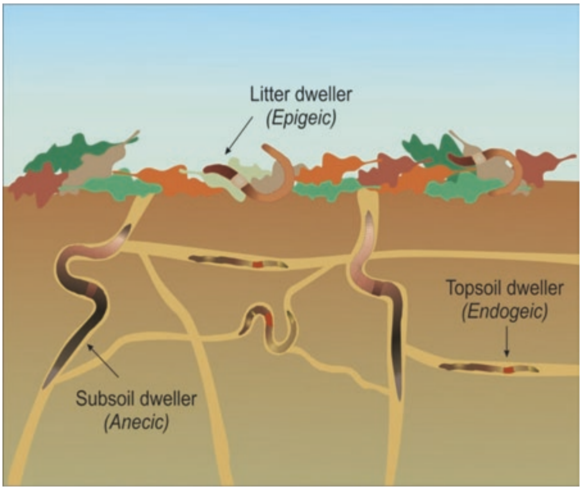

Fig. 16.1 Earthworms are classified into three ecological groups depending on their feeding and burrowing behaviors

16.2.1 South Asia and the Middle East – Farmland Earthworms Unknown

One NT study was found in Iran, where earthworm populations were measured but not reported by the authors who considered their distribution too patchy and small for tillage-mediated interpretations (Moradi et al. 2013).

16.2.2 China – Potential Role of Epigeic Earthworms in Carbon Sequestration

An analysis of a long-term tillage experiment in the Shanxi province using large (1 m^2 × 0.3 m) soil pits digging and sieving the soil found no earthworms in 1992, but by 2006 there were 19 earthworms per m^2 under NT, compared to none under CT (Li et al. 2007). A different method, hand-sorting 0.6 × 0.4 × 0.2 m size pits, that investigated a long-term NT rotation experiment in the Hunan province (rice – fallow or rice - oil seed rape), found median earthworm numbers were 30 earthworms m^2 in the fallow rotation compared to less than 50 earthworms m^2 in the oil seed rape rotation (Huang et al. 2018). The principal species was *Pheretima guillelmi*, and the increase in population was linked to the additional food supply from the oil seed rape litter (221 g m^2). Interestingly, earthworm casts increased essential amino-acids in rice grains, suggesting a novel role of earthworm actions in nutrient cycling that deliver benefits for human nutrition (Huang et al. 2018).

In terms of functions, the role of epigeic earthworms (*Eisenia fetida*) in soil organic carbon (SOC) sequestration under CT and NT plus residues has shown that earthworms enhance the mineralization of SOC in CT but generated SOC in NT (Guo et al. 2019). Further, unlike CT soils, epigeic earthworms (Eisenia *nordenskioldi* pallida) at populations of 385 individuals m^2 in NT soils can promote the accumulation of rhizodeposit carbon by influencing microbial activities (Zhu et al. 2019). The presence of earthworms and other fauna in long-term NT soils influences greenhouse gas emissions, but NT soils have more stable functional food webs that sequester carbon and nitrogen (Zhu et al. 2016).

16.2.3 Southern Africa – Potential for Citizen Science?

In South Africa, there are 282 endemic species from 3 families (*Microchaetidae, Tritogeniidae* and *Acanthodrilidae*), and 44 invasive species from 6 families (*Acanthodrilidae (Benhamiinae), Eudrilidae, Glossoscolecidae, Lumbricidae, Megascolecidae and Ocnerodrilidae*) (Nxele et al. 2015). Earthworm research is limited by the logistics of sampling, being both laborious, time consuming and expensive for species identification data. For example, in South Africa, to dig a 0.5 × 0.5 × 0.2 m soil pit and hand sort the soil for earthworms takes 3–5 people, 45 min to 1 h (Nxele et al. 2015). In addition to labor and travel costs associated with field sampling, the cost of laboratory taxonomic analysis per soil pit was RI 4800 (A$474, U$325, €291, £250) in 2015 (Nxele et al. 2015). Native taxa require a 1 × 1 × 0.2 m soil pit, but deep burrowing earthworms are underrepresented and giant earthworms require different methods entirely (Nxele et al. 2015). The authors recommend future developments to look at improving the efficiency, consistency, ease of use of methods, and getting more people involved with earthworm sampling through the development of field guides and co-ordination to fill knowledge gaps (Nxele et al. 2015).

Because of these sampling difficulties, the distribution and abundance of earthworms in Southern Africa is largely unknown (Janion-Scheepers et al. 2016), and there is almost no knowledge of earthworm populations in agricultural soils (Nxele 2015). Comparing 25-years continuous maize cultivation under CT or NT, one earthworm species, the invasive *Amynthas aeruginosus,* (most probably originating from Guam (Picker and Griffiths 2017)) was found. The population of this invasive species was 3.5 fold higher under NT (175 individuals m^2) compared to CT (50 individuals m^2) (Haynes et al. 2003). Indigenous earthworms have been found in a NT (20 years) sugar cane field from the *Microchaetidae* family, *Geogenia* species, with the authors noting the enthusiasm of the farm owner in discovering the soil biology on his land (Nxele 2015). The presence of earthworms is perceived to be positive from a soil ecosystem services perspective (Nxele 2015), but whether this includes invasive species is unclear (Janion-Scheepers et al. 2016).

In Zambia, earthworm numbers were studied in conventional practices (crop residues removed, ploughed and hand-sown maize) compared to conservation agriculture (crop residues retained, direct seeding into the mulch) over 3 years in a field experiment (Thierfelder and Wall 2010). In 2 out of the 3 years, earthworm numbers were significantly higher under the conservation agriculture with populations of 213 individuals per m^2 to 237 individuals per m^2 (Thierfelder and Wall 2010). The types of earthworms, biomass of earthworms or types of earthworms were not recorded by the scientists.

16.2.4 Austrasia – Potential for Anecic Earthworm Introduction?

Earthworm populations in New Zealand under a pasture to arable rotation transition experiment recorded populations of 363 earthworms m^2 under NT compared to 110 earthworms m^2 under tillage (Aslam et al. 1999). A larger survey of earthworm populations in New Zealand by scientists across over 100 fields revealed only a population of invasive epigeic and endogeic earthworms, but no anecic earthworms, with the authors indicating the potential for introduction to bring about benefits to soil structure and water movement (Fraser et al. 1996).

Little is known about earthworm populations in farmlands across Australia. In Queensland, earthworm numbers up to 17 per m^2 were found in a NT field (Wilson-Rummenie et al. 1999). There was an earthworm population survey for 5-years at a farm in New South Wales, Australia by scientists. No anecic earthworms were reported, and the populations fluctuated over the years, peaking at 239 earthworms per m^2 under NT compared to 36 earthworms per m^2 under CT (Chan and Heenan 2006). However, an unexplained low population was detected in the final year of the survey, with an average of 4 earthworms per m^2. Over time the population shifted from a dominance of the invasive *A. trapezoides* to another invasive earthworm *M. dubious*, and the authors suggested the overall decline was linked to the use of insecticides to control red-legged earth mites (Chan and Heenan 2006). Similar to New Zealand, anecic earthworms are probably uncommon in Australia with some scientists suggesting their introduction could bring about benefits to soil structure and water movement (Fig. 16.2). There is a native anecic earthworm (*S. hamiltoni)* that is sometimes present in arable fields, and *which* forms 6 mm wide × 1.8 m deep burrows that facilitate water infiltration (Chan 2004). Conventional tillage reduced water infiltration rates by 8.3-fold in comparison to NT (Chan 2004).

16.2.5 South America – Absence of Anecic Earthworms

Farmers adopting NT observed increased earthworm populations in their fields in Brazil, and formed a no-till farming group called themselves the ‘earthworm club’ (Brown et al. 2003). In Columbia, farmers use earthworms as symbols of soil fertility and are able to identify multiple species (Zúñiga et al. 2013).

Scientists measuring earthworm populations determined populations of up to 168 earthworms per m^2 of the invasive *Amynthas* spp., with no native earthworms species detected (Brown et al. 2003). Similarly, the invasive *Dichogaster* epigeic earthworms were the most common species in another NT field survey by scientists

Fig. 16.2 Anecic earthworms burrow vertically through the soil, with large (<5 mm) openings to the soil surface, stretching meters below the ground. These burrows improve water movement through the soil, and facilitate deep rooting by plants. (Photo by J. Stroud)

(Santos et al. 2018). In terms of earthworm populations under NT, these range between 5–605 earthworms m^2 compared to native forests with populations of up to 285 earthworms m^2 (Bartz et al. 2013). Although mixtures of native and invasive earthworm species are found under NT in Brazil, invasive species dominate with researchers interested in how to encourage native taxa (Santos et al. 2018). There is an absence of anecic earthworms in NT systems in Brazil (Bartz et al. 2013).

16.2.6 North America – Anecic Earthworm **L.terrestris** *Middens and Soil Processes*

The deep burrowing earthworm *L.terrestris* is an invasive earthworm from Europe that is tillage sensitive (Briones and Schmidt 2017) and can become locally extinct within fields that use CT, as indicated by the absence of middens (Kladivko et al. 1997).

This litter-feeding species forms middens on the soil surface (Fig. 16.3), middens being the gathered plant debris piles that this nocturnal earthworm drags and maintains, directly overlying its permanent burrow. Under NT the abundance is much higher, for example, detected at 28 middens per m^2, compared to CT with 1–3 middens per m^2 (Simonsen et al. 2010). These middens can cover around 25% of the soil surface (Fig. 16.4) and are soil microbial activity hotspots (Subler and Kirsch 1998). The concentration of plant debris patches and microbial activity influences the spatial distribution of soil processes such as organic matter decomposition, N-mineralization, and leaching across fields (Subler and Kirsch 1998). The earthworm burrows have elevated levels of NO_3^- and NH_4^+, and enriched populations of nitrifying and denitrifying bacteria compared to the bulk soil (Parkin and Berry

Fig. 16.3 The anecic earthworm *L. terrestris* drags plant litter into its burrow at night, forming an overlying midden. (Photo by J. Stroud)

Fig. 16.4 *L. terrestris* middens are soil biological, chemical and physical hotspots within fields. Midden counting is a rapid way to assess the presence of this deep burrowing species in a field. (Photo by J. Stroud)

1999). More specifically, sequencing analyses identifies enriched taxa of *Actinobacteria*, including *Micrococcales, Gaiellaceae, Solirubrobacterales*, and *Mycobacterium* (Schlatter et al. 2019). In terms of physical properties, this species forms large (5 mm wide), deep vertical burrows that influence water movement and potential for nitrate leaching through the soil during summer storms (Edwards et al. 1989). If chemicals are applied just prior to a storm then these macropores can increase the risk of leaching, however, across a season there little evidence of an elevated risk of pollution from earthworm activities (Shipitalo et al. 2000). Similarly, there were concerns of macropores leading to preferential flow and leaching of pollutants in Canadian fields, but no significant differences have been detected (Miller et al. 1999). The abundance of middens is significantly positively correlated to soil health scores (including soil microbiological, chemical, and physical parameters), linked to the stimulation of soil microbiology and benefits to soil physical structure resulting from earthworm activities (Jemison et al. 2019).

16.2.7 Europe – Earthworm Ecosystem Services and Disservices

UK Farmers are interested in their soil biology, and mediated through social media co-developed a national earthworm survey method (#60minworms) to determine the presence of epigeic, endogeic, and anecic earthworms on their fields (Stroud 2019). This revealed earthworms are ubiquitous; endogeic earthworms are common, but epigeic and anecic earthworms are less common – the latter absent in 1 in 5 fields. This is important for those adopting NT and returning surface residues, as the absence of litter-feeding earthworms can create problems in crop establishment, pests; and disease (Fig. 16.5).

Fig. 16.5 UK Farmer-scientist partnership co-created knowledge on earthworm populations by handsorting the soil methodology, revealing a low presence of litter-feeding earthworms. (Photo by J.Stroud)

Fig. 16.6 *Lumbricus terrestris* earthworms provide disservices including herbivory of seedlings, enhances greenhouse gas emissions from its burrows through nitrogen cycling and respiration. (Photo by J. Stroud)

For example, the litter-feeding anecic earthworm *L.terrestris* is an important species for the bio-control of *Fusarium culmorum* and its mycotoxin deoxynivalenol, with economists calculating the economic value of this species actions (for the neoliberal policy based payments for ecosystem services model) of €75 per hectare (Plaas et al. 2019). Earthworms have a feeding preference towards *Fusarium* spp. and can decrease its abundance by 20% in experiments (Goncharov et al. 2020).

Whilst *L.terrestris* is tillage sensitive and local extinctions within fields have been detected, this species has been successfully re-introduced into NT fields to improve macroporosity and water infiltration (Nuutinen et al. 2017). It has recently been discovered that under NT in boreal environments when comparing middened and non-middened soil within a field, that *L.terrestris* increases the storage of soil organic carbon and nitrogen into better protected soil fractions of clay soils (Sheehy et al. 2019). However, anecic earthworms also provide ‘disservices’, for example, *L.terrestris* is a granivore and seedling herbivore (Fig. 16.6), and concentrates seeds in its middens (Eisenhauer et al. 2010). The elevated levels of nitrogen and moisture associated with the middens and burrows also causes 43% higher NOx emissions and 32% higher CO_2 emissions compared to non-middened areas of NT soils (Nieminen et al. 2015).

16.3 Outlook

No-tillage provides habitat conditions that facilitates the invasion by earthworms, and earthworms are ecosystem engineers that change soil biological, chemical and physical properties. Little is known about farmland earthworms in many areas of the

World, let alone how to optimize soil biology to bring about benefits to agro-ecosystems. As shown in Europe, farmers are willing to get involved and co-create of knowledge to inform their management practices. This is an exciting development that offers the potential to tackle the contextual challenge of the roles of soil biology in agro-ecosystems.

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Chapter 17
Pesticide Retention, Degradation, and Transport Off-Farm

D. Mark Silburn

Abstract In recent decades, pesticide use in cropping has increased and the products used have changed. They will continue to change due to the introduction of transgenic plants and as weeds and pests develop resistance. A key feature of no till (NT) and stubble retention is that pesticides are intercepted on surface cover. Sorption of pesticides on crop residues can vary between pesticides, crop residues, and ages of residues, but most pesticides can be washed off by rainfall. Dissipation (sometimes involving volatilization and photodecomposition) on crop residues is important and may limit herbicide efficacy if rain does not occur soon enough after application, but this does not seem to occur much in practice. Limited data indicates half-lives may be greater on crop residues than in soil, but both more rapid and slower dissipation have been found. Equally, dissipation in the soil has been found to be slower, equal, or faster in NT compared to conventional tillage (CT). Sorption to NT soils is often greater due to greater organic carbon, but in practice the difference can be minor. Thus, many aspects of pesticide behavior in NT/reduced till systems are variable, inconsistent, or inconsequential. One review of pesticide runoff (mainly soluble herbicides) from NT systems found runoff was typically lower with NT, but this review only considered six natural rainfall studies. A more recent review, which examined 34 studies, found pesticide loads were greater for NT than 'plow till' for two pesticides, lower for another, and not different for the remainder. Similarly, concentrations were greater in runoff from NT for four herbicides and were not different for all others. However, NT (retaining cover) is typically effective in reducing pesticide losses in runoff of compounds that are sorbed to sediment, due to its effectiveness in controlling erosion. If tillage practices do not consistently reduce runoff of pesticides, other practices are available, such as selecting pesticides that are less toxic, more rapidly dissipated, more sorbed, and runoff less.

Keywords Pesticides · No-tillage · Stubble retention · Conventional tillage · Runoff

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17.1 Introduction

Pesticides include herbicides, insecticides, fungicides, and other pest control chemicals, common examples of which can be seen in Table 17.1. Global pesticide use was estimated as 13.2 million Mg of active ingredient (ai) in 2011 and 2012 (Atwood and Paisley-Jones 2017). Herbicide use increased from 20% of all pesticides in 1960 to 50% globally, and 76% in the US in 2008 (Fernandez-Cornejo et al. 2014). Fumigants, insecticides, and fungicides made up 19, 18, and 14% of global use in 2012 respectively. This increase in herbicide use is related to increased area of agricultural land, increased use of conservation tillage (although tilled systems also often use some herbicides), and an increase in use of herbicides in developing countries. The most commonly used pesticides in US agriculture were the herbicides glyphosate (122–132 million kg), atrazine (28–34 million kg), S-metolachlor (15–20 million kg) and 2,4-D (14–18 million kg), and several fumigants (Atwood and Paisley-Jones 2017). Chlorpyrifos was the most commonly used insecticide.

Tillage in this paper will be considered as various levels of intensity, from none except planting (NT), through reduced or minimum tillage, to full tillage. "Conservation tillage" has been defined as "any tillage and planting system that leaves at least 30% of the soil surface covered by crop residue after planting to reduce soil erosion by water, or at least 1.1 tons of crop residue per ha to reduce soil erosion by wind" (Alletto et al. 2010). No till is primarily dependent on herbicides for weed control (and sometime suppression by the mulch layer) whereas reduced tillage systems can use some tillage to help control weeds, which may mean a reduction in the use of herbicides. The amount and types of pesticides being used has changed since NT was first developed due to the introduction of transgenic crops (Benbrook 2016) and these will continue to change as weeds and pests also develop resistance.

Runoff of pesticides is reasonably common and pesticides are regularly detected in streams in agricultural areas in the US (Battaglin et al. 2014; Ryberb and Gilliom 2015), Great Barrier Reef catchment, Australia (Turner et al. 2013; Smith et al. 2014), Brazil (Casara et al. 2012), Europe (Loos et al. 2009) and globally (Stehle and Schulz 2015). In the United States, Battaglin et al. (2014) found that glyphosate was the most heavily used herbicide in agriculture and with genetically modified glyphosate-resistant crops (e.g. soybeans and corn). Glyphosate, and its breakdown product AMPA, were detected frequently in soils and sediment, ditches and drains, precipitation, rivers and streams; and less frequently in lakes, ponds, wetlands, soil water, and groundwater (Battaglin et al. 2014). Of 11,300 insecticide concentrations measured in stream samples globally, 52.4% (68.5% of sites) exceeded the regulatory threshold level for either surface water or sediments (Stehle and Schulz 2015). Thus, pesticide loads and concentrations in streams are of concern. Although, pesticide concentrations in groundwater (and leachate) are typically lower than in streams, and particularly in edge-of-field runoff. For instance, the maximum concentration of glyphosate measured in streams was 35 times greater than in groundwater (Battaglin et al. 2014).

Table 17.1 Physical and chemical properties of some of the pesticides included in the study

Active ingredient	Half-life in soil (days) (field)	Solubility (mg L^{-1})	Soil organic carbon partitioning factor (Koc) (mL g^{-1})	Guideline values for freshwater (µg L^{-1}) to protect 95% of species	Mode of action
Herbicides (soil residual)					
Ametryn	37	200	316	0.33	Inhibitors of photosynthesis at photosystem II (PS2)
Atrazine	29	35	100	0.98	Inhibitors of photosynthesis at PS2
Diuron	42	36	1067	0.23	Inhibitor of photosynthesis at PS2
Hexazinone	105	33,000	54	1.1	Inhibitor of photosynthesis at PS2
Imazapic	232	2230	137	0.41	Inhibits production of amino acids necessary for cell division and growth
Isoxaflutole[a]	1.3	6	145	0.46	Acts by indirect carotenoid biosynthesis inhibition.
Metribuzin	19	10,700	38 (Kfoc) 1/n 1.08[b]	2.6	Selective, systemic with contact and residual activity. Inhibitor of photosynthesis at PS2
Pendimethalin	101	0.33	17,491	2.1	Inhibitors of microtubule assembly
S-metolachlor	21	480	226 (Kfoc) 1/n 1.06[b]	0.71	Inhibitor of cell division
Tebuthiuron	400	2500	80	13	Inhibitor of photosynthesis at PS2
Trifloxysulfuron sodium	64	25,700	306	–	Inhibitor of acetoacetate synthase
Herbicides (knockdown)					
2,4-D	28.8	24,300	39	2520[c]	Increases biosynthesis & production of ethylene causing uncontrolled cell division & so damages vascular tissue.
Fluroxypyr	51	6500	68 (Kfoc) 1/n 0.93[b]	200	Foliar uptake causing auxin-type response. Synthetic auxin

(continued)

Table 17.1 (continued)

Active ingredient	Half-life in soil (days) (field)	Solubility (mg L^{-1})	Soil organic carbon partitioning factor (Koc) (mL g^{-1})	Guideline values for freshwater (μg L^{-1}) to protect 95% of species	Mode of action
Glyphosate	15	10,500	1424	246	Inhibition of lycopene cyclase
Paraquat	2800	620,000	1000,000	–	Photosystem I (electron transport) inhibitor
Insecticides					
Endosulfan	86	0.32	11,500	–	Organochlorine (cyclodiene)

From Pesticide Properties Database https://sitem.herts.ac.uk/aeru/ppdb

[a] rapidly hydrolyses to form herbicidally active Diketonitrile (DKN)

[b] Freundlich (non-linear) isotherm

[c] For marine waters

This paper reviews the impact of tillage systems on pesticide interception, dissipation, and washoff from crop residues, dissipation in the surface soil, and the resulting impacts on runoff, leaching, and groundwater contamination. As far as possible I have used review papers, with some individual field or laboratory studies discussed. Key references that the reader might find useful are: Hornsby et al. (1996) on pesticide properties, Wauchope (1978) and Leonard (1990) on the process and likely amounts of pesticide runoff, Willis et al. (1980) and Dang et al. (2016) on pesticide washoff from crop residues, Flury (1996) on pesticide leaching, Rose and Carter (2003) on effects of tillage on leaching of pesticides, Wauchope et al. (2002) and Koskinen and Harper (1990) on pesticide sorption and Cheng (1990) for everything about pesticides in the soil environment.

17.2 Pesticide Use

Pesticide use has changed considerably between 1960 and 2008. Pesticide use grew rapidly in the first 20 years of this period, from 89 million kg in 1960 to 234 million kg in 2008 on 21 crops in the US (Fernandez-Cornejo et al. 2014). This is because the percentage of area treated with herbicides increased. Also, the total area planted to corn, wheat and, in particular, soybeans, increased in this period. Over 90% of the area of these crop in the US is treated with herbicides. Since peak usage in 1981, the total mass used has decreased slightly because herbicides with lower application rates have been introduced. Pesticide use has also decreased markedly in crops such as cotton due to replacement of older insecticides, such as DDT, with more effective products (requiring less application); changes in the pest being treated; and the introduction of integrated pest management, insect resistant (BT cotton), and herbicide tolerant cotton.

The types of pesticides used by US farmers have also changed markedly (Fernandez-Cornejo et al. 2014). Insecticide were 58% of pesticide used in 1960 but were only 6% in 2008. Herbicide use increased from 18 to 76% in the same period. Fungicide use had dropped slightly from 11–13% in the early 1960's to 7% or less since 1971. The four most heavily used active ingredients in 2008 were glyphosate, atrazine, acetochlor, and metolachlor, all herbicides. However, a few new modes of action have been introduced in recent decades. Sulfonylurea (e.g. chlorsulfuron and metsulfuron-methyl) and imidazolinone herbicides (e.g. imazapic and imazethapyr) were introduced in the 1980s and 1990s and neo-nicotinoid insecticides (e.g. imidacloprid, clothianidin) were introduced in the mid-1990s (Fernandez-Cornejo 2014). One new herbicide mode of action recently developed is VLCFAE inhibitors with the herbicide pyroxasulfone. Some of these products are applied at small application rates (e.g. metsulfuron-methyl at 10 or less g ai ha^{-1} and imazapic at about 100 g ai ha^{-1}) (Mark Congreve, pers. comm.).

17.3 Pesticide Retention

"Retention refers to the ability of the soil to hold a pesticide in place and not allow it to be transported" (USDA-NRCS 1998). However, it may also consider how much sprayed pesticide is intercepted on foliage, crop residues (which may be under foliage), and soil. Washoff from the foliage and crop residues and the loss processes of volatilization and dissipation (the reverse of retention) from all three compartments (foliage, residues, and soil) are also considered. Washoff from foliage is less relevant here, whereas washoff from crop residues are very relevant to the issue of reduced tillage and stubble retention.

17.4 Interaction of Pesticides with Crops and Crop Residues

Pesticide sprayed above crops or fallow will be intercepted on the above ground foliage and crop residue. How they dissipate and are washed off by rainfall will impact on how much arrives in the soil, weed control efficacy, and the potential losses into runoff. Each of these pathways and their importance for determining the fate of pesticides in NT/CT systems are described briefly below.

17.4.1 Interception

Foliage is often the target for pesticide sprays, either with insecticides to control pests, or knockdown herbicides to control weeds. Foliage also reduces pesticide loads on underlying crop residues and soil due to its ability to intercept pesticide before it reaches the ground. Interception can be influenced by factors such as ground (more efficient) or aerial application (less efficient) types, nozzle design and spray volume, the cover and canopy density of the plants, windspeed, and the size of spray droplets (Willis and McDowell 1987). For example, Willis and McDowell (1987) estimate interception of 62 ± 27% for ground spray and 45 ± 20% for aerial application when there is a full plant canopy.

Interception also increases with increasing ground cover of canopies (Willis et al. 1980). A full canopy of a crop such as cotton (with layered broad leaves) is a good interceptor of sprayed pesticides. For example, Silburn et al. (1996) sprayed cotton plants with endosulfan (an insecticide) and residues in the soil (0–0.025 m) after spraying were less than 1% of the spray rate, indicating efficient interception. Similarly, Willis et al. (1985) found 92, 76, and 66% of the applied toxaphene, methyl parathion and fenvalerate, respectively, were intercepted by cotton plants. Interception efficiency can be further increased when plants have waxy surfaces on their leaves, which lipophilic and/or non-polar pesticides can penetrate, making them unavailable for washoff (Krutz et al. 2007).

As well as living plants, Banks and Robinson (1982) also found increasing the mass of crop residue on the soil surface greatly increased interception, and decreased the soil reception, of metribuzin (a herbicide). These results and those of Silburn (2003) thus indicate that the percent surface cover is a good first approximation of the percent pesticide interception likely to be observed.

17.4.2 Sorption on Crop Residues

Crop residues can have sorption capacities 10–60 times higher than soil (Boyd et al. 1990; Reddy et al. 1995; Alletto et al. 2010). However, in the experience of the author, and in studies such as Dang et al. (2016), crop residues such as sugar cane mulch and wheat straw exhibit limited sorption capacity, or at least sorption does not prevent rapid washoff by rainfall. Boyd et al. (1990) also reported that the sorptive capabilities of corn residues and soil organic matter for non-ionic organic compounds were nearly identical once both were converted to a per unit of organic matter basis. In addition, Rampoldi et al. (2011), who measured sorption of glyphosate on soybean and maize crop residues, found that sorption was limited and reversible. Thus, we can see variation in the degree of sorption observed for different pesticides, and possibly crop residue types and ages, in the degree of sorption.

Where sorption does occur, a loss of efficacy of some pesticides can occur (Alletto et al. 2010). The nature of the residues and the degree of decomposition influence interception and retention. Selim et al. (2000) found sorption coefficients of sugar cane residue for either metribuzin or atrazine did not change significantly with the age of the decaying residue over two growing seasons. Sigua et al. (1993) indicated that interception of atrazine was enhanced with fresh maize residues more than with aged maize residues, whereas with metribuzin (Dao 1991), chlorimuron (Reddy et al. 1995) and cyanazine (Reddy et al. 1997) interception or sorption was higher with aged residues. This is related to an increase in the external surface area with decay and an increase in lignin:cellulose ratio.

17.4.3 Dissipation on Crop Residues

Dissipation involves losses by volatilization, degradation or transformation (chemical, biological or photochemical), and washoff. Several papers (Martin et al. 1978; Baker and Shiers 1989; Dang et al. 2016) have found reasonably large (18–64%) initial losses (e.g. 1 day after spraying) of herbicides sprayed on maize crop and sugar cane residues, even though the compounds are not necessarily too volatile. For example, Dang et al. (2016) found losses from cane trash 1 day after spraying of 57% for ametryn and atrazine, 34% for metolachlor, 29% for diuron, 20% for tebuthiuron and 18% for hexazinone (some of this may have been spray that went through the residue). Progressively less of each herbicide was found on the trash at 8 and 40 days after spraying, and by 40 days, the herbicide mass on the trash was only 20–30%, except for hexazinone, which contained only 13%. Other studies have observed half-lives ranging from 19–117 days (with no detectable degradation observed for diuron or tebuthiuron) for 14 herbicides applied to sugar cane residues (Shaw et al. 2013), and 3–11 days for fluometuron and norflurazon sprayed on ryegrass crops (Locke et al. 2005).

Shaw et al. (2013) measured the half-lives of 14 herbicides commonly applied in sugar cane and grains on sugar cane residue over a period of 100 days in a glasshouse (which controlled temperature and soil moisture but would have limited photodegradation). Half-lives for all herbicides on sugar cane residues were slower than has been previously reported, which may be due to the effects of herbicide washoff in field studies and to limited photodegradation in the glasshouse. Degradation rates on cane trash were found to range from 19–117 days, with no detectable degradation observed for diuron or tebuthiuron. The shortest half-life was 19 days for pendimethalin, six herbicides had half-lives of 30–45 days, and six had half-lives of 59–117 days. The half-lives were greater than half-lives measured in nine cropping soils in the same study, except for pendimethalin and paraquat which were less in cane residues. These longer half-lives on cane residues, and the washoff discussed previously, mean applying herbicides to crop residues should not reduce their efficacy (except where initial losses are higher than in soil), but would potentially increase their runoff risk.

Locke et al. (2005) found dissipation of fluometuron and norflurazon on ryegrass crops was often more rapid than in soil, with half-lives from 3–11 days, compared with 7–15 days in the soil surface. Longer half-lives in cane residue than in soil are opposite to what Locke et al. (2005) found but similar to Selim et al. (2000, 2003) for atrazine, metribuzin and pendimethalin on sugar cane residues and Zablotowicz et al. (1998) for 2,4-D and fluometuron in hairy vetch and rye residues.

17.4.4 Washoff from Crop Residues by Rainfall or Irrigation

Some of the pesticides intercepted on crop residues will be washed off into the soil by rainfall or sprinkler irrigation. Rainfall amount had greater influence then rainfall intensity (e.g. Willis et al. 1986). This may well carry over to washoff of other pesticides from crop residues. For example, Martin et al. (1978) found that most of the applied cyanazine, alachlor, atrazine, and propachlor was washed off corn stalk residues during 30–40 mm of rain – little was retained. Pesticide concentration in washoff water declined rapidly and exponentially with amount of applied rain (first-order) in agreement with the exponential model in the Root Zone Water Quality (RZWQ) model (Wauchope et al. 2004). Similar exponential declines have also been observed by other authors (Baker and Shiers 1989; Dang et al. 2016), with some noting that the amount of washoff was not affected by formulation (liquid, wettable-powder or dry-flowable) or method of application (water or oil-water mixtures) (Baker and Shiers 1989). Dang et al. (2016), who studied the behavior of six herbicides (atrazine, ametryn, diuron, hexazinone, tebuthiuron, and S-metolachlor) also observed that the rate of washoff declined with increasing time after application; however, 70% still washed off. Cumulative washoff as a function of rainfall was similar for most herbicides, although the most soluble herbicides did have more rapid washoff (Dang et al. 2016). However, Potter et al. (2011) found that the available washoff fraction (Fwo) had an inverse relationship with water solubility for fomesafen (relatively high water solubility) and pendimethalin (low water solubility). In this case, high water solubility likely contributed to greater penetration into dry crop residue as it took up water from the spray mixture and reduced availability for washoff.

However, it should be noted that the high concentrations in early washoff water will generally infiltrate into the soil where it is needed for weed control and does not go into runoff unless the soil is wet or crusted (Dang et al. 2016). Overall, washoff of herbicides from crop residues by rainfall or overhead irrigation is generally rapid and not limiting to removing herbicides to the soil, except for those herbicides that are more highly sorbed, such as for pendimethalin. Thus, we expect herbicide efficacy to be similar for NT and CT and herbicide runoff will not be greatly different due to spraying on crop residues.

17.5 Pesticide Dissipation in Soil

Dissipation is an important determinant of both environmental fate (runoff and leaching) and efficacy of residual herbicides. Dissipation in soil can involve losses by volatilization, degradation or transformation (chemical, biological or photochemical), plant uptake and, for more mobile pesticides, leaching into the soil. As described above, dissipation has been found both to be more rapid and slower on crop residues than in soil for a range of herbicides.

Tillage practices modify pesticide dissipation in soil, but again in contrasting ways depending on the pesticides (Alletto et al. 2010). Dissipation for pesticides and their degradation products was found to be slower, equivalent, or faster with NT compared to CT according to the many studies cited by Alletto et al. (2010). Slower dissipation in NT systems is often attributed to greater sorption to soil (Zablotowicz et al. 2000), higher soil acidity (Brown et al. 1994), or reduced temperatures (Sorenson et al. 1991) leading to reduced biological degradation. No-till soils can also have somewhat altered properties (e.g. higher organic carbon) and altered moisture, temperature and microbial regimes compared to CT soil, which can lead to differences in dissipation. For instance, degradation of fluometuron was more rapid in NT soil than in CT soil likely due to higher microbial activity (Gaston et al. 2001). The presence of plant residues in the soil can also decrease dissipation if microbes prefer soil organic matter as a substrate over the herbicide, e.g. metribuzin (Locke and Harper 1988). However, the differences in dissipation half-lives due to soil organic matter are unlikely to be large, especially in lower rainfall environments where the change in soil organic matter is small (discussed elsewhere). The behavior of degradation products will also be important and will be influenced by the factors discussed above.

17.6 Effects of Tillage on Pesticide Runoff

The varying effects of NT management on the interaction of pesticides with crop residues and soil can lead to variable impacts on the amount of pesticides lost in runoff. Mixed results have been observed regarding the effect of NT or reduced tillage on runoff, with increases, decreases, and no change observed (Fawcett et al. 1994; Elias et al. 2018). However, where runoff is reduced due to NT (e.g. Freebairn et al. 1996), we would expect a reduction in the amount of pesticide lost in runoff (all else being equal) and vice versa. In addition, because soil erosion is generally greatly reduced with NT, transport of sediment-sorbed pesticides is also generally reduced (Silburn et al. 2002). Major reviews of pesticide runoff under CT and NT were published by Fawcett et al. (1994) and Elias et al. (2018). In a review of studies in the United States (Fawcett et al. 1994), conservation tillage usually reduced runoff losses of pesticides (mostly herbicides) from cropped lands compared with conventional (bare, tilled), although some data were conflicting. For herbicides, the average reductions across all natural rainfall studies were 70, 69 and 42% for NT, chisel plow and ridge till, respectively. This was despite the fact that many of the herbicides ran off in the solution phase rather than adsorbed to sediment. These reductions were associated with the degree to which the treatment reduced runoff. However, herbicide runoff from NT did vary from none to twice that from CT.

More recently, Elias et al. (2018) reviewed published data on concentrations and loads of 24 different pesticides in agricultural runoff from NT and conventional ‘plow till’ (34 studies). Twenty-three of the papers were from the USA and one each from Europe and Canada. Soil organic matter ranged from <1.2 to >5.2% and pH from <5.1 to >8.5. Concentrations of several pesticides (atrazine, cyanazine, dicamba, and simazine) were greater in runoff for NT than CT fields, while all others were unaffected by tillage. In addition, total runoff loads of dicamba and metribuzin were greater, alachlor lower, and all others no different between NT and CT systems. Soils with low to medium soil organic matter had greater pesticide soil concentrations under NT relative to CT. Generally, concentrations in runoff also increased in acidic and moderately alkaline soils under NT. For pesticides with low and moderate affinity for solids, or a high solubility, increased concentrations in runoff were also observed under NT. For pesticides with high affinity for particles, there was no significant effect of NT management. Similar effects occurred for total loads. Thus, there are inconsistences between the two reviews, although the more varied results from Elias et al. (2018) are related to a greater number of studies (6 v 34).

Regardless of the tillage system used, herbicide runoff is generally dominated by a small number of runoff events, usually shortly after herbicide application. This is a typical finding for runoff of pesticides with reasonably rapid dissipation rates (Wauchope 1978). Indeed, Shipitalo and Owens (2003) found that the rainfall received, and timing of runoff-producing rainfall, had a greater effect on atrazine and metabolites, deethylatrazine (DEA) and deisopropylatrazine (DIA) than tillage system.

Other management practices, such as irrigation or the inclusion of cover crops, can also impact on pesticide runoff. For example, Waters (2001) measured sediment, pesticide, and nutrient runoff for irrigated conventional cotton compared to cotton planted into a wheat cover crop in Australia. Wheat-cotton rotation reduced soil erosion by 70% and endosulfan insecticide concentrations in runoff by 40%. In addition, three less insecticide sprays were needed for the wheat-cotton rotation crops. Similarly, Krutz et al. (2007) found total metolachlor loads were 1.3-fold lower in NT than reduced tillage and 1.4-fold lower in rye cover than no cover. Although, conversely, cumulative fluometuron runoff loads were not affected by tillage (NT and reduced tillage) or cover crop (no cover and rye cover). In addition, Potter et al. (2011) found that without irrigation incorporation, relatively high runoff of the herbicide fomesafen, about 5% of applied, from the CT compared with conservation tillage (2.1%), using a rainfall simulator. Runoff losses were reduced by >50% when the herbicide was incorporated by irrigation. In general, increased infiltration rates and amounts are required in residue managed systems if cumulative pesticide losses are to be reduced. However, effects on herbicide loads were generally small.

17.6.1 Other Forms of Management

If tillage practices do not consistently control pesticide runoff, then other practices should be considered to help limit off-site losses. There is considerable variation in toxicity of various pesticides, their application amounts, and in their sorption and runoff potential. For example, glyphosate is 250 time less toxic than atrazine and over 1000 times less toxic than diuron. Similarly, imazapic is applied at an 8 to 17 times lower rate than many of the older soil residual herbicides. Lewis et al. (2013) studied 11 herbicides on rainfall simulator plots in sugar cane fields (two soils) in coastal Queensland. Application of less herbicide on the paddock typically translated to a proportional reduction in the runoff losses. The herbicides typically ran off mostly in the water phase, although pendimethalin and imazapic were predominately transported attached to particles, while glyphosate, 2,4-D and diuron all had some affinity (~ <20%) for the particulate phase. Transport on sediment is more easily controlled because conservation tillage is generally effective in controlling sediment movement. Also, sediment is easier to settle out (e.g. at change of slope or roughness) than dissolved herbicides. As a proportion of the amounts applied, less pendimethalin and the 'knockdown' herbicides (glyphosate, fluroxypyr) were lost in runoff from the paddock compared to the 'knockdown' 2,4-D and the 'old' PSII inhibitors (diuron, atrazine, ametryn) and the new/alternative herbicides (isoxaflutole, metribuzin, metolachlor). However, because some of the emerging products (isoxaflutole and imazapic) and the newer 'knockdown' fluroxypyr are applied at much reduced rates than older products, the actual dissolved runoff losses are also lower. Alternative/new herbicides have a generally lower risk than diuron, based on preliminary ecotoxcity and the measured runoff relative to diuron. For example, risk for glyphosate, pendimethalin, paraquat, and fluroxypyr was 1000 time less than for diuron. The risk assessment can also be carried out at longer times after application by predicting the effect of different half-lives. A subset of these results is presented by Melland et al. (2016) with data from an additional two sites (total four).

Band spraying has also been consistently found to be effective in reducing runoff concentrations and loads (Silburn et al. 2013; Masters et al. 2013; Oliver et al. 2016; Davis and Pradolin 2016; Melland et al. 2016), by about the proportion that the spray rate is reduced. Band spraying was also highly effective in reducing herbicide runoff for furrow irrigation where tailwater flow is isolated from the sprayed hills (Lewis et al. 2013; Silburn et al. 2013; Davis and Pradolin 2016). Similarly, controlled traffic farming has often resulted in a decrease in surface runoff compared with non-controlled traffic (Rohde et al. 2013 in sugar cane; Tullberg et al. 2001 in grain cropping; Silburn and Glanville 2002 in cotton/row-crops). Runoff loads were reduced by 38–40% (Silburn et al. 2002) and 60, 55, 47, and 48% for ametryn, atrazine, diuron, and hexazinone (Masters et al. 2013). Cover and banding also gave useful reductions.

17.7 Effect of Tillage on Pesticide Sorption

17.7.1 Organic Carbon Content Change with No-Tillage and Soil Sorption

For many pesticides, sorption to soil is related to soil organic carbon content. Effects of tillage on soil organic carbon are reviewed in other chapters of this book. However, in summary, NT is often associated with increases in SOC, particularly in the top few centimeters of the soil where the majority of pesticide-soil interactions occur. For example, Ogle et al. (2005) found that management effects were affected by climate with most effect in tropical wet followed by tropical dry, temperate moist and lowest for temperate dry climate. However, some studies also find no significant change in SOC with no tillage (e.g. Page et al. 2013).

For pesticides with low sorption capacity, soil carbon may have little effect on loss via runoff. For example, in some studies of effects of tillage on sorption kinetics (acifluorfen, Gaston and Locke 2000; chlorimuron, Reddy et al. 1995 and cyanazine, Reddy et al. 1997) no effect of tillage system was found. Whereas for alachlor (Locke 1992) and sulfentrazone (Reddy and Locke 1998), sorption was positively correlated with higher soil organic matter and was faster under conservation tillage. However, in practical terms the difference in sorption between tillage systems is often small (e.g. 4.05 for CT vs 5.88 L kg^{-1} for NT in Locke 1992).

Alletto et al. (2010) reviewed the effects of tillage on pesticide fate in soils. They found "for most dissipation processes such as retention, degradation, and transfer, results of pesticide behavior studies in soils are highly variable and sometimes contradictory". They attribute this in part to "the multiplicity of processes and contributive factors, by the variety of their interactions, and by their complex temporal and spatial dynamic" and to the lack of a thorough description of the tillage systems and sampling strategies. The increase in soil organic carbon in reduced tillage (if it occurs) is noted to cause greater pesticide sorption in the topsoil layer (e.g. Staddon et al. 2001) and this is expected to decrease availability of the pesticides for biological degradation and lead to higher persistence. However, Staddon et al. (2001) also found more rapid degradation and greater microbial activity with higher organic matter. Thus, persistence can be partially compensated for by more intensive microbial activity and higher soil moisture under conservation tillage. However, despite these changes, "pesticide transfer is more influenced by initial soil conditions and climatic conditions than by tillage" (Alletto et al. 2010). Finally, "conservation tillage systems such as NT improve macropore connectivity, which in turn can increase pesticide leaching."

17.8 Leaching of Pesticides and Pesticides in Groundwater

No tillage would generally be expected to reduce runoff amounts, increase soil moisture storage and infiltration, and thus increase deep drainage (Flury 1996; Tolmie et al. 2003). For example, deep drainage (leaching) was 3 times greater for NT than CT with winter cropping at two of three tillage trials studied by Tolmie et al. (2003). For pesticides with low sorption, this would increase pesticide leaching, but the effects are highly variable. Flury (1996) review many studies on pesticide leaching. He found studies where pesticide leaching was greater for NT than for CT, but also others where there was no apparent effect of tillage. He could not identify why these differences occurred, although the increase with NT was lower on coarse textured soils than loamy or clayey soils.

Pesticide concentrations in groundwater are typically low, in the order of 0.1 to 5 µg L^{-1} (Hallberg 1989; Shaw et al. 2012) and rarely exceed environmental guideline values (e.g. Shaw et al. 2012). However, even at these concentrations there can be concerns about long term chronic human health, although environmental impacts are much less often a concern. Detections in sampling surveys of groundwater are variable but can be from 0–32% of wells and up to 70% (Shaw et al. 2012). Frequency of detections have risen as the analytical limit of reporting have decreased. In most USA corn-belt areas, the herbicide atrazine was the most commonly detected product in groundwater (Hallberg 1989). Mobile and/or volatile soil fumigants, and nematicides used on vegetable or specialty crops were also commonly detected (Hallberg 1989). More soluble, less sorbed herbicides, such as atrazine, hexazinone and metolachlor (sorption coefficient per unit of organic carbon Koc < = 100 L kg^{-1}), are also often among the pesticides detected (Shaw et al. 2012). However, somewhat more sorbed compounds, such as diuron (Koc = 1070) and chlorpyrifos (Koc = 8150) are also found (Shaw et al. 2012). This may mean that water and solutes have moved via preferential flow paths, which can be enhanced by conservation tillage (Flury 1996; Alletto et al. 2010). Many products used in an area and in analytical suites (100 s) will not be detected, indicating that either the water flux is too small or that sorption has prevented their movement.

17.9 Conclusion

No till will generally give lower runoff loads and sometimes concentrations for more highly sorbed compounds. An older review found that pesticide runoff (mainly soluble herbicides) typically was lower with NT, but this study only examined six natural rainfall studies and five rainfall simulation studies. A more recent and larger (34 studies) review found pesticide loads and concentrations are sometime lower with NT, sometimes greater, and were not different for others. Given this, suggestions are made for other ways to control pesticide runoff, including selecting pesticides that are less toxic, less persistent, more sorbed, and runoff less. Washoff of pesticides from crop residues by rainfall was typically reasonably rapid, however, rapid dissipation can occur after spraying. Many other aspects of pesticide behaviour in NT/reduced till systems are variable, inconsistent, or minor.

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Part III

Climate Change Mitigation and Adaptation

Chapter 18
No-Till Systems to Sequester Soil Carbon: Potential and Reality

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Abstract The conversion of soils from conventional till (CT) to no-till (NT) management has been identified as a soil management practice with the potential to increase soil organic carbon (SOC) sequestration and help mitigate global climate change. However, the changes in SOC observed in NT systems have often been variable and dependent on a combination of factors, including climate, cropping system, soil type and crop/soil management. This had led to large variation in the rates of sequestration observed worldwide. In addition, there is concern some studies may have overestimated SOC sequestration rates due to methodological issues, with some authors concluding that once these methodological factors are considered, the potential for NT to sequester C on a worldwide scale may be limited. When the effect of NT on N_2O and CH_4 emissions are also considered, the benefits of NT management to mitigate climate change can be further eroded and NT may even increase net greenhouse gas (GHG) emissions - for example from fine textured and poorly drained soils where NT management increases N_2O emissions. However, the potential for net C sequestration in NT systems is site specific and where site conditions/management favor SOC accumulation and lead to neutral or decreases in N_2O production, significant decreases in global warming potential (GWP) can be observed. This highlights the need to consider the net GWP of NT on a soil type, site or regional basis.

Keywords Soil organic carbon · Carbon sequestration · No-tillage · Global warming potential

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18.1 Introduction

It has been well documented that the conversion of native vegetation to cultivation and cropping results in significant declines in SOC (Kopittke et al. 2017). This loss occurs due to both the decreases in C input under cropping, and increases in soil mineralization rates due to the disruption of soil aggregates and exposure of previously protected organic matter to microbial decay (Six et al. 2000). However, it has been noted that if this lost C could be replaced and stored (a potential soil C sink) than it would represent a significant opportunity to sequester C from the atmosphere and contribute to the mitigation of global climate change. Changes to a range of agricultural management practices have been identified as having the potential to achieve this, including the conversion of soils from conventional tillage (CT) to no-till (NT) management (Lal 1997; West and Post 2002; Abdalla et al. 2013).

While some studies have reported increases in SOC stocks following conversion from CT to NT (Franzluebbers 2010; Aguilera et al. 2013; Conceição et al. 2013; Francaviglia et al. 2017), others have also reported no change (Angers et al. 1997; Luo et al. 2010) or even decreases (Christopher et al. 2009; Du et al. 2017). These varied results are due to the different climates, soil types and soil/crop management techniques present in different locations, indicating that rates of sequestration are likely to be site specific. Consequently, it is the aim of this chapter to review information on the factors governing SOC sequestration under NT and the estimates of realistic SOC sequestration rates worldwide. The overall impact of NT on greenhouse gas (GHG) reduction given its impact on the emission of CH_4 and N_2O, will also be discussed.

18.2 Measurement of Soil Carbon Sequestration

When assessing SOC sequestration, it is essential to be aware of methodological aspects that can affect the rates observed. For example, significant differences in estimates can occur when stocks are measured over shallow (<0.2–0.3 m) compared to deeper (>0.4 m) soil depths (Angers et al. 1997; Angers and Eriksen-Hamel 2008; Blanco-Canqui and Lal 2008; Christopher et al. 2009). This occurs because NT promotes higher concentrations of C at the soil surface (C stratification due to the accumulation of crop residues in this location), but lower concentrations at depth due to the absence of soil mixing. Differences in root distribution and rhizodeposition between NT and CT systems can also influence SOC distribution (Sisti et al. 2004; Boddey et al. 2010; Piccoli et al. 2016). Where these differences exit, it is important to consider the entire profile so that the different distributions of SOC are adequately sampled (Angers and Eriksen-Hamel 2008; Blanco-Canqui and Lal 2008; Du et al. 2017). Some authors have proposed that soil sampling needs to exceed at least 0.4–0.5 m, and preferably encompass the entire root zone to fully capture differences (Boddey et al. 2010; Gentile et al. 2011; Olson 2013). Although where it is confirmed that differences at greater depths do not exit, sampling within the plough layer alone (e.g. top 0.3 m) may be sufficient (Govaerts et al. 2009).

Due to differences in bulk density between NT and CT systems, it is also desirable to use an equivalent soil mass, rather than a fixed depth, to compare between management types. Sequestration of SOC can be overestimated when using fixed depths due to the higher bulk density often observed in the surface of NT soils (Gentile et al. 2011; Olson 2013; Du et al. 2017). Ideally, rates of sequestration should also be determined by measuring SOC at the beginning and end of an experiment, rather than simply measuring the difference between NT and CT plots with the assumption that the CT treatment did not change over time. This is not always a valid assumption e.g. if all treatments lose C over time, or if erosion occurs from the CT plots (Olson 2013). For those studies that fail to use 'best practice' methodologies it is important to interpret results with care.

18.3 Factors Governing SOC and C Sequestration in No-Till Cropping Systems

A soil's SOC stock is determined by the difference between C inputs (biomass) and losses (erosion, decomposition, leaching), and the effect of NT management on the balance between these processes governs whether it increases or decreases SOC stocks. Various factors can influence the impact of NT systems on this balance, including climate, crop rotation, soil type and crop/soil management, as discussed below.

18.3.1 Climate

Climate can affect SOC sequestration due to its impact on both plant biomass production and decomposition rates (Ogle et al. 2005; Govaerts et al. 2009; Ogle et al. 2012). The potential for SOC sequestration is greater in areas where biomass production is highest, and decomposition rates lowest. For this reason, SOC increases in NT systems are generally observed to be lower in arid and semi-arid v humid locations, due to the reduced biomass production possible in these areas (Six et al. 2004; Ogle et al. 2005; Francaviglia et al. 2017). Higher soil decomposition rates can also decrease the likelihood of C sequestration, with higher C turnover typically observed in tropical v temperate locations due to warm moist conditions (Six et al. 2002). In addition, processes such as freeze/thaw cycles in colder environments and wetting and drying cycles in drier environments can also increase mineralization (Butterly et al. 2010; Edwards 2013), and may reduce the potential for SOC storage in drier and cooler climates (Ogle et al. 2019).

Overall, the effect of climate on C stock change following the introduction of NT will be dependent on the balance achieved between biomass production v decomposition in NT v CT systems. In one meta-analysis, the relative increases in SOC upon conversion to NT (estimated after a 20 year period) for different environments were tropical moist[1] (23% increase) > tropical dry (17% increase) > temperate moist (>16% increase) > temperate dry (>10% increase) (Ogle et al. 2005), and a later study based on data from 178 experimental sites also confirmed that greater SOC storage would occur in tropical moist compared to cool dry climates (Ogle et al. 2019). However, a different meta-analysis concluded that rates of C sequestration were similar between temperate and tropical locations once the whole plough layer was considered (Six et al. 2002). In an analysis conducted across the USA and Canada, it was observed that maximum sequestration occurred under NT when the ratio of mean annual precipitation:mean annual potential evapotranspiration was 1.27 mm mm^{-1} (Franzluebbers and Steiner 2002). At ratios <0.75 no sequestration under NT occurred, probably because low precipitation limited the ability of plants in both systems to fix C, or limited decomposition even when residues were mixed with the soil. At ratios >1.74 there was also little SOC storage potential within NT systems, possibly because abundant moisture at the soil surface and decreased aeration at depth increased decomposition of surface retained *v* buried residues, and/or lower soil temperatures limited yield and thus biomass input (Franzluebbers and Steiner 2002; Gregorich et al. 2005; Ogle et al. 2012).

18.3.2 Crop Types and Crop Rotation

Greater SOC sequestration is more likely to be observed in situations of greater C input (under both CT and NT management). This can be achieved by greater residue return, more intense cropping rotations, and/or the growth of higher biomass crops (Christopher and Lal 2007; Govaerts et al. 2009; Luo et al. 2010; González-Sánchez et al. 2012; Virto et al. 2012; Du et al. 2017). Indeed, where NT is implemented without concurrent increases in biomass input, it is not generally observed to lead to SOC sequestration relative to CT, with long fallow periods in particular associated with an absence of sequestration (Halvorson et al. 2002; Diekow et al. 2005).

In addition, greater SOC sequestration can be observed following increases in biomass input in NT v CT systems (Franzluebbers and Steiner 2002; Govaerts et al. 2009; Conceição et al. 2013). For example, in studies across the USA and Canada it was found that the annualized change in SOC with increasing cropping intensity was greater in NT v CT (Franzluebbers and Steiner 2002). In some instances, especially in drier locations, the introduction of NT can also increase the ability to intensify cropping (and potentially increase biomass input), due to increased soil moisture

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[1] Tropical = mean annual temperature of >20 °C; dry = mean annual rainfall of <1000 mm

and the faster turnaround time between harvest and planting in the absence of cultivation (Govaerts et al. 2009).

18.3.2.1 Crop Type

The type of crop grown can influence SOC sequestration under NT. Different crops may have different effects on the quantity, quality, and periodicity of C inputs and can modify the soil in different ways (e.g. rates of water extraction, nutrient use), which can influence mineralization rates and the growth of subsequent crops (Huggins et al. 2007). For example, crop rotations that return greater amounts of residue to the soil, and in particular have greater root C additions, are often associated with greater SOC stock in NT systems (Huggins et al. 2007; dos Santos et al. 2011; Conceição et al. 2013). Greater biomass production is also often associated with greater water use, which can decrease soil water contents and lead to reductions in mineralization rates (Havlin et al. 1990). However, different crops may also respond differently to the changed growing conditions under NT v CT and where NT has a negative impact on yield (and hence biomass input), this may reduce sequestration capacity. For example, the ability of NT to sequester C in western but not eastern regions of Canada has partly been attributed to the fact that NT had limited or negative effects on yields in the east (maize dominated), but yield advantages in the west (wheat dominated) (Gregorich et al. 2005).

Crop residue quality may also influence C sequestration. For example, a recent analysis of the literature suggested that the increase in microbial biomass and the production of microbial residues associated with addition of high-quality litter (low C:N, lignin) can increase micro- and macro-aggregate formation and increase the protection of particulate organic material (Castellano et al. 2015). Thus, in two identical soils, the soil where high quality residues are added should reach its equilibrium C content more quickly (Castellano et al. 2015). Indeed, in some situations the addition of low quality residue to the soil can lead to overall decreases in SOC as soil microorganisms increase the mineralization of existing SOM to obtain the nutrients they require for growth (Fontaine et al. 2004; Richardson et al. 2014).

18.3.3 Soil Type

While climate can affect the balance between production and decomposition, soil properties determine the level of C sequestration possible within a given climate (Palm et al. 2014). A number of aspects of soil type can influence SOC sequestration, including texture, SOC content and topography.

18.3.3.1 Texture

Adsorption onto the surfaces of clay minerals and metal oxides is one of the primary ways SOC can resist decomposition in soil (Barré et al. 2014). The clay fraction is also involved in the formation of soil aggregates, which protect SOC from biodegradation (Barré et al. 2014). Consequently, soils with higher clay contents have a greater ability to retain SOC (Lal 1997; Liang et al. 2002; Six et al. 2002). In sandy soils, any increases in SOC tend to accumulate in the particulate organic C (POC) fraction, which has a higher turnover time and is more susceptible to loss following disturbance (Feller and Beare 1997; Castellano et al. 2015).

In accordance with this, studies in the Canadian prairies have observed a linear relationship between the amount of SOC sequestered following conversion to NT and soil clay content (between ~27–63% clay content) (Liang et al. 2002). Similarly, other authors have observed that reduced intensity of tillage has little (Chivenge et al. 2007) or reduced (Nyamangara et al. 2014) impact on SOC storage in sandy soils, but does lead to higher SOC concentrations in soils with higher clay content (Chivenge et al. 2007; Nyamangara et al. 2014). Although it should be noted that some meta-analyses have also observed greater SOC sequestration following adoption of NT in coarse compared to fine textured soils (Du et al. 2017), while others observe little impact of texture (Puget and Lal 2005). Analysis of the SOC sequestration rates possible in different climatic regions on either heavy (loamy, silty, clayey) or light (sandy) textured soils based on data from 178 experimental sites suggests that the amount of SOC likely to be sequestered in heavy and light textured soils may vary depending on climate (Ogle et al. 2019). For example, this analysis found that there would be a net SOC increase in the sandy soils of tropical moist, tropical dry, warm temperate moist and cool temperate moist climates following the introduction of NT, but that in heavier textured soils, increases were only likely in soils in tropical moist and warm and cool temperate moist climates. The reason for these differences could not be determined from this study, but were likely related to differences in C input, decomposition rates and physical protection of C in the soil in different regions (Ogle et al. 2019).

Soil mineralogy is also likely to impact SOC sequestration, although the effect of different minerals are often contradictory, and it is not currently clear how mineralogy affects the magnitude of soil sequestration (Barré et al. 2014). However, some analyses have suggested that soils dominated by 1:1 clay minerals are likely to have reduced capacity to stabilize C due to their reduced CEC compared to 2:1 minerals (Six et al. 2002). Moreover, protection within soil aggregates is not as important a mechanism for SOC protection in soils dominated by 1:1 minerals (Six et al. 2002; Zotarelli et al. 2005).

18.3.3.2 Baseline SOC Content

The amount of SOC present in a soil at the time NT is introduced will have a large impact on the amount of C that can subsequently be sequestered. A soil that is highly depleted in SOC following years of cultivation will have greater potential to sequester C compared to a site where C concentrations are already high and near the equilibrium content that can be achieved under NT in that environment (Steinbach and Alvarez 2006). Sites that already have high background concentrations of SOC tend not to show any increase in SOC stocks, or even lose SOC, following the introduction of NT management (VandenBygaart et al. 2002; Govaerts et al. 2009).

18.3.3.3 Topography

Topography can affect SOC sequestration, largely due to its influence on soil erosion. Areas that have previously experienced erosion typically have lower SOC stocks due to the preferential removal of SOC (Lal 2003), and thus have greater potential to sequester SOC following the introduction of NT. This effect is likely to be greatest in topographical positions most susceptible to erosion i.e. sloping areas (Govaerts et al. 2009). For example, one study that examined changes in SOC stocks following conversion to NT observed that areas with low SOC stocks due to past erosion (convex positions) had a greater capacity to sequester SOC compared to depositional areas (concave and toeslope positions). On the other hand, depositional areas often lose SOC following conversion to NT, partly due to reductions in C addition from upslope via erosion (VandenBygaart et al. 2002).

18.3.4 Soil and Crop Management

18.3.4.1 Tillage Type

In some instances, the type of tillage conducted is believed to have an impact on the change in SOC stocks following conversion to NT. For example, in areas where full inversion tillage is carried out, residues may be buried in a region where poor soil aeration can limit decomposition (relative to the soil surface), particularly under cool, moist climatic conditions (Gregorich et al. 2005; Christopher et al. 2009). Where this is the case, SOC stocks can be similar or even decline following conversion to NT (Gregorich et al. 2005; Blanco-Canqui and Lal 2008; Christopher et al. 2009). Conversely, where shallower, non-inversion tillage is conducted, and such burial does not occur, overall positive gains following the introduction of NT are more commonly observed (Gregorich et al. 2005). However, it should be noted that when tillage type is considered on a broader scale and over a range of climate types, tillage intensity can also be found to have limited impact on SOC sequestration (Steinbach and Alvarez 2006; Haddaway et al. 2017; Ogle et al. 2019) and further studies are required that include all tillage types in the same experiment to fully evaluate the differences between inversion and non-inversion tillage (Ogle et al. 2019).

18.3.4.2 Residue Management

Crop residues can be defined as plant root or top material remaining in or on the soil after harvest. Increasing residue input by either reducing removal (ceasing burning or grazing), or by increasing crop production, can potentially lead to increases in SOC storage (Duiker and Lal 1999, 2002; Liu et al. 2014; Abdalla et al. 2016). Indeed, linear increases in SOC stocks are often observed with increasing rates of residue addition (Duiker and Lal 2002; Virto et al. 2012; Liu et al. 2014), with the proportion of C retained greater in NT v CT systems (Duiker and Lal 1999, 2002).

In situations where there is limited residue return, either due to removal or due to poor crop biomass production, SOC sequestration is generally not observed (Dendooven et al. 2012; Virto et al. 2012; Palm et al. 2014). This can be a particular problem in more arid regions, where competition for residue can be high (e.g. from grazing animals) (Chivenge et al. 2007; Govaerts et al. 2009; Palm et al. 2014). Increasing residue input by increasing crop production can be a challenge in these areas, especially in small holder operations where the capacity of farmers to increase soil fertility is limited (Chivenge et al. 2007). Thus, in such circumstances, the conversion to NT may have little impact on SOC storage. Situations where the characteristics of the NT system lead to reduced yields (e.g. lower soil temperatures, increases in disease) can also lead to decreases in residue inputs and lower or no SOC sequestration (Yang et al. 2013).

18.3.4.3 Soil Nutrient Management

The addition of nutrients via fertilizers can influence soil SOC sequestration due to their impact on both decomposition rates and the production of biomass. Nutrient addition, particularly N, will often increase plant biomass production, leading to greater C inputs into the soil and greater SOC storage (Alvarez 2005; Christopher and Lal 2007; Macdonald et al. 2018). No increases in SOC storage following N addition have also been observed, although this tends to occur in areas where SOC stocks are already high and there is limited capacity for further increases (Christopher and Lal 2007). Nitrogen addition can also affect SOC decomposition, with both increases, and decreases in SOC storage observed following N addition - with the direction of change largely dependent on the makeup of organic materials, the microbial community, and pre-existing N availability (Neff et al. 2002; Macdonald et al. 2018).

While it is well known that nutrient addition can affect SOC sequestration, less information is available on the different effects in NT v CT soils. In a study of sites in Canada and the USA, for example, it was observed that while the amount of SOC stored under NT and CT was greater with increasing rate of N fertiliser application, there was no significant difference in the rate of change in SOC with NT v CT (Franzluebbers and Steiner 2002). However, other studies have observed that SOC sequestration is unlikely in NT unless there are sufficient nutrients present to facilitate the processing of organic material into stable forms of C (Lal et al. 2007; Kirkby et al. 2014), indicating that SOC sequestration following conversion to NT is likely to be low in nutrient limited environments.

18.3.4.4 Time

The time NT management has been in place can also influence the rate of SOC sequestration. Following the introduction of NT, sequestration will initially be high and then gradually approach a new steady state as the soil reaches the maximum C content possible under the new management. For example, a meta-analysis conducted in Spain observed that those studies conducted for <10 years had a sequestration rate of 0.85 Mg ha^{-1} year^{-1}, while those that had been conducted for >10 years averaged 0.16–0.4 Mg ha^{-1} year^{-1} (González-Sánchez et al. 2012). Estimates of the time taken to reach steady state include 15–20 years (West and Post 2002) and 25–30 years (Alvarez 2005). Some studies have also noted an initial decrease in SOC under NT v CT, particularly in drier temperate climates, although after 5–10 years accumulations are generally observed (Six et al. 2002; Six et al. 2004; Steinbach and Alvarez 2006). This initial decrease has been attributed to the slower decomposition and reduced soil mixing with residues on the soil surface (Six et al. 2002).

18.4 Estimates of Realistic SOC Sequestration

Numerous meta-analyses have been conducted to estimate the likely magnitude of SOC sequestration worldwide (Table 18.1). These studies report average sequestration rates ranging from −0.15 Mg ha^{-1} year^{-1} in areas such as the midwestern USA (Christopher et al. 2009) to +0.93 Mg ha^{-1} year^{-1} in tropical Brazil (Bernoux et al. 2006) (Table 18.1). However, it should be noted that the studies included in these analyses have often not sampled the whole soil profile (<0.4 m depth), have not compared SOC stocks on an equivalent mass basis, and include studies that have only been conducted for relatively short periods of time (<5 years). Most studies are also based on comparisons between treatments at the end of an experimental period, rather than comparison of SOC stocks under NT at the beginning and end of an experiment. Consequently, the uncertainty surrounding these estimates is high and some authors have even concluded that worldwide, the potential of NT to sequester SOC is limited once this uncertainty is taken into account (Powlson et al. 2014; Powlson et al. 2016).

Table 18.1 Worldwide estimates of carbon sequestration rates following conversion to NT

Study location	Sequestration rate (Mg ha^{-1} $year^{-1}$)	Reference
Midwestern USA	−0.15	Christopher et al. (2009)
Central USA	+0.4	Johnson et al. (2005)
Southeastern USA	+0.45	Franzluebbers (2010)
Canada	nsd	Angers et al. (1997)
Canada	West:+0.32	VandenBygaart et al. (2003)
	East: −7	
Mediterranean climatic zones.	+0.44	Aguilera et al. (2013)
Mediterranean regions	+0.3	Francaviglia et al. (2017)
Spain	+0.51	González-Sánchez et al. (2012)
Tropical Brazil	+0.35	Bayer et al. (2006)
Subtropical Brazil	+0.48	
Tropical Brazil	+0.93	Bernoux et al. (2006)
Subtropical Brazil	+0.54	
Argentine Pampas	0.4 years: 0	Steinbach and Alvarez (2006)
	4–9 years: +0.46	
	>10 years: 0	
China	+0.25	Du et al. (2017)
Sub-Saharan Africa	+0.37	Powlson et al. (2016)
Indo-Gangetic Plains	+0.54	
African continent	+0.14	Gonzalez-Sanchez et al. (2019)
Worldwide	+0.33	Kirkby et al. (2016), Six et al. (2002), and Puget and Lal (2005)
Worldwide	nsd	Luo et al. (2010)
Worldwide	+0.26	Alvarez (2005)
Worldwide	Tropical +0.86	Mangalassery et al. (2015)
	Temperate +0.17	
	World: +0.52	
Worldwide	+0.48	West and Post (2002)

However, several broad trends can be identified. In environments where rates of crop production are inherently low due to climate or soil fertility factors, and where farmers have insufficient economic resources to ensure optimum crop production, the conversion to NT is unlikely to lead to significant SOC sequestration (Cheesman et al. 2016; Powlson et al. 2016). Similarly, in environments where CT increases SOC storage relative to NT due to the burial of residues in zones with lower rates of decomposition, NT is also unlikely to sequester C, and may even lead to SOC loss relative to CT (Christopher et al. 2009). However, in regions where soil and climatic conditions are favorable for biomass production and where NT does not negatively impact yield, then moderate rates of sequestration may occur. However, the large range in the sequestration rates observed indicates that the ability of NT to sequester SOC is likely to be highly site specific.

In addition, current estimates of SOC sequestration are generally based on data from experimental research plots where growing conditions are carefully and consistently controlled. These experimental conditions may differ substantially from conditions in actual farmer’s fields, where decisions surrounding management are taken according to multiple economic and practical considerations, and there thus may be considerable differences between the SOC sequestration observed by scientists compared to that achieved by farmers. To achieve SOC sequestration in the long-term, it will also be necessary for farmers to maintain NT management over an extended period. Any decision to convert back to CT may lead to the re-emission of sequestered C, leading to further uncertainty regarding the level of SOC sequestration that can be realistically achieved.

It is also important to consider that while the potential for SOC sequestration may exist in certain regions, whether it is likely to be adopted by farmers will depend on a range of socio-economic factors. For example, the adoption of NT in some developing regions can be limited by lack of access to specialized planting equipment and the increased time and labor requirements where herbicides are unavailable (Giller et al. 2009). Where NT management leads to yield reductions, the prospect of its adoption is also unrealistic.

18.5 Perspectives

When considering the benefits of SOC sequestration with NT management from a climate change perspective, it is also essential to conduct a full lifecycle assessment. This includes assessment of changes in CH_4 and N_2O emissions, and an account of CO_2 emissions from agricultural operations (e.g. fuel usage).

It is well accepted that NT uses less fuel than CT management. For example, fossil fuel emissions from tillage and herbicide production/application were estimated to be 53 kg C ha^{-1} year^{-1} for intensive tillage (moldboard plough) 45.1 kg C ha^{-1} year^{-1} for minimum tillage (chisel and disc plough) and only 29 kg C ha^{-1} year^{-1} for NT (Kern and Johnson 1993). However, the impact on CH_4 and N_2O emissions can be more variable.

18.5.1 CH_4 and N_2O Emissions

The impact of NT on N_2O emissions is governed by the interaction between soil and climate factors that affect soil aeration and there is potential for NT to both increase or decrease N_2O emissions. Where NT leads to increased bulk density and higher soil water contents, greater microbial biomass, and higher concentrations of labile SOC, there is potential for greater rates of nitrification/denitrification and N_2O emissions (Palm et al. 2014). Conversely, where NT leads to lower soil temperatures and/or improvements in soil structure and better drainage, denitrification may be lower and N_2O emissions may decrease (Govaerts et al. 2009; Palm et al. 2014).

In line with this, reviews of studies worldwide have reported increases, decreases, and no change in N_2O emissions from NT v CT systems (Six et al. 2002; Steinbach and Alvarez 2006; Rochette 2008; van Kessel et al. 2013; Palm et al. 2014). However, one review concluded that greater N_2O emission were most likely where NT was practiced on fine textured and poorly drained soils, whereas in well drained soils differences between tillage systems were relatively small (Rochette 2008). It has also been noted that N_2O emissions from NT soils decrease over time (Six et al. 2002; Six et al. 2004; van Kessel et al. 2013; Palm et al. 2014; Mangalassery et al. 2015). For example, the results of a meta-analysis indicated that in both humid and dry temperate environments, N_2O emissions were higher in NT v CT systems during the first 10 year period, however, after 20 years N_2O emissions were lower under NT in humid temperate climates and similar regardless of tillage in dry temperate climates (Six et al. 2004). Similarly, in a second meta-analysis, NT significantly reduced N_2O emissions in experiments >10 years, especially in dry climates (van Kessel et al. 2013). It has been hypothesized that the decrease in N_2O emissions is likely due to increases in SOC and associated improvements in soil structure over time, which decreases the tendency for the formation of anaerobic conditions conducive to N_2O production (Six et al. 2004; van Kessel et al. 2013). However, overall, due to the large spatial and temporal variability in N_2O emissions, and a paucity of measurements from some climatic regions (e.g. tropical locations) worldwide estimates of emissions under NT v CT systems are currently uncertain (Six et al. 2002; Palm et al. 2014; Mangalassery et al. 2015).

Fewer studies have been conducted into the effect of NT on CH_4, however, while results are variable, most studies in aerated systems observe either no difference or greater CH_4 uptake in NT systems (Six et al. 2002; Six et al. 2004; Abdalla et al. 2013; Mangalassery et al. 2015). This has been attributed to the greater aggregate stability and porosity in NT soils that facilitates the diffusion of CH_4 into oxidizing zones, and a greater abundance of methanotrophic bacteria (Six et al. 2002; Abdalla et al. 2013; Mangalassery et al. 2015). In rice paddy systems, increases in residue retention are known to increase CH_4 emissions due to the increases in available C (Palm et al. 2014), although where residue inputs are kept constant between tillage systems, large reductions in CH_4 emissions have been observed with NT, and attributed to slower decomposition rates (Abdalla et al. 2013).

18.5.2 Net Effects

Fewer studies have examined the net impact of NT on GHG emissions, and large uncertainty still exists around emissions estimates. For example, one global meta-analysis concluded that NT would have positive impact on net GWP in a range of soils and climatic regions (Sainju 2016). Conversely, other authors have concluded that, in some environments, NT may have only a small or even negative impact on net GHG emissions due to increases in N_2O emissions (Gregorich et al. 2005; Steinbach and Alvarez 2006). Other analyses still have concluded that greater GHG emissions are likely under NT in the first 5–10 years of adoption, but after 20 years net GWP is negative in humid temperate areas, and weakly negative in dry temperate areas as N_2O emissions decline (Six et al. 2004).

Despite the variability in results, it is clear that in some individual instances NT can have significant benefits for net GHG production. For example, one long-term (19 years) Mexican study found that NT with residue retention led to a net GWP of -6.27 Mg CO_2 ha^{-1} $year^{-1}$, while CT with residue retention led to net emissions of 1.89 Mg CO_2 ha^{-1} $year^{-1}$ (Dendooven et al. 2012). Similarly, work conducted in India by Parihar et al. (2018) observed that net GWP was ~18% lower under NT compared to CT due to higher SOC sequestration and lower N_2O emissions. In a long-term Australian trial (>40 years) net GHG emission were over 50% lower in fertilized (urea) NT systems compared to fertilized CT systems where cultivation and stubble burning were conducted, largely due to the greater preservation of SOC, removal of emissions associated with stubble burning and decreased fuel usage (Wang and Dalal 2015).

However, even in those instances where NT results in reduced GHG emission, as the sites approach their equilibrium C content, their ability to further sequester C, or slow C loss, will decline and net GHG emissions will be a function of reductions in CO_2 emissions due to fuel savings, combined with the net impact on N_2O emissions and CH_4 emissions/consumption. Given the likely large impact of N_2O emissions on long-term net GWP, the efficient management of N fertilizers is clearly important to maximize any potential decreases in GHG in NT systems. In addition, the large variation in SOC sequestration and emission of other GHGs depending on climate, soil type and management suggest that it is necessary to consider the net effect of NT on total GWP on a site by site or region by region basis.

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Chapter 19
No-Till Farming Systems to Reduce Nitrous Oxide Emissions and Increase Methane Uptake

Daniel Plaza-Bonilla, Jorge Álvaro-Fuentes, Jorge Lampurlanés, José Luis Arrúe, and Carlos Cantero-Martínez

Abstract Agricultural activities represent a significant fraction of global greenhouse gas (GHG) emissions to the atmosphere, with a preponderant impact on nitrous oxide (N_2O) and methane (CH_4) fluxes. The production of these gases in the soil is controlled by different soil characteristics (O_2 availability, mineral N content, temperature, pH, organic carbon, and redox potential), which are regulated by climatic conditions and agricultural management practices. In turn, soil physical properties regulate the transport and diffusion of these gases up to the soil surface before they are emitted to the atmosphere. No-tillage (NT) farming, being key for the enhancement of several ecosystem services, can also present benefits in terms of GHG mitigation if combined with best management practices adapted to the specific conditions of NT soils. No-till needs to be managed to maintain adequate soil structural conditions to keep a suitable level of soil aeration, thus reducing the potential for denitrification and methanogenesis. Other management practices such as nitrogen fertilization and irrigation must be oriented towards an efficient use of water and nitrogen, avoiding excesses that lead to high GHG losses. The potential of biological nitrogen fixation must be maximized by adding value to the introduction of legumes into crop sequences.

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19.1 Introduction

No-tillage or no-till (NT) is defined as a "system of planting or seeding crops into untilled soil by opening a narrow slot, trench or band only of sufficient width and depth to obtain proper seed coverage" (Derpsch et al. 2010). No-till is a central pillar in Conservation Agriculture production systems, where its advantages are synergistically maximized when combined with the maintenance of soil cover and the diversification of crop rotations. The implementation of NT presents a large amount of benefits in terms of ecosystem services (Kassam et al. 2009). For instance, when accompanied by an adequate soil cover with cover crops or crop residues, NT significantly reduces soil erosion by water and wind (McCalla and Army 1961; Unger and McCalla 1980), increases soil water holding capacity (Lal 1989), crop water use efficiency (Unger et al. 1991; Fereres et al. 1993; Sayre and Hobbs 2004; Cantero-Martínez et al. 2007), soil surface organic matter (SOM) content (Hobbs 2007), and soil biodiversity (Verhults et al. 2010; Henneron et al. 2015).

In addition to ecosystem services, NT can also have a significant impact on the emission of nitrous oxide (N_2O) and methane (CH_4). Nitrous oxide and CH_4 are powerful greenhouse gases (GHG), with a global warming potential 298 and 25 times greater than CO_2, respectively. The emission of these GHG can be significantly impacted by agricultural activities (IPCC 2013). Tillage systems influence soil N_2O and CH_4 emissions through modifications to the availability of soil substrates (e.g. mineral N, easily decomposable C) for microbial activity, and the soil environment (e.g. porosity, temperature, etc.). The greater amount of water stored under NT systems has been pointed out as a risk for higher N_2O emissions from soils, mainly through enhanced denitrification (Ball et al. 1999) when compared to conventional tillage (CT). However, that aspect is modulated by pedoclimatic conditions, mainly through precipitation, with higher N_2O emissions under NT in wet environments (Skiba et al. 2002), but a lack of difference between tillage systems, or even lower N_2O emissions under NT, in semiarid areas (e.g. Plaza-Bonilla et al. 2014a). Tillage effects on CH_4 emissions have been less widely covered by the literature, possibly due to the smaller magnitude of these emissions on the global warming potential of agriculture in upland soils, although as shown by Hütsch (2001) in a thorough review, the use of reduced tillage systems would be a positive practice to enhance CH_4 oxidation by soils.

During the last three decades, extensive research has been carried out in many areas of the globe to (i) quantify the role played by agricultural practices in the emission of GHG by soils; (ii) identify the most promising practices and cropping

Fig. 19.1 Soil N_2O and CH_4 emissions quantification. From upper left and clockwise (i) detail of barley (*Hordeum vulgare* L.) cropping in a semiarid Mediterranean area under no-tillage (plot on the left) and conventional tillage (plot on the right) during a greenhouse gas emission measurement campaign; (ii) a polyvinylchloride ring delimiting the sampling area; (iii) gas sample extraction with a polypropylene syringe; (iv) gas sample storage in a borosilicate vial; (v) soil sampling for the determination of ancillary variables (moisture and mineral N); and (vi) gas chromatography system equipped with an electrical conductivity detector and a flame ionization detector for the simultaneous determination of N_2O and CH_4. (Photos: Carlos Cortés-Moragrega and Daniel Plaza-Bonilla)

systems to mitigate these emissions; and (iii) calibrate models to check the impact of different scenarios. Obtaining reliable data entails the study of realistic field conditions, during intensive sampling campaigns and following a robust methodology (Fig. 19.1).

Agricultural activities represent around 14% of global GHG emissions (IPCC 2013), a value that can be reduced under NT farming systems provided best management practices adapted to the specific conditions of NT soils are adopted. Helgason et al. (2005) analyzed a large dataset covering field experiments located in Canada and found greater N_2O emissions associated to the use of NT in humid regions, while the opposite was observed in arid regions. For all of that, as warned by Snyder et al. (2009), it cannot be taken for granted that a change from CT to NT will mitigate the overall emission of GHG of a given cropping system. This chapter discusses the idiosyncrasy of NT farming systems in relation to GHG emissions according to different pedoclimatic conditions, with special emphasis on soil structure, and provides different mitigation measures aimed at reducing N_2O emissions and increasing CH_4 uptake.

19.2 Impact of Soil Type and Climate on Methane and Nitrous Oxide Emissions

Soil N_2O and CH_4 production occurs during different processes involved in soil N and C cycles. Nitrification and denitrification are the two main processes controlling the production of N_2O, and CH_4 is an end product of the anaerobic decomposition of soil organic carbon (SOC). Furthermore, in the presence of oxygen, soil CH_4 can be oxidized by the action of methanotrophic bacteria. All these reactions are directly controlled by soil characteristics and climate conditions.

Soil nitrification depends on the quantity of ammonium and oxygen present in the soil since it is an aerobic process mediated by autotrophic ammonia-oxidizing bacteria. Denitrification is produced under anaerobic conditions by a broad group of heterotrophic microorganisms (Smith 2017). Accordingly, soil oxygen availability is a major driver of production and emission of N_2O from soils, and commonly evaluated using measures such as water-filled pore space (WFPS) (Linn and Doran 1984). Linn and Doran (1984) observed that at 60% WFPS maximum aerobic microbial activity occurs, but above this threshold anaerobic conditions limit aerobic microbial activity. Consequently, N_2O production from nitrification declines at a WFPS >60%. However, soil N_2O from denitrification is mostly produced at 70–80% WFPS as an intermediate step of N_2 production. As WFPS approaches 100%, however, highly reducing conditions can develop, which favor the complete reduction of nitrate to N_2 (Butterbach-Bahl et al. 2013). Accordingly, the main N_2O production pathway depends on the soil water regime. For example, in arid and semiarid areas, it is generally assumed that soil nitrification dominates over denitrification as the main N_2O production pathway (Galbally et al. 2008).

The WFPS is mostly controlled by soil moisture and soil physical properties. Soil moisture is directly affected by climate, which regulates precipitation and crop evapotranspiration. Greater soil water availability usually leads to greater N_2O emissions. For instance, in a simulation of cumulative N_2O emissions in winter arable crop rotations covering a water deficit gradient under Mediterranean climate, Plaza-Bonilla et al. (2017) found an exponential increase in soil N_2O emissions (from 0.2 to 3.8 kg N_2O N ha^{-1} $year^{-1}$) with increasing water availability (from 300 to 1000 mm). Similarly, in a meta-analysis for Mediterranean conditions, it was estimated that cumulative soil N_2O emissions depend on the annual precipitation recorded (Cayuela et al. 2017). In this last study, areas with annual precipitation <450 mm emitted 0.4 kg N_2O N ha^{-1}, but when the annual precipitation was >450 mm emissions reached 2.3 kg N_2O N ha^{-1} (Cayuela et al. 2017).

Compaction also tends to reduce soil aeration, with greater decreases in oxygen availability occurring the greater the degree of compaction. Denitrification in compacted soils may thus be complete (and produce N_2) or incomplete (and produce N_2O) affecting the emission rates of soil N_2O (Ball 2013). Similarly, soil texture and soil drainage may also influence soil N_2O emissions. Fine-textured soils and poor drainage favor higher soil N_2O emissions compared to coarse-textured and well drained soils in which more soil aeration is expected (Rochette 2008). For instance, in an experiment with 13 different soils in Scotland, soil N_2O emissions were positively related to soil bulk density and clay content (Skiba and Ball 2002).

Another soil property with a significant impact on soil N_2O emissions is pH. It has been observed that soils with low pH emit more N_2O compared to soils with high pH at a similar level of N inputs (Wang et al. 2018). Although the process behind the controlling effect of pH on soil N_2O production is still not clear, it has been observed that during denitrification N_2O reductase could be affected by low soil pH, increasing the N_2O:N_2 ratio (Wang et al. 2018). In soils with high salt content, inhibition of N_2O reductase has also been observed with a concomitant increase in soil N_2O production and emission rates (Yu et al. 2019). Furthermore, soil salinity can reduce soil respiration, favoring the accrual of SOC and, thereby, the increase in soil N_2O emissions by increasing substrate availability for heterotrophic microorganisms (Yu et al. 2019).

Soil CH_4 production is mainly controlled by soil O_2 availability, pH, redox potential, and mineral N content. Net CH_4 emissions from agricultural soils take place under anaerobic conditions, as found in rice paddies, where methanogenic bacteria use organic carbon compounds (Le Mer and Roger 2001). In contrast, oxidation of soil CH_4 occurs via the activity of methanotrophic bacteria (Le Mer and Roger 2001). Accordingly, soil O_2 availability is also the major driver of CH_4 emissions from soil. It is known that in many conditions both methanogens and methanotrophs are simultaneously active in soils and the dominance of one or the other determines whether the soil acts as source or a sink for CH_4. Soil texture may directly affect soil O_2 availability and thus the production and/or consumption rates of CH_4 in soils. Compared to sandy soils, clay soils are expected to more easily develop anaerobic conditions and thus soil CH_4 production (Plaza-Bonilla et al. 2014b). However, some studies have observed that the ability of clay particles to strongly protect SOC from microbial attack may hinder methanogenesis (Le Mer and Roger 2001). Another soil property that controls the production and emission of soil CH_4 is organic C availability. The addition of C inputs (e.g. crop residues) increases soil CH_4 emissions in paddy soils (Liu et al. 2014). The results of a global meta-analysis performed by these last authors concluded that straw return compared to its removal doubled the amount of soil CH_4 emitted in paddy soils due to i) the provision of increased substrate to methanogenic microorganisms; and ii) the decrease in soil O_2 concentrations due to increased soil respiration. Also, pH is a driver for CH_4 dynamics in soil. Methanogens are sensitive to pH variations (soil pH close to neutrality is the most appropriate for CH_4 production) whereas methanotrophs show higher tolerance (Le Mer and Roger 2001).

Temperature also has an indirect effect on both N_2O and CH_4 emissions both due to its impact on the activity of N_2O and CH_4 producing/consuming organisms, and due to its general impact on soil respiration, which can affect microbial oxygen demand and thus soil oxygen concentrations. Increasing N_2O emissions with increasing soil temperatures have been reported in several field and laboratory studies (e.g. Dobbie and Smith 2001). In general, there is a positive correlation between the increase of temperature and the increase of N_2O emissions in the range of temperatures normally measured in the field. A threshold of 11 °C was suggested by

Stanford et al. (1975), below which denitrification rate sharply decreases. Denitrifying activity has also been observed to increase between 4 and 37 °C (Braker et al. 2010) while nitrification decreases as temperature falls from 20 to 5 °C (Russell et al. 2002). However, Powlson et al. (1988) found that denitrifiers in a temperate English soil reduced nitrate at lower temperatures than did denitrifiers in a subtropical Australian soil, with a sharp increase between 5 and 10 °C in the temperate soil. Likewise, in the cool climate of Northern Ireland, Smith et al. (2012) reported very large N_2O emissions from N-fertilized grassland at soil temperatures of 10–11 °C. In other words, microorganisms are able to adapt to their own environment (i.e. soil thermal regime), which makes it difficult to define a universal temperature function. Furthermore, it is possible to observe significant N_2O emissions in cold environments and during freezing and thawing periods. In such climate conditions where the topsoil of both forest and arable soils remains frozen during part of the winter, a significant amount of total annual emissions may occur within a brief period after thawing. The main reason is the development of favorable conditions to stimulate anaerobic microbial activity (Kim et al. 2012).

Temperature has also a large but variable influence on CH_4 emission from soils (Bartlett and Harris 1993). Methane emissions depend on CH_4 production, consumption, and transport. Of these processes, methane production has been found to be the most temperature sensitive and variable (Segers 1998). Methane production increases with increasing temperature, with an average optimum around 35 °C (Baldock et al. 2012). Low soil temperatures reduce CH_4 production by decreasing the activity of methanogens, but also that of other bacteria involved in methanogenic fermentation (Le Mer and Roger 2001). Dryland agricultural soils are a net sink for CH_4 due to their dominant oxidative condition (Dalal et al. 2008). Temperature effects on CH_4 consumption are less significant than those related to CH_4 production (Dunfield et al. 1993). However, several field and laboratory studies have demonstrated that rates of soil CH_4 uptake increase with increasing soil temperature due to the temperature sensitivity of the underlying enzymatic process (Luo et al. 2013).

19.3 Soil Structure and Its Role in Greenhouse Gas Transport and Diffusion

The transport of gases through the soil profile has a major impact on both GHG production and emission as it determines the rate at which O_2 enters the soil and the rates at which GHGs are emitted from the soil. Although the driving forces for gas transport are concentration and/or pressure gradients, the ease with which gases move through the soil is also related to pore space configuration and continuity. Other characteristics of soil structure that enhance gas transport processes are stability (ability to retain its arrangement) and resilience (ability to recover structural form through natural processes) (Kay and Angers 1999). Soil water content also plays a critical role as it affects the amount of soil pore space available for gas transport.

Soil structure and soil water content can be modified by management practices, especially tillage and irrigation (Moreno et al. 1997; Murray and Grant 2007; Plaza-Bonilla et al. 2013; Lampurlanés et al. 2016). Tillage increases soil porosity compared to NT, but this increase is temporary. Besides, the pores in tilled soils tend to be unconnected and the soil surface is prone to sealing. This results in lower infiltration rates that reduce soil water content, but can also reduce gas diffusivity and emissions to the atmosphere. On the other hand, NT soils, although generally with lower porosity, have a more stable and resilient structure, with more continuous and interconnected porosity. However, they can often have a greater water content than CT soils, which can reduce the air-filled pore space and hence gas diffusivity.

Soil structure characterized by stable, resilient, and interconnected soil pores will facilitate O_2 transport through the soil, favor CH_4 uptake and reduce N_2O production via denitrification. Rainfall and irrigation events will increase soil water content and consequently reduce air-filled pore space. The ability of the soil structure to transport water to deeper layers will determine the time needed to recover aerated conditions. No-tillage, vertical tillage, and inversion tillage are from more to less likely to create such conditions (Lampurlanés et al. 2016).

Once N_2O is produced, restrictions on its transport and the maintenance of anaerobic conditions will favor its reduction to N_2. Inversion tillage, which buries crop residues, enhances N_2O production at sites deeper in the soil profile. However, in NT or vertically tilled soils, N_2O production occurs at or near the surface, which favors its release to the atmosphere (Ball 2013). Infiltration of water can transport and trap N_2O in the subsoil (Clough et al. 2005), increasing the likelihood of conversion to N_2, but N_2O can also be released again as the soil dries, or through the plant by transpiration (Chapuis-Lardy et al. 2007). These processes are more likely to occur in NT or vertically tilled soils.

19.4 Main Characteristics of No-Till Farming Systems Influencing CH_4 Uptake and N_2O Emission

No-tillage is based on the absence of soil disturbance and crop residue maintenance, which protect the soil surface against the impact of rainfall drops, contribute to soil structural stability and enhance water infiltration and water storage. This situation positively affects O_2 availability, pH stability, soil organic carbon, and biological activity. In water-limited environments (rainfed drylands), this greater water availability can increase biomass production, SOM content, and soil biological activity, which are beneficial for the reduction and uptake of CH_4. However, under humid or irrigated conditions, NT can lead to an excess of water in the soil, promoting N_2O and CH_4 emission. In these environments, however, drainage can be improved by incorporating deep rooted crops into rotations to improve subsoil structure. Improvements in drainage have been observed in some studies, for instance, Lampurlanés et al. (2001) observed greater root system development at depth under NT compared with CT.

Tillage reduction also affects soil mineral N content. Higher intensity tillage promotes SOM mineralization and the release of mineral N, which can increase denitrification and nitrification and thus N_2O release (Doran 1980; Christensen et al. 1994). In some NT soils, lower levels of soil mineral N are also found due to a higher crop-N uptake when NT enhances yields, and this can reduce the levels of N_2O emission per unit of yield produced (Barton et al. 2016).

Several authors have observed soil compaction when NT is adopted (Ehlers et al. 1983; Franzluebbers et al. 1995; Unger and Jones 1998), although the degree of compaction is dependent of soil characteristics such as texture and structure, soil moisture content, and the management practices of the cropping system. Under NT, poorly structured, moist soils, heavy machinery use, and flood irrigation can reduce soil aeration and increase GHG emissions (Ball 2013). However, in some situations, the improvement of soil structure under NT is also observed when NT is maintained over the long term (Plaza-Bonilla et al. 2013). Because of this, the maintenance of NT over time should be considered as a potential strategy for reducing GHG production and emission from soils.

No-tillage also affects soil temperature and, consequently, soil N_2O and CH_4 emissions, due to its impact on moisture content and crop residue cover (Gupta et al. 1983). The higher the soil moisture content the more difficult it is to warm the soil, which influences crop development, microbial activity, and hence GHG emissions. Crop residues also shade the soil surface, which affects its temperature. Taking into account these factors affecting soil warming or cooling, different soil temperature dynamics arise between summer and winter cropping in NT systems. In summer-fall to winter cropping under NT conditions, soil temperatures are high after summer and tend to decrease over time. However, crop residues in NT systems shade the soil and prevent more heat escape than in CT systems (Santiveri et al. 2003). In winter to summer cropping, the soils under NT are colder and wetter than under CT. Warming these NT soils is more difficult because crop residues shade the soil and reduce solar radiation. Then soils tend to be colder under NT (Baeumer and Bakermans 1973), with the possible consequent effect on the dynamics of N_2O and CH_4 emissions.

19.5 Mitigation of Greenhouse Gas Emissions Under No-Till Farming Systems

19.5.1 Management Strategies to Minimize N_2O Emissions

The interaction between the availability of mineral N, principally NO_3^-, and the level of moisture in the soil are the key regulating mechanisms for N_2O emissions (McSwiney and Robertson 2005). Therefore, in agricultural production, modification of N fertilization and irrigation practices has the greatest potential to minimize N_2O losses. It is well known that soil N_2O emissions follow an exponential increase when N inputs increase to exceed crop needs (Shcherbak et al. 2014). Therefore, the optimization of N fertilizer management through the “4R” approach, using the right rate, right source, right timing, and right placement has been recommended to decrease soil N_2O emissions. The reduction of N rates according to crop needs and taking into consideration (i) the availability of soil N; and (ii) the potential mineralization of soil N during crop growth, is also key to reduce N_2O emissions. In addition, the use of the different 4R strategies in combination is expected to have a greater impact than a single one. For instance, Venterea et al. (2016) tested the last hypothesis, quantifying the impact of applying N fertilizer in three split applications when combined or not with changes in N source and rate on N_2O emissions under maize (*Zea mays* L.) production. They failed to observe reduction in N_2O emissions when N fertilizer splitting was not combined with other strategies. Differently, the split of N fertilization combined with the use of inhibitors and a reduced N rate was able to reduce N_2O emissions by 20–53% (Venterea et al. 2016). Therefore, the combination of strategies devoted to improving crop N use would entail greater mitigation of N_2O emissions compared to a single strategy.

Another key strategy to reduce N fertilization needs in crop production is the introduction of legumes into crop rotations, as sole crops, cover crops, or intercrops (Jensen et al. 2012). With the introduction of legumes, biological N_2 fixation reduces the need for high rates of N fertilizers. This not only reduces the direct emission of N_2O from agricultural soils, but also the indirect emission of GHG thanks to the energy savings related to fertilizer manufacture. Although the literature on the impact of agricultural practices on GHG emission has significantly grown during the last three decades, the focus on the impact of crop diversification on NT-based farming systems has been minor. However, lower N_2O emissions under legume cultivation compared with non-legumes have been reported in NT farming (Schwenke et al. 2015), although other studies found no differences (Guardia et al. 2016). On the other hand, a few other authors have analyzed the impact of introducing legumes on soil N_2O emissions at the crop rotation level, with contrasting results. For instance, Bayer et al. (2015) assessed the impact of tillage and maize-based crop sequences including a grass (oat, *Avena strigosa* Schreb) or legume (vetch, *Vicia sativa* L.) cover crop on soil N_2O emissions in a subtropical Acrisol of Southern Brazil. The authors observed an interaction between tillage and crop sequence on soil N_2O emissions. Thus, while oat/maize and vetch/maize cropping systems presented similar emission under CT, NT increased N_2O emission in the vetch/maize sequence (Bayer et al. 2015). Similarly, in a cropping systems study covering two types of tillage (CT and NT) and five NT cover crop-based cropping systems carried out on an Ultisol of Brazil, Bayer et al. (2016) found greater N_2O emissions under legume cover crops when using NT compared with CT. However, these emissions were offset by soil CO_2 sequestration. Therefore, full consideration of NT impacts on GHG emissions should consider the entire C footprint of the system, including direct and indirect emissions.

The use of irrigation to overcome water limitations for crop production modifies soil water content, increasing WFPS. To mitigate GHG emissions irrigation must be oriented towards improved water use efficiency, avoiding moisture excesses and

Table 19.1 Mean soil nitrous oxide emissions and water-filled pore space (WFPS) over a maize cropping season under different sprinkler irrigation strategies

Irrigation management	WFPS (%)	Soil N_2O emissions (mg N_2O N m^{-2} day^{-1})
DH	40.3	1.75
DL	41.0	2.03
NH	51.1	3.37
NL	49.7	2.85

Data from: Franco-Luesma et al. (2019)

D daytime irrigation, *N* nighttime irrigation, *H* high irrigation frequency, and *L* low irrigation frequency

matching consumptive water demand (Snyder et al. 2009). This is especially important during periods of N fertilizer application and/or high soil temperatures, as it occurs during cultivation of summer crops such as maize. The use of water saving techniques such as drip irrigation can be useful to mitigate soil N_2O emission in cropping systems. However, their profitability, as well as their acceptance by farmers in arable cropping are doubtful (O'Brien et al. 1998). Besides the amount of water applied with irrigation, the timing of irrigation can also influence the amount of N_2O emitted. In this regard, in a maize monoculture experiment in NE Spain comparing different sprinkler irrigation strategies, Franco-Luesma et al. (2019) measured the impact of irrigation time (daytime vs nighttime) and frequency (low vs high) on soil N_2O emissions during two maize cropping seasons. The authors found a 29% increase in the emissions when irrigating at night compared with daytime irrigation during one of the cropping seasons studied as a result of greater WFPS (Table 19.1). However, the application of water at night reduced water losses and led to 11% greater maize yield. The authors did not observe any difference between irrigation frequencies on N_2O emissions (Franco-Luesma et al. 2019).

Given the benefits of NT on soil water storage and conservation (Lampurlanés et al. 2016), it has long been claimed that the use of this technique could entail greater production of N_2O in soils, although variable responses have been reported in the literature depending on the pedoclimatic conditions and the duration of NT (van Kessel et al. 2013). The creation and maintenance of an adequate soil porosity and pore continuity can significantly reduce the amount of anaerobic microsites where denitrification can take place. For instance, in a NT chronosequence carried out in a rainfed semiarid area of NE Spain, Plaza-Bonilla et al. (2013) observed a significant increase in SOC and water-stable macroaggregates at the soil surface (0–0.10 m) with increasing the number of years under continuous NT management. Therefore, the benefits of NT on soil structural stability could reduce the susceptibility of NT farming systems to emit N_2O, at least under some pedoclimatic conditions, over time. For instance, in the same area of NE Spain, Plaza-Bonilla et al. (2014a) evaluated the impact of tillage and N fertilization strategies on soil N_2O emissions in two field experiments differing in the number of years since their establishment (3 and 15 years). After 2 years of GHG measurements they observed a different impact of tillage systems on soil N_2O emissions depending on the duration of NT. In the long-term experiment they found no differences in soil N_2O

emissions between CT and NT (0.137 and 0.141 mg N_2O N m^{-2} day^{-1} under CT and NT, respectively), while lower emissions of N_2O were found under CT compared with NT in the short-term experiment (0.139 and 0.205 mg N_2O N m^{-2} day^{-1} under CT and NT, respectively) (Plaza-Bonilla et al. 2014a). In this regard, van Kessel et al. (2013) carried out a meta-analysis on 239 direct comparisons between CT and NT or reduced tillage to study the impact of tillage on N_2O emissions. Contrary to what was expected, across all comparisons the use of NT or reduced tillage did not increase the emission of N_2O. Indeed, a reduction of N_2O emissions was found when using NT or reduced tillage in the long-term experiments (> 10 years) especially in dry climates. A similar finding was observed by Six et al. (2004) when studying different datasets from the literature. They found that soil N_2O emissions were higher under NT than CT independently of the climate in the first 10 years after the adoption of NT. However, in those situations where NT had been continuously maintained over 20 years, N_2O fluxes were lower in NT compared with CT in humid climates and similar between tillage systems in dry climates. In humid climates and under some soil textures, soil compaction entails a greater risk of N_2O emissions when performing NT. For instance, Ball et al. (1999) measured the impact of tillage (CT, based on mouldboard plough and NT) and different levels of soil compaction on N_2O emissions on a cambisol and a gleysol in Scotland. The presence of soil compaction enhanced soil N_2O emissions under NT in periods with heavy rainfall, mainly due to reduced gas diffusivity and air-filled porosity.

Besides the impact of NT farming on soil N_2O emissions *per se,* it is also important to consider the productivity component to fulfill the demand of food, feed, and fiber when assessing the impacts of this technique. In this context, van Groenigen et al. (2010) proposed the yield-scaled N_2O emissions (YSNE) indicator in which soil N_2O emissions are standardized to a unit of production (such as a N uptake, kg of grain, etc.). For instance, in a combined experimental and modelling approach, Plaza-Bonilla et al. (2018) estimated the YSNE of 18 years of barley production under CT and NT management practices and with varying N fertilizer rates in a field experiment located in a rainfed Mediterranean area of NE Spain. The authors found 2.8–3.3 times lower YSNE when using NT compared with CT, mainly due to similar N_2O emissions between tillage systems and greater barley grain yield production under NT. In that case, the benefits of NT in soil water conservation played a major role on crop productivity under harsh rainfed conditions. Differently, in a colder and wetter environment of the Upper Midwest USA cropped to maize, Venterea et al. (2011) found 50% greater YSNE under NT compared with CT, due to lower grain production under NT as a result of lower soil temperatures in spring which delayed crop growth.

19.5.2 Management Strategies to Maximize CH_4 Uptake

Soil CH_4 oxidation can be enhanced under NT. The maintenance of an adequate soil structure is important to maximize soil CH_4 uptake by methanotrophic bacteria, given its positive impact on soil aeration. For instance, in compacted soils the ability of these bacteria to oxidize atmospheric CH_4 can be reduced by 30–90% (Mosquera et al. 2007). Similarly, Ball et al. (1999) warned about the deleterious impact of long-term soil structural damage on soil CH_4 consumption pointing out that CH_4 oxidation may be better preserved by NT compared to CT based on mouldboard plough. As suggested by Hütsch (1998), continuous NT would support methanotrophic bacteria thanks to improved gas diffusion and better soil structural conditions. Moreover, the same author pointed out the adverse effect of CT on the methanotrophic community, which could also explain the reduction of CH_4 uptake usually found under this tillage system (Hütsch 2001). As an example, in a comparison of soil samples (0–0.12 m depth) from two sites in Germany, including a field site with CT and NT, a set-aside treatment, and an undisturbed forest site, Hütsch (1998) measured 4.5–11 times greater CH_4 oxidation rates under NT compared with CT.

As is the case with N_2O, long-term NT also positively affects CH_4 uptake by soils, through its impact on soil structure and on the recovery of soil methanotrophic community. In this regard, Jacinthe et al. (2014) found an increase of CH_4 oxidation with longer duration of NT when working in different fine textured Alfisols of the US Midwest. Similarly, Plaza-Bonilla et al. (2014b) found a differing effect of NT duration (3 vs 15 years) on CH_4 oxidation in two rainfed field experiments devoted to barley production in NE Spain. Twofold higher cumulative CH_4 uptake was found under NT compared with CT in the long-term experiment (15 years) while the contrary was observed in the short-term one (3 years).

The use of irrigation can also influence CH_4 production in soils and its emission to the atmosphere. For instance, different irrigation strategies can be implemented to mitigate GHG emissions. In this regard, in an experiment carried out in the semiarid North China Plain, Wang et al. (2016) observed greater net CH_4 uptake when using surface drip irrigation compared with flood irrigation under winter wheat (*Triticum aestivum* L.) production. In rice (*Oryza sativa* L.) cultivation, novel aerobic production systems using sprinkler irrigation present a significant potential to reduce CH_4 emissions while lowering the water footprint compared with the traditional flooded systems. For instance, in a field experiment carried out in SW Spain, Fangueiro et al. (2017) studied the impact of different tillage systems (CT vs NT) and irrigation types (sprinkler vs flood irrigation) on CH_4 emissions under rice production. Over 3 years, the use of sprinkler irrigation reduced by 99% the emissions of CH_4 compared with the traditional flood irrigation system. Interestingly, while no differences between tillage systems were found on CH_4 emissions under sprinkler irrigation, greater emissions of this gas were observed under CT compared with NT under flood irrigation (Fangueiro et al. 2017), presumably due to the enhancement of organic C decomposition through tillage when incorporating rice residues in the soil. In this regard, to mitigate GHG in rice paddy cultivation it is recommended to compost the rice straw, incorporate the straw some time in advance to flooding period, and use it as a substrate for energy production (Jakrawatana et al. 2019).

Nitrogen fertilization also has a profound effect on the ability of methanotrophic bacteria to oxidize CH_4, particularly when using ammonium-based fertilizers. Therefore, N fertilization strategies should be applied to avoid the inhibition of CH_4 oxidation. The presence of ammonium in the soil inhibits the process of oxidation as a consequence of its competition with CH_4 for CH_4-monooxygenase, an enzyme which catalyzes the oxidation of CH_4 (Bédard and Knowles 1989). Consequently, it is common to observe a net emission of CH_4 just after ammonium N fertilizer application in upland soils (e.g. Plaza-Bonilla et al. 2014b). Tillage can also stimulate the decomposition of soil organic N, which releases NH_4^+, reducing soil CH_4 uptake during a transient period following tillage operations (Peterson et al. 2019). Furthermore, tillage can also interact with N fertilization type reducing CH_4 uptake depending on the type of fertilizer used. For instance, in a maize-soybean (*Glycine Max* (L.) Merr.) rotation carried out in Minnesota (USA) Venterea et al. (2005) reported higher CH_4 uptake when using reduced tillage in combination with urea ammonium nitrate or broadcasted urea, compared with the use of CT, while the contrary was observed when using knife-injected anhydrous ammonia.

19.6 Conclusions

No-till does not mitigate N_2O emissions and increase CH_4 uptake in all pedoclimatic conditions and cropping systems. To maximise its potential in terms of GHG mitigation, NT must be maintained over the longer-term to allow the improvement of soil structural conditions that enhance porosity and aeration, reducing the risks for denitrification and methanogenesis. Moreover, to mitigate GHG emissions, NT farming must be combined with appropriate management practices with a particular focus on improved N fertilization, the enhancement of biological nitrogen fixation in crop rotations, and agronomically sound irrigation management practices. When adequately adapted to the idiosyncrasy of each farm, the potential of NT to mitigate GHG emissions, as well as to enhance other ecosystem services while improving farming-related aspects, justifies the use of NT in a broad range of conditions.

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Chapter 20
Soil Carbon Sequestration as an Elusive Climate Mitigation Tool

Brian Murphy

Abstract The depletion of soil organic carbon (SOC) under agricultural practices is estimated to have contributed 78 Pg of carbon (C) to global emissions. As this depletion occurred with more exploitive land management practices there is the potential to re-sequester some C as SOC with the widespread adoption of more restorative, conservative land management practices. This chapter explores the potential for the re-sequestration of C as SOC through biomass inputs from photosynthesis and lower rates of decomposition of SOC. The upper limit of sequestration is set by the net primary productivity (NPP) at a general value of 2–8 Mg C ha^{-1} $year^{-1}$ depending on soil type and climate. The measured changes in SOC stocks associated with changes to more restorative and conservative land management practices are commonly in the vicinity of 0.2–0.8 Mg C ha^{-1} $year^{-1}$. These rates are very dependent on the climate, soil type and details of land management practices. The success of changes in land management practices to sequester C is confounded by potentially high transaction costs, uncertainties in the achievable C sequestration rates, and low returns for sequestered C. The chapter emphasizes that C sequestration, under agriculture also has the objectives of meeting the objectives of soil security, especially food and water security.

Keywords Soil carbon sequestration · Land management · Rates · Biomass · Decomposition · Net primary productivity

20.1 The Global View

The total pool of carbon in the soil is about 1500 Pg (Petagrams = 10^{15}gms = giga tones), compared to 770–800 Pg in the atmosphere and 500 Pg in terrestrial vegetation. Since the industrial revolution, it is estimated that emissions of CO_2 into the

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atmosphere due to land use change (136 Pg) combined with emissions from the burning of fossil fuels (270 Pg) (Lal 2004), have increased concentrations in the atmosphere from 280 ppm by volume in 1750 to 412 ppm in 2019 (NASA). Of this increase, the depletion of soil organic carbon (SOC) under agriculture is estimated to have contributed 78 Pg of C. Many suggest that this depletion was associated with exploitive land management practices and that there is potential to re-sequester this lost SOC by using more restorative and conservative management practices (Lal 2004; Govers et al. 2013; Stockmann et al. 2013). It has been estimated that agricultural soils could potentially sequester 30–60 Pg over 25–50 years (Lal 2004). On an annual basis this would decrease fossil fuel emissions by 7–8 Pg C year^{-1}. However, the question is how realistic and practical are the opportunities for SOC sequestration?

20.2 The Biophysical Boundaries - Mechanisms That Can Change the Amount of SOC in Soils

20.2.1 General Model

The term “soil carbon sequestration” implies transferring atmospheric CO_2 into long-lived pools and storing it securely so that it is not immediately remitted (Lal 2004).

The amount of SOC in a soil is dependent on the net accumulation of carbon from inputs and outputs and can be estimated by the equation:

$$\begin{aligned}\mathrm{SOC}_{\mathrm{stocks}} = {} & \text{Plant biomass}_{\mathrm{soc}} - \text{Decomposition}_{\mathrm{soc}} + \text{Amendments}_{\mathrm{soc}} \\ & + \text{Deposition}_{\mathrm{soc}} - \text{Erosion}_{\mathrm{soc}} - \text{Leaching}_{\mathrm{soc}} \ldots\ldots\ldots\end{aligned} \tag{20.1}$$

This equation implies that any environmental, geomorphological, soil or land management factors that influence the terms in the model will also influence SOC stocks. Some of the simple definitions of land management practices such as conservation tillage, direct drilling and stubble retention (SR) cannot take into account all the factors that control the inputs and outputs of SOC and this has been a cause of considerable uncertainty and variability the effects of land management on SOC sequestration.

For example, the amount of plant biomass produced is strongly affected by climate, soil type, land form position and land management, so all these factors will affect SOC stocks. Similarly, decomposition will be strongly influenced by climate, especially temperature and to a lesser extent by moisture. The influence of each of these factors will produce definite measurable spatial patterns in SOC stocks across the landscape and each will operate at different scales.

Erosion and deposition sequences and profiles will also be strongly influenced by climate, soil type, landform and land management (Chappell et al. 2012; Elliott et al. 1997; Kravchenko et al. 2006). The removal of soil from upper and midslope areas and deposition in lower slope areas can also result in the redistribution of SOC in the landscape (Kravchenko et al. 2006; Hartemink et al. 2017), while some SOC is lost altogether if it is removed into streams (Hartemink et al. 2017).

Soil amendments (composts, biochar) can be added to soil, although their ability to increases SOC stocks is variable (Quilty and Cattle 2011). Much depends on the chemical and physical characteristics of the organic amendments.

20.2.2 Carbon Inputs

20.2.2.1 Plant Biomass – Inputs from Photosynthesis

The sequestration of carbon from the atmosphere into the soil is achieved through photosynthesis. The upper limit of SOC sequestration by plant activity is thus set by ecosystem net primary productivity (NPP), which varies depending on climatic conditions (rainfall, evaporation and temperature) and soil fertility (Scurlock and Olson 2002; Bolinder et al. 2007; Huston and Wolverton 2009; Mahli et al. 2011; Haverd et al. 2013; Monteith 1972, 1977). Although, it is unlikely any land management systems would approach potential NPP because of limitations in the processes of converting accumulated plant biomass into SOC, NPP give an indication of the upper limits of how much carbon can be sequestered as SOC. The NPP for a range of climate/vegetation/soil zones are shown in Table 20.1.

The plant material produced during photosynthesis can contribute to SOC in the following ways:

- *Above ground plant litter* can be incorporated into the soil through natural processes such as bioturbation (e.g. earthworms), self-mulching soil surfaces, or mechanical disturbance (e.g. tillage). The amount of above ground biomass produced by plants can be estimated from the yield of agricultural crops using the Harvest Index (HI) (ratio of harvested product to total above-ground biological yield). The values for HI range from 0.2–0.25 for canola to 0.3–0.4 for wheat, up to 0.45 for sorghum (Unkovitch et al. 2010). In the absence of tillage, SOC tends to accumulate at the surface, as demonstrated by de Moraes Sa and Lal (2009).
- *DOC* enters the soil when water-soluble C in litter sitting on the surface is moved into the profile during leaching. The amount of SOC that is held as DOC is typically small, about 1% (Allen et al. 2010). However, over time the total amount of SOC moved as DOC can be substantial (Naff and Asner 2001). Neff and Asner (2001) suggest about 25% of total SOC in a soil profile can come from the carbon added as DOC. It is also possible for the DOC flux to be completely removed from the soil depending on the desorption and adsorption properties of the soil mineral fraction (Kindler et al. 2011).
- *Root material and rhizodeposition* is increasingly recognised that an important contributor to SOC (Rees et al. 2005; Kuzyakov and Schneckenberger 2004;

Table 20.1 Estimates of net primary productivity for different ecosystems and locations, including Australia. As a perspective, the annual global emissions from fossil fuels and cement manufacturing are about 7.8 Pg C year^{-1} (Ciais et al. 2013)

Environment/ ecosystem	NPP above and below ground (Mg C ha^{-1} year^{-1})	Area of Ecosystem (10^6 ha)	Total sequestration potential (Pg C year^{-1})
Huston and Wolverton (2009) - global			
Tropical forest	7.83–2.51	1750–1760	13.70–21.90
Temperate forest	6.25–7.79	1040	6.50–8.10
Boreal forest	1.90–2.34	1370	2.60–3.20
Tropical savanna and grasslands	5.40–6.41	2250–2760	14.90–17.70
Temperate grasslands and shrublands	2.98–3.93	1250–1780	5.30–7.00
Croplands	3.04–5.04	1350–1600	4.10–6.80
Deserts and semi-desert	0.51–1.26	2770–4550	1.40–3.50
Tundra	0.89–1.79	560–950	0.50–1.00
Wetlands	12.29	350	4.30
Haverd et al. (2013) – Australia			
Tropics	6.57 (5.11–8.03) max 14.60	39	0.256 (0.199–0.313)
Savanna	4.02 (4.75–3.29) max 14.60	162	0.651 (0.533–0.770)
Warm temperate	7.30 (6.50–8.10) max 14.60	32	0.234 (0.208–0.259)
Cool temperate	7.67 (6.57–8.76) max 10.95	34	0.261 (0.223–0.298)
Mediterranean	4.02 (3.21–4.82)	55	0.221 (0.171–0.265)
Desert	1.10 (0.73–.46)	439	0.483 (0.320–0.641)

Lorenz and Lal 2005; Martinez et al. 2016; Gross and Harrison 2019; Schmidt et al. 2011). The amount of root material added to the soil is dependent on plant biomass production and the root:shoot ratio. Kuzyakov and Scheckenberger (2004) estimated that 20–30% of carbon assimilated by photosynthesis in cereals and 30–50% in pasture grasses is translocated below ground into roots and the rhizosphere, with the total C addition estimated at 1.5–2.2 Mg of C ha^{-1} year^{-1} based on a grain yield of 6 Mg ha^{-1} or a biomass of 12 Mg ha^{-1} for a cereal crop. A pasture with 6 Mg ha^{-1} of biomass is estimated to allocate a similar amount of carbon below ground. A large proportion of this root deposition occurs in the top 0.5 m of the profile (Williams et al. 2013; Fan et al. 2016).

Within the soil profile there are different zones where different processes dominate the formation of SOC (Eyles et al. 2015; Lorenz and Lal 2005). Closer to the surface, litter has a dominant role, while deeper in the soil root turnover and rhizodeposition becomes more important. Some evidence suggests there is an upper vegetation zone (< about 0.5 m), where SOM is affected primarily by plant inputs (above- and belowground), climate, microbial activity and physical aggregation and is prone to destabilization. In a lower zone (> ~0.5 m) SOM inputs from the vegetation zone are controlled primarily by mineral phases and chemical interactions, resulting in more favourable conditions for SOM persistence (Cagnarini et al. 2019; Murphy et al. 2019).

20.2.2.2 Inputs of Carbon from Soil Amendments

Soil amendments such as composts and biochar can also be added to soil to increase SOC stocks, although their ability to increase SOC stocks is variable (Quilty and Cattle 2011). This is partly because compost rates need to relatively high to have significant effects. For example, Gibson et al. (2002) in a review of a range of trials, suggest that 50–150 Mg of compost (recycled organics) are required to produce an increase of 1% SOC. The chemical and physical characteristics of the organic amendments also play a role in how effective the amendment is in increasing SOC.

Materials that are readily decomposed, have a low C:N ratio and are low in resistant organic compounds, such as lignins and phenolic compounds, may add less carbon to the SOC because they are readily mineralised (Abbasi et al. 2015). However, others suggest that high-quality litters (low C:N ratio and low lignin contents) enhance microbial biomass, and in turn, microbial residues, which dominate the relatively stable mineral-associated SOM and ultimately increase SOM more than low quality litter (Castellano et al. 2016). A priming effect can also occur when low quality litter is added to the soil, as microorganisms decompose existing SOM to release nutrients, and the addition of low-quality litter can actually reduce SOM levels (Fontaine et al. 2004). Compost amendments can also have indirect effects on SOC stocks by adding nutrients that increase plant biomass production and that can increase the activity of soil fauna, such as earthworms (Tisdall 1985), and soil flora.

It is also essential that the accounting process reflects the “whole of life” costs and benefits attributed to the ameliorants added to the soil. So, not only is the carbon sequestered as SOC included in the accounting process but also the fossil fuel consumption involved in the manufacture, transport and application of the soil ameliorants (Gibson et al. 2002).

20.2.3 Rates of Decomposition

Decomposition of SOC, which is driven by biological activity, is strongly influenced by climate (especially temperature and moisture) and soil aeration (Parton et al. 1987; Sierra et al. 2012: Huang et al. 2018). As a general rule, decomposition rates are most rapid under conditions of higher temperature, adequate moisture and in the presence of oxygen and visa versa. For example, in a review of Australian data on SOC stocks, Valzano et al. (2005) showed, supported by Hoyle et al. (2016), that 12.8 °C and 17.4 °C were potentially critical values for the storage of SOC. At less than 12.8 °C, SOC stocks were higher as decomposition rates become slower. At more than 17.4 °C SOC stocks were lower due to increased decomposition, indicating that in warm to hot temperatures with adequate moisture it is difficult to accumulate SOC stocks without large inputs of biomass.

Decomposition can also be affected by the degree SOC is protected from decomposition by the soil matrix (Hassink 1997; Krull et al. 2001; Baldock and Skjemstad 2000). The amount of protection is related to the amount of silt plus clay, which binds with SOC and protects it from decomposition, and thus soils of fine texture can store more SOC than sandy ones (Carter et al. 2003). More aggregated soils also tend to contain more SOC as aggregates protect SOC from decomposition (Tisdall and Oades 1982). There are a number of models to predict decomposition rates (Corbeels 2001; Sierra et al. 2012; Janik et al. 2002; Parton et al. 1987; Liu et al. 2016; Campbell and Paustian 2015; Kwiatkowska-Malinda 2018). In these models the decomposition of soil organic matter is estimated using different decay rates for different SOM fractions. Usually, there are four active pools of decomposable plant material pool (DPM), a resistant plant material pool (RPM), a microbial biomass pool (BIO) and a humified organic matter pool (HUM). A fifth pool is included to account for inert carbon or char material (IOM). Each pool has its own characteristic decomposition rate constant in a first-order process in which the soil carbon is converted to CO_2, BIO and HUM. The rates of decomposition are then driven by temperature and moisture or rainfall inputs.

20.3 Land Management Impacts on SOC Stocks

20.3.1 Characterizing Land Management Systems

Some previous classifications of land management practices have been based largely on tillage operations and residue or stubble management (Murphy et al. 2011; Chenu et al. 2018; Reicosky 2015; Lal 2015). These land management practices included minimum tillage and reduced tillage (MT), no-till or direct seeding (NT) and stubble retention (SR). These were a very useful classification for evaluating erosion risk, especially when comparing them to conventional tillage (CT) and stubble management. However, given the mechanisms that control C inputs and outputs for SOC, the classification of land management practices based on tillage and residue management alone is not likely to be directly related to the relative inputs and losses of SOC. This is even less likely given that management practices are becoming less differentiated and those practices involving a large number of tillage operations and earlier and severe stubble burning are becoming less common (Llewellyn and D’Emden 2009; Pratley and Rowell 2003; Hamblin and Kyneur 1993). It is perhaps not surprising that so many conflicting reports and results about the effects of various cropping practices on SOC sequestration are presented (Baker et al. 2007; Hermle et al. 2008; Luo et al. 2010; Hoyle et al. 2016; Murphy et al. 2011; Conyers et al. 2015; Reicosky 2015; Chenu et al. 2018).

The reasons that classifications based on tillage operations and residue management are not completely effective in predicting the likely implications of land management on SOC levels are, summarised below and in Table 20.2.

Table 20.2 Land management options to sequester SOC (Hoyle et al. 2016; Murphy et al. 2011; Chenu et al. 2018). Details of land management options to consider, requires a more detailed description of land management option than then the previously used minimum tillage (MT), no-till (NT), and conventional tillage (CT)

Biomass production
Has the biomass productivity been restricted by the following?
a. Nutrient deficiencies
b. Agronomic management factors (poor emergence, poor performing plant varieties, etc.)
c. Soil physical condition
d. Soil chemical imbalance
e. Heavy grazing.
Annual average temperature
As a general indication
a. <12 °C high biomass production and low decomposition rates – Build-up of soil carbon is likely
b. 12 to 17 °C – Moderate biomass production and decomposition – Potential for land management to have an effect on increases in SOC.
b. >17 °C high decomposition – High decomposition rates – Build-up of soil carbon less likely
Average annual rainfall
As a general indication under NT management
a. <450 mm – SOC build-up less likely
b. 550–700 mm –highest build-up of SOC likely
c. >1000 mm – SOC may not accumulate
Tillage type
a. Inversion deep (>0.2 m) – Likely to result in large amounts of organic matter at depth – Unlikely to have build-up of SOC under NT – Interaction with climate is also expected.
b. Inversion shallow (<0.2 m) – SOC maintained largely near surface – Likely to have SOC build up under NT.
c. Tyne deep (>0.2 m) – Likely to result in moderate amounts of SOC at depth – Likely to have a build-up of SOC under NT
d. Tyne shallow (<0.2 m) – SOC maintained largely near surface – Likely to have SOC build up under NT
Stubble management
a. Stubble burnt in CT treatment (early burn) – Likely to have SOC build-up under NT
b. Stubble burnt in CT treatment (late burn) likely to have small SOC build-up under NT
c. Stubble incorporated in CT treatment – Effect will depend on tillage type and climate
Initial soil carbon levels
If initial SOC is high, modified cropping practices may not increase SOC. however, in degraded soils with low levels of SOC there can be a high potential to sequester carbon.
These values and guidelines are tentative and are largely indicative rather than being definite values

1. Biomass input is a major determinant of the amount of SOC in a soil. Many factors other than tillage operations or residue management can influence biomass production. Biomass production and can be restricted by nutrient deficiencies; agronomic management factors such as poor emergence, or poor performing plant varieties; limiting soil physical conditions such as limited rooting depth, low water holding capacity, high soil strength or high bulk density; or soil chemical limitations such as soil acidity or soil salinity.
2. Annual average temperature and rainfall can influence the potential for biomass production.
    (a) <12 °C - high biomass production and low decomposition rates can lead to a build of SOC, regardless of tillage operations and residue management (Hemle et al. 2008).
    (b) >17 °C - high decomposition rates make it difficult to build up SOC regardless of land management (Valzano et al. 2005; Hoyle et al. 2016)).
    (c) <450 mm annual average rainfall - low biomass production and it is difficult to build up SOC regardless of land management (Murphy et al. 2011; Hoyle et al. 2016).
    (d) 550–700 mm annual average annual rainfall - possible to increase SOC under some land management options e.g. MT, NT and SR (Murphy et al. 2011; Hoyle et al. 2016).
    (e) Tillage practices vary widely in their depth and volume of soil disturbed and the energy and aggressiveness applied to the soil (Reicosky 2015; Chenu et al. 2018; Murphy et al. 2011).
    (f) The burning of stubble can also vary in its effects depending on the timing and heat of the burn.

Overall, when trying to identify land management options to increase SOC there is a need to consider the mechanisms that control the inputs and losses of SOC more carefully than have perhaps been applied in the past using the somewhat simplified land management classes of CT and NT (see Table 20.2 and Murphy et al. 2011; Hoyle et al. 2016; Conyers et al. 2015).

20.3.2 Global Perspective

It has been proposed that SOC should be increased by 0.4% or 0.6 Mg C ha^{-1} year^{-1} across the globe, the 4 per mille program, to offset fossil fuel emissions (Minasny et al. 2017). This will be challenging given many areas (deserts, tundra and mountains) have limited capacity to sequester C. As well, the expected C sequestration rates for changes in land management are often less than 0.6 Mg C ha^{-1} year^{-1} (see Table 20.3). Although, Minasny et al. (2017) point out that higher rates of C sequestration are often expected where soil carbon stocks are initially lower (<30 Mg C ha^{-1} 0.3 m^{-1}).

Table 20.3 Estimated rates of soil carbon sequestration under a range of land management changes

***Expected in early years of adoption before SOC reaches equilibrium levels**

Source	**Land management change**	**Depth (m)**	**Rates of change in soil carbon stocks t C ha^{-1} yr^{-1}***
Chan et al. (2011)	Crop to crop/pasture rotation (33% pasture)	0–0.3	+0.22
	Crop to crop/pasture rotation (50% pasture)	0–0.3	+0.25
	Crop to crop/pasture rotation (67% pasture)	0–0.3	+0.40
	Pasture to crop	0–0.3	-0.28
	Pasture to improved pasture	0–0.3	+0.76
Sandeman et al. (2010)	Crop rotation (crop/pasture rotation)	0–0.15	+0.20
	Stubble retention	0–0.15	+0.19
	Reduced tillage	0–0.15	+0.34
	Crop to pasture	0–0.15	+0.30–0.60
Read et al. (2012)	Rehabilitation of scalded lands using water ponding	0–0.3	+>1.0
Freibauera et al. 2004	Zero tillage/no-till	0–0.3	+0.3, +0.4
	Perennial grass	0–0.3	+0.6
	Composting	0–0.3	+0.4
	Crop residue	0–0.3	+0.7
	Arable to woodland	0–0.3	+0.3–0.6
	Arable to grassland	0–0.3	+1.2–1.7
Stockmann et al. 2013	South Africa – CT to NT	0–0.3	zero
	Brazil CT to NT crop rotation with legume	0–0.3	0.04–0.88
	Canada CT to NT	0–0.3	0–0.16
	Canada wheat fallow to NT	0–0.3	0.20–0.30
	Canada annuals to perennials	0–0.3	0.45–0.77

In a major review, Stockmann et al. (2013) identified the potential for sequestration at the global scale and reported rates of 0–1.53 Mg C ha^{-1} year^{-1}, but commonly in the range of 0.2–0.70 Mg C ha^{-1} year^{-1} for changes in cropping systems and converting cropping systems to pastures. West and Post (2002) concluded that the expected C sequestration rates were 0.57 Mg C ha^{-1} year^{-1} for changes in cropping management to NT and 0.2 Mg C ha^{-1} year^{-1} for the introduction of rotations. The adoption of NT in a "Systems Approach" on a global scale was advocated by Lal (2015), who identified a range of land management options with potential to sequester 0.047–1.7 Mg C ha^{-1} $year^{-1}$. For Europe, Freibauera et al. (2004) identified cropping management, pasture management and the additions of composts as having the potential to sequester C at rates ranging from 0.05–0.8 Mg C ha^{-1} $year^{-1}$r.

Some authors have questioned whether the suggested SOC sequestration rates are realistic. Freibauera et al. (2004) identified a range of potential limitations or side-effects to C sequestration, including increased risk of disease, increased use of industrial fertilisers, and reduced flexibility in farming operations in order to achieve permanence for C sequestration. The potential for NT practices to result in lower yields was identified by Pittlekow et al. (2015) and the lower yields and biomass would make it difficult for these cropping practices to sequester carbon in comparison to CT practices. The need to measure SOC stocks to depths greater than 0.3 m has also been highlighted, as gains in the surface of the profile under NT can be accompanied by losses at depth in some environments (Baker et al. 2007; Meersmens et al. 2009).

In assessing overall greenhouse gas emissions, the use of industrial fertilisers (particularly N and P) to maintain or increase plant productivity to sequester SOC is a limitation. It has been estimated that to produce and transport 1 kg of inorganic N fertiliser will emit 1.2 kg of C (Schlesinger 2000). With rates of N fertiliser of 15–90 kg N ha^{-1} $year^{-1}$ required to maintain productivity, even in dryland cropping, this can negate much of the C sequestered and emphasises the need for N-fixing legumes as a rotation within cropping systems. Cropping and pasture systems that require the addition of lime to prevent acidification can also increase emissions and reduce the impact of any carbon sequestered. For example, the reaction of 1 Mg ha^{-1} of lime ($CaCO_3$) can release 0.12 t of C, while the mining, crushing and transport of the lime can emit 0.435–0.5 Mg C ha^{-1}. This compares to the estimated amount of sequestered carbon of 3.9 Mg C ha^{-1} over 26 years (Conyers et al. 2015).

One further limitation of sequestering carbon as SOC is the potential to increase the emission of N_2O and CH_4, and there is a need to also assess emissions of these gases when estimating the full impact on global warming potential of land management practices (Sainju 2016). In more moist soils, NT can increase N_2O emissions, although this can be offset by adding lime (Garcia et al. 2016). In drier soils, NT can often have lower N_2O emissions (Tellez-Rio et al. 2018).

Overall, on a global basis there is definite potential to sequester C as SOC, but this potential needs to be assessed on a site by site basis taking into consideration the many factors that can influence overall global warming potential of land management change.

20.3.3 Australian Experience

Sandeman et al. (2010) identified that the major management options for sequestering carbon under Australian cropping systems could be divided into:

1. Maximising efficiency of water and nutrient use;
2. Increasing productivity by irrigation and fertilization;

3. Stubble management, including incorporation and SR;
4. Minimising soil disturbance and adopting reduced or NT;
5. Including pasture phases in the cropping system; and
6. Using organic materials from offsite sources.

These authors concluded that the measured rates of sequestration (relative between treatments) from across Australia were: inclusion of rotation 0.20 Mg C ha^{-1} year^{-1}; change from SB to SR 0.19 Mg C ha^{-1} year^{-1}; and adoption of NT v CT 0.34 Mg C ha^{-1} year^{-1}.

The potential for conservation agriculture, including NT and pasture rotations, to increase carbon levels in soils, or reduce the rate of loss of SOC has also been reported by several other authors (Luo et al. 2010; Dalal and Chan 2001; Grace et al. 2010; Chan et al. 2010, 2011). Using a set of 30 trials, Luo et al. (2010) demonstrated that: changes in SOC occurred on average across all soil types and climates; changing from CT to NT increased SOC by 9.6%; changing from SB to SR increased SOC by 10.2%; and changing to NT + SR increased SOC by 16.4%. However, the actual changes varied depending on soil type and climate, with the largest increases observed on non-Vertosol soils and where rainfall was 500–600 mm. There was also evidence that it was essential to ensure adequate amounts of N were available to obtain the increases in SOC. This is consistent with a wide range of studies showing the need to ensure adequate nutrients are available to obtain increases in SOC (Kirkby et al. 2011; Tipping et al. 2016; Mouginot et al. 2014).

It should also be noted that since pasture phases were introduced into Australian cropping systems in the 1950's and 1960's and NT in the 1980's and 1990's, a substantial amount of the potential increases in SOC from may have already been made (Llewellyn and D'Emden 2009; Pratley and Rowell 2003; Hamblin and Kyneur 1993).

20.3.4 Importance of Initial Levels of SOC Stocks

One of the most important criteria affecting a site's ability to sequester SOC is its current level of SOC relative to the equilibrium SOC capable of being sequestered by a particular management practice in that particular environment. This has been recognised in a number of publications (Yang et al. 2013; Minasny et al. 2017; Chenu et al. 2018), although it is perhaps not so widely recognised at the policy level. It has been proposed that programs to sequester SOC should concentrate on degraded lands that have low SOC levels that can be increased by restoration through improved land management practices (Govers et al. 2013; Dalal et al. 2004). An example of this has been the restoration of scalded areas in semi-arid areas of south eastern Australia using water ponding methodologies. This has been shown to successfully sequester 7–10 Mg C ha^{-1} over 5–10 years (Read et al. 2012).

20.3.5 *Context of Sequestering SOC and Interaction with Other Objectives of Sustainable Land Management*

In addition to greenhouse gas reduction, sequestering SOC is important to improve soil condition and health and improve the performance of ecosystem functioning (Loveland and Webb 2003; Murphy 2015; Lal 2004, 2013, 2015). By improving the condition of the soil, the soil is more likely to provide the basic needs of food security, water security, energy security, climate change mitigation and adaptation, human health and well-being and preservation of biodiversity (McBratney et al. 2014).

As a consequence, the objective of soil carbon sequestration is not solely the net removal of C from the atmosphere. It is a potential gain if land management practices can be developed that achieve the objectives of soil security with reduced emissions or some C sequestration, even though in absolute terms the amount of C in the soil has not increased or emissions reduced. There is perhaps scope for the application of the concepts such as emission intensity (emissions/unit product) as proposed by Henry et al. (2012) in which the objective is to produce food with the lowest greenhouse gas footprint achievable while giving consideration to other environmental impacts.

20.4 Mechanics of Carbon Trading and Policy

While there appears to be a potential for SOC sequestration, this potential has been largely unrealised from a carbon trading perspective (Amundson and Biardeau 2018; Smith et al. 2005). This may be because of:

1. High transaction costs, including the cost and difficulty of measuring SOC stocks, establishment of contracts, and the potential need for new equipment – although new methods for measuring SOC based on near-infra-red (NIR)and mid-infra-red (MIR) spectrophotometry and improved statistical methods are being developed (Viscarra – Rossel et al. 2016; de Gruitjer et al. 2016);
2. The uncertainties around the potential rates of SOC sequestration under different land management practices and the longevity of this C storage should land management subsequently change;
3. A lack of technical support to land holders to implement management options and enter into contracts;
4. Farmer resistance to the intrusion of privacy and government regulations, combined with scepticism about the realities of anthropic climate change; and
5. Low returns for sequestered carbon. The current trading price for carbon in Australia is \$12 per Mg of CO_2 equivalent which is equivalent to about \$ 44 Mg^{-1} of C (CER 2019). Given that the maximum rates of sequestration appear to be 0.5–1.0 Mg C ha^{-1} $year^{-1}$, this gives an income based on carbon trading of \$22

to \$44 ha^{-1}. This is a smaller return than can be achieved by cropping or even grazing animals.

One potentially useful approach to establishing a program for soil carbon sequestration is to have credible data available about the existing soil carbon stocks, and the expected soil carbon stocks under a proposed land management change. If the existing level of SOC stocks are close to the expected level of soil carbon stocks, then the potential for carbon sequestration to occur is minimal and vice versa (Lorimar Ward et al. 2013; Murphy et al. 2012). However, this does introduce the policy dilemma that the program may be rewarding land holders who have degraded their soils and run SOC levels down in the past.

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Part IV
Economic and Social Impacts

Chapter 21
Economic Assessment of No-Till Farming Systems

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Abstract This chapter considers the nature of the economic benefits of no-till (NT) based farming systems. The focus is on capturing the full costs of resource inputs associated with NT in achieving desired changes in productivity and resource use efficiency. We attempt to place available evidence within a broader framework of economic assessment. We draw on experience in advanced agricultural economies and present insights from India and Sub-Saharan Africa, and highlight the nature of externalities that may contribute to the deviation of likely private and social benefits in the technology change associated with NT adoption. Implications for policy and planning for guiding the process of NT adoption and enhancement are mooted.

Keywords Private and social benefit · Technology adoption · Adoption drivers

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21.1 Introduction

No-till (NT) farming characteristically involves placing seeds directly into undisturbed soil that has retained the crop residue from the previous crop, and has evolved to a farming system that incorporates diversification of crop species, including the inclusion of legumes. Initially introduced to overcome productivity decline in traditional conventional tillage (CT) owing to soil degradation, its wider adoption after the 1990s was supported by the awareness of environmental sustainability prompted by the Brundtland Commission report, *Our Common Future*, in 1987. To date, its major attraction relates to its credentials for conserving soil, water and energy resources and time saving in diversified farming systems involving repeat cropping.

The lowering of tillage intensity and residue retention under NT works to enhance soil organic matter, contributing to better soil structure, water-holding capacity and microbial activity. Hence, compared to CT, which involves several passes of tillage and exposes the soil to moisture depletion, NT systems could offer both yield and cost advantages (Scott and Farquharson 2004). This is particularly so in environments where soil moisture availability could constrain crop and pasture production. Drawing on this advantage, more recently NT has been presented as a climate-smart agricultural practice for its potential to mitigate net greenhouse gas emissions by increasing soil organic carbon (SOC) and its potential to limit yield variability under exposure to climate variation. More broadly, the reduced time required for land preparation under limited tillage systems have triggered innovations in cropping system design, permitting increased land use intensity through rotational cropping of grain, oilseed and pulse crops. Hence, from the farmers' perspective, NT can be regarded as an alternative to traditional CT farming. However, specific requirements such as seeding equipment, greater precision associated with timing of planting and agronomic care may mean that NT is more suited to high-end farmers who have entrepreneurial skills and abilities to commit a higher level of farm business management.

Overall, the benefits of NT have been widely accepted to be an advantage in production systems prone to seasonal moisture deficits, such as in Australian grain growing areas, the US Mid-West and Canada, and in some parts of Europe. High levels of reported adoption rates of this technology in these locations may lend support to the relative advantages noted above, although those advantages will not always translate to economic benefits. In particular, because this technology represents a package of practices designed to transform conventional industrial farming, various contextual factors that influence the level of adoption will determine the resultant net economic benefit. On the other hand, as this volume claims, NT as a technological innovation has been associated with an increased reliance on herbicides and mechanical inputs for direct seeding. As such, these practices and associated land use change involve spillovers, or externalities, within and beyond farm gate, and create deviations in the level of economic benefits to individuals undertaking practice change, as well as to the wider community.

Although efforts have been made to introduce NT systems into other locations, such as India, Africa, and China, their adoption remains patchy. Like other technological innovations, its impact will vary across locations given the variable nature of farming. Hence the economic assessment of NT systems ought to focus on the objectives of farming, the policy and institutional settings of the operating environment, and the nature of limiting variables in a given context, which collectively influence the optimal combination of inputs to production and the benefits drawn from the outputs generated. Such a comprehensive focus is required to better understand the efficiency of alternative production processes and the conditions under which that efficiency can be sustained.

Such a comprehensive assessment of the economic merits of NT systems is beyond the scope of this chapter. Rather, this paper examines the issues surrounding the need to develop estimates of the full costs of NT, and to identify some of the subsequent issues we expect will arise once reliable measures of full costs are known. We believe it is of wider economic and social benefit that some of these broader and longer-term issues are highlighted at this mature stage of development of NT technologies.

Our objective is to place available evidence within a broader framework of economic assessment and highlight the nature of information asymmetry that may contribute to the deviation of likely private and social benefits. Implications for policy and planning for guiding the process of NT adoption and enhancement are mooted. Because of its extreme reliance on herbicides for weed control, and in particular the use of non-selective herbicides such as Glyphosate, comments are made about the risks faced by NT systems due to potential health and environmental hazards and the potential for social pressure to limit chemical use in agriculture. Finally, we draw attention to the care that must be taken in attempts to extend these systems into developing countries where adequate safeguards cannot be guaranteed and the likely costs may outweigh benefits, and risk making societies poorer. Implications for research and development in seeking context-relevant technologies and the need to strengthen policy and institutional settings to safeguard compliance and promote risk mitigation are noted.

21.2 Conceptual Framework

21.2.1 Optimizing Resource Use in Production – Private and Social Costs (Opportunity Costs)

At a very general level, economic *production* is the physical conversion of inputs into outputs, which are used either for final consumption or as an input to further production. More specifically, production includes any transformation adding to the *social total* of some desired goods at the expense of a reduction in the amounts of others. The economic value of a particular parcel of land or unit of labor may be defined in terms of its *resource cost, opportunity cost, or social cost*. These can be described as what it might cost to buy, the value of what it might produce, or the value that it might contribute to society. An economically efficient allocation will ensure that the resource cost, opportunity cost, and the social cost of inputs to production are equal at the margin, and, in turn, are equal to the price of inputs. Hence economic rationale in optimizing resource use in production is to equate prices to social (marginal) costs, the full cost of producing an additional unit, to obtain the most efficient allocation of resources.

Farmers make production decisions based on the costs they incur and the price they expect to receive for their produce. The farmers' costs are considered private, as they include the costs a farmer pays to purchase capital equipment, hire labor, and buy materials or extension advice. In some situations, fertilizer may be subsidized by the government, or water may be provided below its supply cost. Such incidences create direct subsidies, encouraging farmers to produce a greater level of output; depending on the context that may or may not be socially desirable. While analysts often focus on such direct subsidies, indirect subsidies such as unaccounted externality costs of production are ignored in discussions and hence escape economic analysis.

No-till systems seek to balance objectives of using land and other inputs to generate a marketable output, say wheat, against objectives of conserving farm capital for alternative uses, which may include retirement, or transfer to natural uses. In such choices, it creates a basis for economic benefits in terms of income to input providers, value added opportunities for purchasers of wheat, and benefits to final consumers of food derived from wheat produced.

The prices paid in competitive markets, like in Australia, usually reflect its true benefits. However, inadvertently, NT also creates environmental costs in terms of land and water degradation and health hazards that may arise from chemical use. Such costs are not reflected in farmers' income or the costs to consumers, and are hence borne by the public who suffer from consequences such as losses in biodiversity or by paying for restoration of habitat and polluted waterways. As these costs are external to the producers and consumers, they are considered external costs.

In a competitive market, considering only the private costs in economic assessments will understate the true costs, especially if the production process also creates external costs. The full social costs are equal to:

$$\text{Private Costs} + \text{External Costs} = \text{Social Costs} \tag{21.1}$$

In considering the economic benefits of alternative technologies, the difference between these two elements of cost constitutes the net social benefit, or the true measure of economic value.

$$\text{Social Benefit } (\text{Price}) - \text{Social Costs} = \text{Net Social Benefits} \tag{21.2}$$

21.2.1.1 Environmental Benefits of NT

A factor behind the development of NT was the minimization of environmental costs, such as soil erosion and high runoff volumes. Reduced tillage also means less fuel use and hence less greenhouse gas emissions. Also, enhanced organic matter retention may, under some circumstances, lead to reduced carbon emissions. Collectively, these improvements could lead to positive external impacts. Economic analysis thus needs to account for such expected benefits and the formula above can be refined to:

$$\text{Price} + \text{Environmental \& Health Benefits} - \text{Social Costs} = \text{Net Social Benefits} \quad (21.3)$$

Given the associated uncertainty, the above estimates would need to be developed taking the probability of success under different contexts into account. Formal methods of economic assessment thus need to be used to derive meaningful estimates.

21.2.2 *Why It Matters*

Including the full costs of production and consumption in economic assessments has broader implications. The graphical representation of (marginal) costs and demand for a product, say wheat, in Fig. 21.1 can help understand these implications. The intersection of the demand curve (the downward sloping line) and marginal cost curve (OSC) represents the socially efficient rate of output (OS) in a competitive market. The social price of such a commodity ought to be P_S. Whereas, when the market price (P_P) does not include external costs, the output produced will rise to O_P. Farmers receive a lower price and consumers pay less at the market. But as citizens they bear the additional cost, represented by the vertical distance between

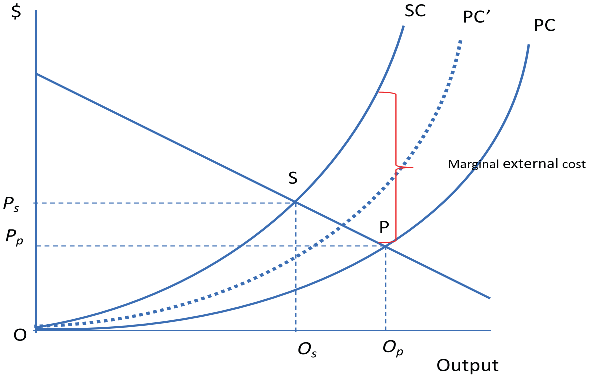

Fig. 21.1 Cost implications of technology choice. (Adapted from Field and Field 2016, p. 69)

the OSC and the marginal private cost curve (OPC). Moreover, if the commodity so produced is exported, the low price of imports will dampen the incentives for local producers of substitute goods, and encourage the exporting country to produce more of the commodity, while exposing the society to greater costs.

However, if the technology package incorporated within NT does incorporate substantial reduction in net externality costs, it may represent the situation depicted in OPC´ in Fig. 21.1. The output will fall, the price would rise and the social cost would be lower. The higher prices may discourage consumption, creating opportunities for producers of substitute goods. It then represents a net improvement in social welfare benefiting all participants. Reaping the full benefit, however, requires that the producers of substitute goods also follow improved practices that create lower social costs. Essentially, improved practices need to be adopted across agriculture to enhance net benefits.

21.3 The Economics of No-Till Farming

21.3.1 Smallholder Production Systems in Sub-Saharan Africa

This section provides a thorough review of the empirical studies conducted on the economics of NT[1] in Sub-Saharan Africa (SSA) using farm household survey data. More specifically, the review sheds light on the impacts of NT on gross margin, production risk, and input demand along with the drivers of its adoption.

21.3.1.1 The Impact of NT on Gross Margin and Production Risk

Although NT systems have the potential to improve productivity, this alone is not sufficient to encourage adoption by smallholder farmers as improved crop productivity could be accompanied by increased input use and hence higher costs of production. Thus, when investigating the impact of NT systems, gross margin analysis, which captures the revenue advantage over cost of production, has been used as a predictor for assessing its diffusion potential. Teklewold et al. (2013) investigated the impact of NT on gross margin using data on maize plots in Ethiopia and found that NT could lead to a higher gross margin than CT. Adopting both NT and crop diversification (CD)[2] could further increase gross margins.

Another important outcome variable that smallholder farmers would consider when they make adoption decisions is the impact of NT on production risk. Generally, smallholder farmers are risk averse and would be reluctant to adopt productive, but high-risk, agronomic practices. However, they would be happy to

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[1] NT here refers to either zero or single pass/plough while leaving crop residues on the plot.

[2] Crop diversification here refers to spatial or temporal diversification of maize with legumes.

trade-off higher yields for more secure outcomes. Hence, a new agronomic practice that could reduce production risk, particularly downside risk, would be preferred even if it does not lead to higher gross margins.

Kassie et al. (2015b) examined the impact of NT adoption on production risk using data on maize plots from Malawi and observed that adopting NT instead of CT decreases production risk. The risk premium—a monetary value that a farm household is willing to pay in order to avoid the uncertainty and secure the same average return—was positive and increased when NT was adopted in combination with CD. The risk premium derived from adopting CT + CD was ~9% of the mean yield.

21.3.1.2 The Impact of NT on Input Use

As NT adoption includes a range of possible agronomic practices, the impact of NT on input demand hinges on farmers' resource endowment, institutional settings that impact services and costs, and agroecological settings. Hence, the direction of its impact is often an empirical question relating to the operating context.

In SSA, where market imperfections and high transaction costs are pervasive, the impact of NT on input demand has important effects on the likelihood of its adoption by smallholder farmers. For instance, given the thin rural labor markets, a farm household with low labor endowment could fail to take up NT if it demands higher peak labor use compared to CT. Similarly, a credit-constrained farmer is less likely to adopt NT if it requires higher chemical fertilizer and herbicide use, even though this might increase gross margin or reduce production risk. This is particularly so for the many smallholders who are largely subsistence farmers. Any cash outlay would become a large constraint when the surplus available for sale is low and produce markets are poor and unorganized.

Tessema et al. (2018) studied the impact of NT on input demand (chemical fertilizer, herbicide, and female and male labor demand), using data on maize plots from Ethiopia. The econometric analysis shows that while NT increases chemical fertilizer and herbicide use, it reduces female and male labor demand.

21.3.1.3 Drivers of NT System Adoption

The rate of NT and associated CD adoption can vary widely between countries, as illustrated in Fig. 21.2. Many factors can contribute to low and uneven rates of NT adoption in the region. As discussed above, gross margin and production risk are important drivers. This implies that socioeconomic and biophysical conditions of smallholder farmers that influence gross margin and production risk are the key underlying factors behind NT adoption (see example, Teklewold et al. 2013; Tessema et al. 2016).

The adoption of NT could also be impacted by whether it has been promoted in conjunction with CD as this could affect its impact on gross margin and production

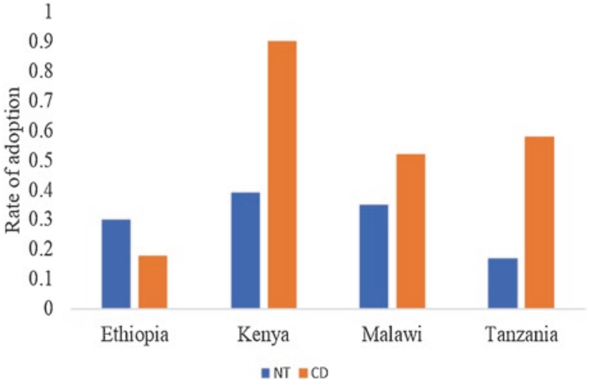

Fig. 21.2 The rate of NT and crop diversification adoption in Sub-Saharan Africa. (Source: Kassie et al. 2015a)

risk. Kassie et al. (2015a) studied the interdependence in adoption between NT and CD using maize plots from Ethiopia, Kenya, Malawi and Tanzania. The results show that NT and CD show a positive association in Tanzania, a negative association in Kenya, and no association in Malawi and Ethiopia. Positive associations indicate that the adoption of CD induces the uptake of NT and vice versa, while a negative association indicates that the two practices can substitute for each other. In general, their results suggest that the odds of NT uptake could be further mediated by whether NT is being promoted along with CD, or CD is already part of the farming system.

As stated earlier, the impact of NT on input demand might also have ramifications for its adoption in SSA where market imperfections and high transaction costs are pervasive. Focusing on resource endowment, Teklewolde et al. (2013) investigated factors underlying adoption using maize plots from Ethiopia. Low farm household asset endowment was found to be a key factor that hinders farmers from adopting NT. Essentially, NT demands higher level of input management skills and requires additional outlays, which poor smallholders may not possess.

It is also important to note that the studies above examined the economics of NT at the plot rather than farm household level, and thus fail to evaluate the trade-offs and all key drivers involved in adopting NT and its niche zones for scaling up. For example, crop residues, which are integral to NT, can also be used as livestock feed. A farm household is less likely to adopt NT if crop residues generate higher returns for livestock production, even if it may mean lower return from their cropping enterprise. Jaleta et al. (2013) examined the interdependence of NT adoption and livestock production in Kenya. They found that farmers with a lower livestock endowment stand a better chance of adopting NT and vice versa, possibly because using crop residues for livestock might generate higher return.

While potential benefits, such as higher gross margin or lower production risk, may encourage adoption decisions, lack of information and behavioral anomalies could also be important to the diffusion of improved agronomic practices such as NT. Farmers often follow their neighbors, not necessarily taking all information into account (Tessema et al. 2016).

21.3.2 *Insights from South Asia*

As illustrated in the Africa case study, agroecology and social circumstances significantly influence NT adoption. No-till is regarded as a solution to stubble burning in the Indo-Gangetic Plain (IGP), which extends across eastern Pakistan and northern India to Bangladesh and Nepal. In this region stubble burning can be widespread in rice-wheat production systems and lead to reductions in soil health, and significant environmental and public health issues due to the emission of smoke and particulate matter.

The success of the Green Revolution has seen access to fertilizer, pesticide, and water inputs rapidly increase in the region, resulting in improved regional food security and farmer livelihoods. However, increasing costs of production, shrinking growing windows and market access, and a lack of awareness about alternatives to stubble burning have increased pressure on farmers to burn stubble rather than explore alternatives such as NT.

Despite the existence of NT options for 10–15 years—most notably the Happy Seeder (HS), which can sow wheat into rice stubble with reduced or NT (Fig. 21.3)—farmer adoption rates remain very low. Accurate estimates of adoption are not widely available, although some indicate that uptake could be as low as 0.001%.

In 2017, a study was conducted with 500 farms to explore the reasons for the poor adoption rate across five regions of Haryana, Punjab, West Bengal, Bihar and northern Bangladesh to assess NT adoption drivers in the IGP.

21.3.2.1 Results

A detailed account of the study findings are available in Loch et al. (2018). Major practical barriers to adoption across the IGP include low-to-no practical enforcement of stubble burning bans, weed and pest control concerns, poor seed

Fig. 21.3 A Turbo Happy Seeder zero-till seeding machine. (Source: Sidhu et al. 2015)

germination under NT, a general lack of awareness of technology availability, and limited access to the machinery, spare parts, service, and technical advice. Farmers also held firm perceptions that a clean (i.e. ploughed and stubble-free) landscape was needed ahead of sowing, and did not appreciate that effective planting could be achieved into standing stubble. Further, although extension officers knew about the technology and its potential benefits, they were unable to demonstrate these to farmers in the field to overcome farmer awareness and/or trust issues.

While a lack of farm labor in the region might drive adoption, this was offset by the requirement for trained operators and expertise when using NT technology. Even where custom-hire center businesses were involved, these often lacked practical expertise and access to incentives, which were more commonly targeted at farmers.

The financial barriers to adoption were particularly important. Although farmers' clubs or cooperative business models were viewed quite favorably by financiers and banks, the underlying cost of the machinery—particularly the HS—remained relatively high, creating adoption challenges for farmers. This was despite the presence of subsidy support packages from national and (some) state governments. There was evidence from the study suggesting that in response to the 50% subsidy manufacturers had doubled the purchase price, meaning that the relative cost to farmers remained unchanged. As such, many farmers viewed the subsidy system as corrupt and thus did not engage with it. Figure 21.4 shows the mean adoption rates for Happy Seeder and NT technologies across the IGP region. As expected, HS adoption was highest in the Haryana and Punjab states where manufacturers and dealers are mainly located.

However, farm economics remains the crucial barrier to adoption. A single farmer purchasing and operating a NT machine would not be economically feasible. The technology is used 2–3 times per year and over a very short window of opportunity between crops, which means that for the rest of the season it is not utilised. While custom-hire center business models that allow the use of a machine across multiple farms are more economically attractive, the short operating window means

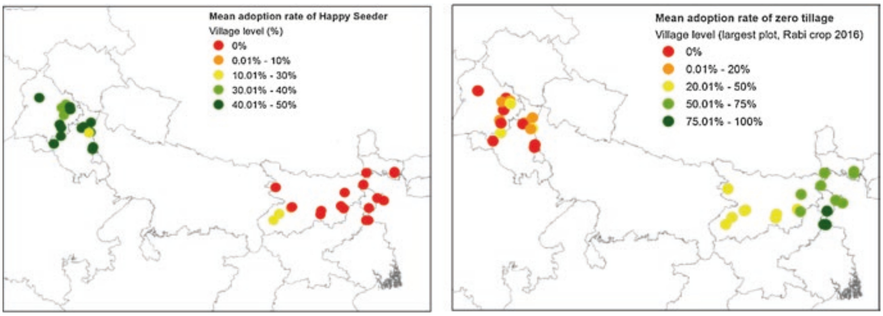

Fig. 21.4 Spatial distributions of Happy Seeder and (generic) NT technology, IGP. (Loch et al. 2018)

that farmers must compete for the service and, if not provided on time, would resort back to stubble burning before the planting window closes.

A comparison of adoption drivers derived from cost of production data across conventionally sown wheat crops and NT/Happy Seeder (HS) sowing practices indicated that NT sowing practices were generally associated with lower individual input costs and total system costs; except for fertiliser, herbicide and fungicides in the NE of India and Bangladesh. Happy seeder users reported lower costs across all categories. Some of these cost differences can be explained by the differences in farm input subsidies across Indian states (e.g. there may be lower fertiliser subsidies in West Bengal, Bihar, which are relatively poorer states), and differences in agro-climatic conditions. The relatively wet, humid, and tropical conditions of north-east India and Bangladesh would require additional costs for fungicide, herbicide. and insecticide applications, and irrigation can be relatively more expensive resulting in farmers avoiding such costs. However, overall the gross margin differences between adopters and non-adopters for both technologies was relatively low; NT adopters reported a 0.5% lower gross margin than non-adopters, although HS users reported a 4.5% higher gross margin. In general, the economic benefits did not appear to offset the considerable costs involved in purchasing, operating, and maintaining the technology for users.

The social benefits from adopting NT technology would include reduced stubble burning, along with lower input costs and sustainable intensification. However, the study found that biophysical concerns surrounding practices like NT were not adequate to motivate increased adoption for a majority of farmers. Claims of increased yields are often anecdotally associated with NT, and a recent meta-analysis has concluded that in terms of temporal stability (i.e. yield benefits over time), a transition to NT practices does prove advantageous (Knapp and van der Heijden 2018). However, farmers, in general, are far-removed from the scientific literature and prefer to gather evidence themselves that clearly demonstrate input savings and yield improvements on their own farms. This is generally near impossible to achieve in the short-term and may be challenging to show even in the longer-term (e.g. soil carbon improvements directly linked to NT adoption).

This case study highlights that while the existing system of cultivation contributes to high social externality costs associated with stubble burning across the IGP region of South Asia, this in itself it has not been a strong driver of adoption of NT practices. Despite potential benefits, the risk-return equation in this case is neutral leading to insufficient transformation by farmers across the IGP. Unless fundamental change is experienced in risk-return trade-offs, social externality costs associated with stubble burning will continue to be borne by the broader society.

21.3.3 Largescale Production Systems

In large scale agricultural production systems in Australia, US, Canada, and parts of Europe, the NT farming system is in a mature phase of development. However, the shift from CT to NT has taken decades to realize and the process of adaption and adaptation to changing circumstances is ongoing (Llewellyn et al. (2012). In Australia, progressive creation of an enabling environment, driven through an aspiration for higher performance and risk management, has been the key feature of success. Demand-induced innovation by farmers and agricultural engineers, enabling agronomic technologies such as herbicides and crop disease resistance, extension processes, and economic influences within a competitive market setting have contributed to this transformative change. The continued search for refinement has also included the incorporation of controlled-traffic farming, remote sensing and climate science technologies, and a strategic approach to risk management based around spatial and temporal diversification, including into off-farm ventures. These activities have been supported through collaborative and on-farm R&D to develop ways to adapt the NT system to suit diverse local farming conditions.

21.3.3.1 Assessing Performance

Wide adoption of NT as an alternative farming approach has led to the consensus that where it is widely adopted, the system is at least as profitable as conventional methods and offers significant nonmonetary advantages, such as preservation of rapidly deteriorating soil or water resources. While a growing body of analyses involving a range of partial to composite measures supports the economic viability of these farming practices, systemwide appraisals using time series analyses or comprehensive comparative assessments that can account for the dynamic forces at play are lacking. This observation has also been made by Pannell et al. (2014), and National Research Council (1989) in relation to assessment of alternative farming systems. While the interest in aspects of environmental sustainability and cleaner production has intensified in recent times, this interest has not translated into systematic studies to assess such credentials.

It is generally believed that farms using the complete NT system (NT + stubble retention + CD) are inclined to have higher yields. Comparison of gross margins also tend to support the general view that they are associated with greater profitability than farms that practice some level of tillage. As suggested in Ibendahl (2016), there are at least two possible explanations for this. First NT could be a superior technology that is both higher yielding and also more profitable. Second, NT producers could be representing a cohort of superior farm managers, which would lead to greater yields and profits. Moreover, it is possible that their entrepreneurial abilities help them choose strategic options that mitigate emerging risks, such as climate variation, and resultant vulnerability to income fluctuations. Therefore, in comparing alternative farming systems, this self-selection bias needs to be accounted for.

However, a key feature of economic assessment that is embodied in farm management advice has been the reliance on partial measures that focus on marginal changes. They are only relevant for decision making under certainty —when individual, social, institutional and natural conditions that govern production and consumption remain unchanged, or are uniform across contexts. When that is not true, as is often the case, the decisions that are based on marginal changes run the risk of deviation from expected outcomes and declining performance over time. It must also be noted that the competing technology 'CT' has itself undergone similar transformation over the past four decades, subjected to similar performance pressures and induced by the same drivers of technological change. Equally, knowledge spillovers between the two sectors are common, and in some cases, the same farmer may undertake both systems as the extent of adoption is largely partial.

Industrywide Performance Productivity analysis undertaken by the Australian Bureau of Agricultural and Resources Economics and Sciences (ABARES) shows that average productivity growth across all broadacre agriculture (that is, non-irrigated cropping and extensive livestock industries) has been ~1% yr.^{-1} for more than three decades. This has been largely due to reduced input use (−0.9% yr.^{-1}), rather than output growth (0.1% yr.^{-1}) (Gray et al. 2014). This may imply that, given a large proportion of farmers in these industries are reported to be engaged in NT-based technologies, their adoption has led more to economizing input use, rather than gaining a yield advantage. That may also imply that the externality load created by these farms may have declined, because externalities are a joint product of input use. These estimates are not corrected for variations in seasonal conditions and the likely impacts of climate change. Such impacts could be substantial (Hochman et al. 2017), as could the impact of other soil limitations (Orton et al. 2018). Incorporating the confounding impacts of these factors in economic assessments is complex and controversial.

Performance parameters themselves are socially determined—as collective and individual consumer preferences progressively change government policy settings and market demand for goods and services. Obviously, technological change has helped farmers meet ongoing performance challenges. The ABARES analysis also points out that productivity growth of cropping specialists averaged 1.5% yr.^{-1} between 1977–1978 and 2010–2011, higher than the rate observed on farms in the beef (0.9%) and sheep (0.0%) industries. Productivity growth also varies considerably across farms, industries, and regions; and productivity growth by itself does not lead to profit growth and farm viability. The Australian dairy industry is a case in point.

Farm Scale Analyses As outlined in Thomas et al. (2007) a range of factors work together in determining farm scale performance under NT. Farmer attitudes and aspirations, machinery conversion or replacement costs, build-up of soil and stubble-borne plant diseases, use of residual herbicides that may limit crop options, dual use of land for grazing and cropping, herbicide resistance, build-up of hard-to-kill weeds, the need for soil disturbance in some situations, and concerns by farmers about the effects of herbicides on the environment and human health are noted as important. Moreover, advancing climate change and associated increase in climate variability and performance risks call for greater flexibility in farming systems to adapt to an uncertain operating environment.

Pannell et al.'s (2014) analysis of farm level economics stands out as they incorporate all the above aspects in their study. The economics are defined broadly to include not just short-term financial benefits and costs, but also the whole-farm management context, constraints on key resources such as labor and capital, risk and uncertainty, interactions between enterprises, and time-related factors such as interest rates and the urgency of providing for the farm family. They confirm the oft-noted fact that, as with other technologies, NT systems can increase or decrease farm profits, depending on the context. They note that favorable contexts include larger farms, more resources, less uncertainty, and longer time horizons. These aspects have been noted in the progress made in NT in developed economies, as are benefits of partial adoption of a subset of components, which can sometimes be superior to full adoption (Stevenson et al. 2014).

21.4 The Drivers of No-Till Farming Future

21.4.1 Largescale Production Systems

In looking forward, as a technology in its mature phase of development in western economies, the priority is for maintaining the efficacy of NT, and especially to find ways to minimize the social costs of individual elements, such as herbicide use. This is particularly so because the observed success factors are highly related to overcoming environmental constraints, mainly moisture, for private benefit (Bellotti and Rochecouste 2014). For example, limited available studies that take account of the full range of costs and benefits suggest that the potentially higher social and private profit of NT over CT could be context specific, and depend on the choice of crop, the local costs of inputs, and the social valuation of environmental benefits. Essentially, the key factors determining the private and social profitability of NT and CT are yields and production costs, rather than environmental performance (Lankoski et al. 2006).

Of particular importance are the growing social concerns over extensive use of herbicides, in particular Glyphosate, due to its potential negative impacts for human health, ecosystems, and agricultural system stability. The public and scientific debate about the use of Glyphosate continues (Danne et al. 2019), as does some successful legal proceedings for compensation. Reductions in herbicide availability have the potential to erode any benefits of NT if its dependence on extensive herbicide use cannot be addressed. Advances in precision agriculture technologies and improved understanding of alternative management options (Rogers et al. 2016) could offer some ways to overcome such challenges. However, there is also a clear role for public policy in setting standards, and for industry in adhering to improved protocols to minimize exposure to future economic and social costs.

21.4.2 Smallholder Production Systems

The challenge in extending the technology set to resource poor settings with limited markets and poor institutional arrangements looms large, and insights drawn from the studies above identify key problems that need to be overcome. The problem of quality, availability, and safe and effective use of herbicides in resource-poor conditions stands out as critical, and hence greater development of appropriate integrated weed management strategies that can be combined with small-scale planters are required. There is also a need to optimize the performance of small-scale planters to suit farmers' needs in different agro-ecological environments. To make better use of developed country experience and the positives associated with NT concepts for small holders, more adaptive research and on-farm evaluation is needed across a diverse range of soils, cropping systems and agro-ecological regions (Johansen et al. 2012).

These include addressing i) participation constraints, such as land fragmentation; ii) capital constraints that makes machine purchases unviable and enhancing private sector participation in providing machinery services; and iii) socially responsible provision of input services generally. Critical assessments such as Pender (2008) and Giller et al. (2009) offer useful insights, as do studies that show the potential for success (Keil et al. 2015; Keil et al. 2019). Additionally, it is also critical that the impact of NT on the landscape and the ecosystem services that underpin agricultural production and livelihoods are taken into account in relevant assessments (Snyder et al. 2016). Accommodating these concerns in socially diverse and spatially heterogeneous farms and farming systems remains challenging (Tittonell et al. 2010).

For instance, technological change and its transfer to developing countries is often portrayed as a critical part of the solution to a resource problem such as climate change, based on the assumption that the transfer of resource-conserving technologies will result in reduced use of natural capital. However, the well-known potential for a rebound effect, where a technological change that is directed to reduce resource use in fact leads to higher use prompted by lower costs, could undermine ultimate outcomes. For this reason, the transfer of resource-conserving technologies without incentives to alter behaviors may not result in desired resource-conservation benefits (Sarr and Swanson 2017). Enablers such as climate information services, in particular, should become part of the solution (Singh et al. 2016).

In considering these challenges, the nature of the production function embedded in NT, which determines the aggregate supply function and the marginal cost of supply and hence the offer price of farm output, becomes the critical lever for change. If the price of inputs is not determined in a competitive market and the market price does not take the full account of externalities, or unpaid costs of resource use, then production functions that incorporate different proportions of inputs will lead to suboptimal resource use. This means the value of output produced will exceed its true social value as the costs of externalities are often borne by society.

Matters become complicated, because agriculture is often considered a special case as the demand for food is price inelastic, meaning the basic demand for sustenance is price non-responsive. Socially, the basic food demand needs to be met and the inability of society to meet this also creates social externalities. Economists themselves disagree on the way to separate these two issues of production and consumption. Although they are inextricably linked, at the minimum, production can be a source of a living wage that guarantees basic consumption income and thereby social stability and opportunities for progression. Hence, the authors believe that the social externalities of food supply and consumption can both be treated within the problem of production by taking account of the array of opportunity costs and the value of forgone alternatives in the use of available resources. This involves understanding the linkages across sectors within the economy, and in particular between the rural non-farm economy and the farm economy (Van Den Berg and Kumbi 2006).

21.5 Conclusion

Economic assessment of NT can yield useful information that helps maximize its benefits and establish its technical feasibility. To make such technologies attractive to producers, both in resource rich and resource poor contexts, the private benefits from additional output produced and the extra effort expended needs to be presented along with the likelihood of success under existing operating conditions. Because the benefits of technological change ultimately spill over to wider society as enhanced consumption opportunities, how the technology set affects such opportunities at the present and in future needs to be appropriately assessed, together with the risks to wider resource use and health and environment. Establishing the social desirability of technological change can only be made through such efforts. A successful technology bundle, such as NT, will only become so if it is technically feasible, economically viable, and socially sustainable. Therefore, the scope of assessments can range from a simple comparison of annual gross margins, through to whole farm assessment of technological change, to sectoral assessments examining change in agricultural sector productivity, to international comparisons.

Accessible literature and farm management advice on NT and related technologies have largely relied upon assessments of gross margins that have essentially led to the development of the technology as a popular choice. While they are useful, the ability of gross estimates to cover variable costs is an ongoing concern, and they are of little use in comparing economic benefits of practice change.

Methods of commercial agriculture have evolved over time with mixes of public and private investment, involving varying levels of taxation and subsidies. This has caused distortions within agriculture, as well as distortions between agriculture and rest of the economy. This makes economic assessments much harder to undertake.

The first step is to develop accurate and comparable measures of the full costs of the various modes of production that are not distorted by differences in taxes or subsidies, both implied and real. This is particularly important in assessing an externally induced innovation regime such as NT, where the technology set involves imported knowledge and input bundles, as well as local adaptations to accommodate the input bundle to suit local constraints. This gives rise to many specific issues such as measuring and valuing capital inputs, comparing expenditures at different points in time of the innovation cycle.

We hope the private and social cost framework and the discussion provided will help inform opportunities for improving economic assessments in considering further developments in NT and in the ongoing efforts to make the technology set more desirable for all concerned.

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Chapter 22
Socioeconomic Impacts of Conservation Agriculture based Sustainable Intensification (CASI) with Particular Reference to South Asia

John Dixon, Maria Fay Rola-Rubzen, Jagadish Timsina, Jay Cummins, and Thakur P. Tiwari

Abstract Compared to the past successes of global food supply, reduced natural and social capitals, Food-Energy-Water insecurities, climate change and volatile international commodity markets threaten future food production. Among the options for sustainable agriculture, various No-till (NT) practices have been adapted to different farming systems around the world. One particular adaptation, Conservation Agriculture based Sustainable Intensification (CASI) that combines the strengths of conservation agriculture and sustainable intensification, has succeeded in a number of farming systems including parts of South Asia. Farmer-participatory on-farm research results in the irrigated Rice-Wheat Farming System of Bangladesh, eastern India and Nepal showed that CASI strengthened the Food-Energy-Water nexus through increased food crop productivity, and energy and water use efficiencies. Furthermore, CASI reduced greenhouse gas emissions and improved natural resources. Notable socioeconomic impacts of CASI were improved household food security and income, reduced production costs, better

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returns to labor, benefits to women, expanded social capital and strengthened system resilience. These socioeconomic benefits are important drivers of smallholder adoption of CASI and underpin the prospects for widespread scaling. These impacts from South Asia are an example of the potential for CASI adaptation for other irrigated and dryland farming systems elsewhere in South Asia, as well as in East Asia, the Middle East and Africa.

Keywords Farming systems intensification · Natural resource management · Risk · Gender · Innovation systems · Scaling up · South Asia

22.1 Introduction

The projected growth of global population and consumer purchasing power points to the need for greatly increased food production by mid-Century. The historic growth of food supply over the past 60 years was essential to meet the expanding demand for food, reduce hunger and avert famines. However, the intensification of agriculture resulted in substantial environmental costs, including depleted aquifers, degraded land and reduced resilience (Beddington et al. 2012; Paroda 2018). Considering the expected surge in demand for food by 2050, strengthening the underlying Food-Energy-Water nexus is an essential foundation for the sustainable intensification of agriculture to meet food demand while conserving, or ideally enhancing, natural resources and adapting to climate change (Shah et al. 2012; FAO 2014, 2016).

No-till (NT) cropping is a promising approach to sustainable food systems. One adaptation of NT practices is Conservation Agriculture based Sustainable Intensification (CASI) that embodies the strengths of conservation agriculture and sustainable intensification. Conservation agriculture is an agroecosystem approach distinguished by three well-known principles, viz, NT, maintenance of a permanent soil cover, often by stubble retention (SR), and diversification of crops, typically through rotation or inter-cropping (Hobbs 2007; Kassam et al. 2018) – with due regard to improved farm profit or livelihoods (Dixon 2003; Joshi et al. 2010). Sustainable intensification (SI) is a broad concept that emphasises concurrent improvements of agricultural productivity and environmental conditions (Godfray et al. 2010; Oborn et al. 2017). Pretty et al. (2018) defines SI as 'agricultural processes or systems in which production is maintained or increased while progressing toward substantial enhancement of environmental outcomes'. Generally, SI strengthens the Food-Energy-Water nexus, improves food and nutrition security, reduces rural poverty and promotes rural transformation (Grafton et al. 2016).

Typical intensification and conservation practices of CASI include NT, SR, on-farm diversification, planting of improved cultivars and management of nutrients, weeds and pests. The concept of CASI resonates with the food production-intensification and the environment-sustainability narratives and policies of many national and international organizations. The choices of CASI innovations depend on the specific farming system context and supporting institutions, including input and produce markets. Naturally, a systems approach to CASI facilitates R&D and accelerates impacts (Lal 2015; FAO 2016).

The socioeconomic impacts of CASI depend on a foundation of integrated Food-Energy-Water securities and functional pathways to adoption in order to generate environmentally, economically and socially efficient farming systems. Such adoption pathways of CASI innovations require effective policies and institutions. Farm households benefit from improved food security, increased net income (partly from savings in production costs), reduced labor requirements, increased returns to labor and reduced risks associated with production and marketing. The effects on Food-Energy-Water securities, especially the efficiencies of energy and water use, can be assessed using on-farm trial data. Household surveys and focus-group discussions underpin the estimation of farm household benefits and assessment of institutions for scaling, value chains, social capital and spillovers. Selected socioeconomic impacts from several CASI applications in the Rice-Wheat Farming System of South Asia – supported by South Asian National Agriculture Research Systems (NARS), the Australian Centre for International Agricultural Research (ACIAR) and the Australian Department of Foreign Affairs and Trade, among others – illustrate the magnitude of socioeconomic impacts from CASI more generally across South Asia and in other regions.

The South Asian Rice-Wheat Farming System is one of the major food bowls of the world and covers approximately 13 Mha of the Indo-Gangetic Plains in Bangladesh, India, Nepal and Pakistan (Dixon et al. 2001; Timsina and Connor 2001). The farming system has evolved since the Green Revolution, for example expanding rice areas in the western region and increasing wheat and maize areas in the eastern region (Erenstein et al. 2010). The eastern Rice-Wheat Farming System, and specifically the Eastern Gangetic Plains in Bangladesh, eastern India and Nepal, is a hotspot of food insecurity, poverty, resource degradation and severe climatic stress (Dixon et al. 2016). The Eastern Gangetic Plains contains more than 450 million inhabitants with a population density of approximately 1000 persons km^{-2}, and 68 million farm households, of whom more than 70% are marginal. Figure 22.1 illustrates six contrasting farming subsystem zones in the eastern region, which are characterized by different natural resources, cropping and livestock patterns, and availability of markets and machinery services (Tiwari et al. 2017). Such a classification is useful for targeting CASI innovations, understanding pathways to adoption and impact, and identifying scaling strategies and partners (Gathala et al. 2018a).

The foundation for CASI research in the region was established by the Rice-Wheat Consortium and subsequently strengthened by the Cereal Systems Initiative for South Asia and the Borlaug Institute for South Asia, as well as a variety of other research initiatives. The Sustainable and Resilient Farming Systems Intensification (SRFSI) Project conducted on-station and on-farm trials and surveys on CASI in the eastern region (Islam et al. 2019). The Happy Seeder Policy project investigated the value chains for the provision of NT planting services to combat, inter alia, rice straw burning (SB) (Loch et al. 2018). A meta-analysis of Happy Seeder NT planter

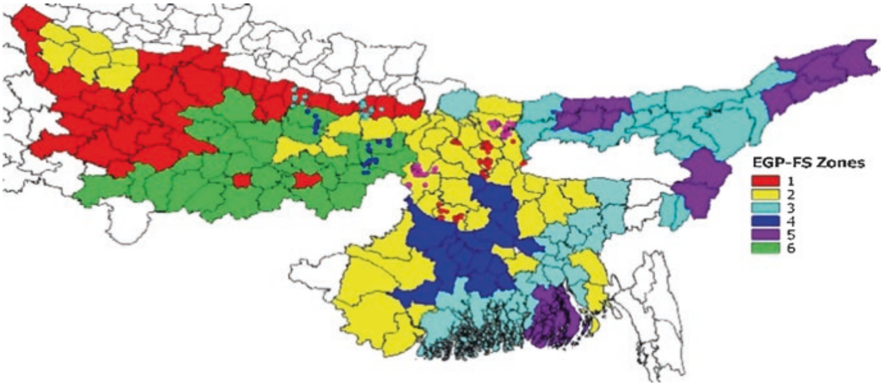

Fig. 22.1 Farming subsystem zones of the eastern Rice-Wheat Farming System. (Tiwari et al. 2017)

studies confirmed its viability as an alternative to rice SB in north-west India (Shyamsundar et al. 2019). The Farmer Behaviour Insights project is investigating another key issue, viz, farmer decision making on CASI adoption in the Eastern Gangetic Plains (Rola-Rubzen and Murray-Prior 2018).

The results of these research initiatives shed considerable light on the Food-Energy-Water nexus and socioeconomic impacts of CASI. The next section highlights the contributions of CASI to the Food-Energy-Water nexus, and Sect. 22.3 summarises farm household benefits including gender equity and risk reduction. In Sect. 22.4 the institutions for scaling CASI are discussed. Key lessons and conclusions outlined in the final Sect. 22.5.

22.2 Food-Energy-Water Nexus

Converging Food-Energy-Water insecurities are a major threat to food systems in South Asia (Shah et al. 2012). Globally, food crop intensification depends on the availability of energy and water (FAO 2014). The nature of the cropping system, including food and cash crop rotations and production technologies, influence the status of the Food-Energy-Water nexus, as illustrated by the following research on CASI in South Asia.

On-farm trials with double or triple cropped rice-based systems under CASI were conducted by the SRFSI Project with more than 400 farmers across the Eastern Gangetic Plains. Food production was evaluated under full and partial CASI practices (the latter with CASI except for kharif rice) against farmers' conventional practices including conventional tillage (CT) (Islam et al. 2019). The results showed that, for all cropping systems, food productivity was higher under CASI (averaged over partial and full practices) than with CT, whether measured in total annual food grain (in rice grain equivalents based on crop prices) or food energy (Table 22.1).

Table 22.1 CASI contributions to Food-Energy-Water by cropping system

System performance indicators	Cropping systems*	CT	CASI	Improvements CASI cf. CT (%)
System grain **yield** (Mg ha^{-1} $year^{-1}$) and food energy productivity (in parentheses, GJ ha^{-1} $year^{-1}$)	RW	8.6 (304)	8.9 (315)	+3.2 (+4)
	RM	11.8 (520)	12.3 (541)	+3.9 (+4)
	RL	12.4 (261)	13.2 (269)	+5.9 (+3)
	RWMb	10.9 (408)	11.6 (408)	+6.2 (0)
	RWJ	13.8 (478)	14.2 (470)	+3.0 (−2)
System **energy** use (GJ ha^{-1} $year^{-1}$) and EUE (in parentheses, MJ MJ^{-1})	RW	30.0 (12)	27.0 (14)	−10.0 (+15)
	RM	35.3 (15)	32.9 (17)	−6.8 (+13)
	RL	20.0 (13)	18.3 (15)	−8.5 (+15)
	RWMb	40.7 (10)	36.4 (11)	−10.6 (+14)
	RWJ	34.7 (14)	32.8 (14)	−5.5 (+4)
System irrigation **water** use (ha-cm $year^{-1}$)** and WUE (in parentheses, kg grain m^{-3} water)***	RW	20.8 (4.9)	18.2 (6.1)	−12.5 (+24)
	RM	23.1 (8.9)	20.3 (11.1)	−12.1 (+25)
	RL	– (0.50)	– (0.52)	– (+4)
	RWMb	– (0.71)	– (0.75)	– (+6)
	RWJ	– (0.63)	– (0.67)	– (+6)
System CO_2 equivalent emissions (Mg ha^{-1} $year^{-1}$)	RW	1.55	1.36	−12
	RM	1.81	1.65	−9
	RL	1.00	0.90	−10
	RWMb	2.11	1.89	−10
	RWJ	1.71	1.26	−26

Source: Data from Gathala et al. (2018b) and Islam et al. (2019) recalculated and summarized.
Notes: **RW* Rice-wheat, *RM* Rice-maize, *RL* Rice-lentil, *RWMb* Rice-wheat-mungbean, *RWJ* Rice-wheat-jute; **Jute, lentil and mungbean were grown predominantly under rainfed conditions, hence irrigation water use is not reported for RL, RWMb and RWJ systems; ***Values for RW and RM are system irrigation WUE and for RL, RWMb and RWJ are system total (rain and irrigation) WUE

Diversifying the rice-wheat system by incorporating mungbean as a third crop (RWMb) increased the annual food rice-equivalent yield by 2.3 Mg ha^{-1} under CT, and by 2.7 Mg ha^{-1} under CASI. Furthermore, the combination of diversifying the rice-wheat system by incorporating a jute crop (RWJ) and converting from CT practices to CASI boosted annual food productivity from 8.6 Mg ha^{-1} in rice grain equivalent yield (or 304 GJ ha^{-1} food energy) to 14.2 Mg ha^{-1} (470 GJ ha^{-1}).

From a Food-Energy-Water perspective, CASI practices increased rice-equivalent food grain productivity by 3–6% (depending on the cropping system) compared with CT practices. Moreover, in rice-wheat and rice-maize systems, CASI saved more than 12% of irrigation water, which improved irrigation water use efficiency (WUE) by 24 or 25% compared to CT. In other cropping systems, total WUE (including rainfall) increased by 4% for rice-lentil (RL) and 6% for rice-wheat-jute (RWJ). Mainly by eliminating tillage and reducing labor and water use, CASI practices saved energy in all cropping systems and increased energy use efficiency by 13–15% for rice-wheat, rice-maize and rice-lentil systems. There were also significant reduction of greenhouse gas (GHG) emissions (CO_2 equivalent), by 9% for the input-intensive rice-wheat and 26% for the rice-wheat-jute system.

These results demonstrate that smallholder farmers in South Asia can improve the Food-Energy-Water nexus in the eastern Rice-Wheat Farming System by adopting CASI practices. Additional improvements in Food-Energy-Water securities are feasible through system diversification by incorporating mungbean or jute into the rice-wheat system (facilitated by faster crop establishment with CASI), or through switching to rice-maize or rice-lentil cropping systems. Timsina et al. (2011) also report high system productivity from irrigated rice-maize and rice-wheat-mungbean cropping systems in South and SE Asia. The improvement of Food-Energy-Water securities and reduction of GHGs of the rice-wheat system from this CASI research in the eastern Rice Wheat Farming System resemble the outcomes from CASI practices across other parts of South Asia (Hari Ram et al. 2011; Aryal et al. 2015; Ladha et al. 2015; Gathala et al. 2015, 2016; Kumar et al. 2018). Notably, the greatest improvement to the Food-Energy-Water nexus in these irrigated farming systems stemmed from increased WUE. Conversely, in rainfed farming systems in South Asia (and other regions), the primary sources of improved Food-Energy-Water nexus are increases in food grain productivity and energy use efficiency.

22.3 Farm Household and Gender Impacts

22.3.1 Benefits for Female- and Male-Managed Households

The livelihood benefits for farm families who adopt CASI, and effects related to gender, are central to socioeconomic impacts. In case studies of 46 men and women farmers in the eastern Rice-Wheat Farming System, Rola-Rubzen et al. (2016) found that the impacts of CASI were quite diverse, and included savings in labor use, reduction in production costs, increased crop yields, higher net farm income and better household food security.

A follow-up interview survey of 1780 households in the eastern Rice-Wheat Farming System (Rola-Rubzen et al. 2019) compared the performance of CASI and CT practices for male-managed and female-managed farm households. Combining the male- and female-managed groups, the overall results indicate higher average yields, and thus better household food security, from CASI practices for kharif rice (3.4 Mg ha^{-1}), wheat (2.4 Mg ha^{-1}) and rabi maize (7.1 Mg ha^{-1}) compared with CT practices – respectively 3%, 13% and 8% greater (Table 22.2). The adoption of CASI practices also increased yields for spring maize, mungbeans and kidney beans – but not for mustard in the one reported district. Considering the traditional rice-wheat system and the relatively recent rice-maize system, farmers reported approximately 7% greater system food grain productivity under CASI than CT for both systems. As is common, farmers reported lower yields in these early years after adoption of CASI than were measured in on-farm trials – approximately 34% less for the rice-wheat system and 14% less for the rice-maize system. In the case of female-managed farms, the adoption of CASI also led to higher average yield for wheat in one district, and for rice in another district. Interestingly, female-managed farmers achieved slightly greater improvements in food grain yield from CASI adoption than male-managed farms.

Family labor is a key smallholder resource. Understanding farming systems and technology adoption requires knowledge of labor management and its allocation to different crops, livestock and off-farm activities. Overall, the adoption of CASI

Table 22.2 Crop yield and labor use (hired and family) under CASI cf. CT by crop and district[#]

	Yield (kg ha^{-1})			Hired labor (hr ha^{-1})			Family labor (hr ha^{-1})		
Crops/districts	CASI	CT	sig	CASI	CT	sig	CASI	CT	sig
Kharif rice									
Sunsari	3550	4112		195	478	***	181	93	*
Dhanusha	4293	3548	*	219	405	***	150	160	
Female	*4074*	*4008*		*121*	*392*	***	*180*	*151*	
Coochbehar	2328	1846	***	74	181	***	115	153	**
Female	*2109*	*1804*	***	*104*	*191*		*125*	*139*	
Malda	2382	2581	***	203	299	***	162	150	
Rangpur	5263	5294		549	614	**	335	419	**
Spring rice									
Rajshahi	5039	4666	***	360	491	***	360	495	***
Wheat									
Sunsari	2632	2244	**	160	156		61	55	
Dhanusha	2072	1854		134	119		115	111	
Female	*2290*	*2152*		*115*	*131*		*86*	*103*	
Malda	1876	1759		121	140		116	240	***
Rajshahi	3136	2582	***	336	456	***	228	246	
Rabi maize									
Sunsari	6377	6514		146	326	***	59	83	
Coochbehar	4050	3575	***	85	100		72	248	***
Malda	3608	4060		97	170	***	154	161	
Rajshahi	11,022	9358	***	304	403	***	197	340	***
Rangpur	10,523	9350	***	529	527		337	369	
Kharif mung bean									
Rajshahi	1233	1137		371	361		258	206	*
Mustard									
Malda	723	834		159	119	*	47	39	
Kidney bean									
Sunsari	1905	1673		223	294		82	121	

Source: Rola-Rubzen et al. (2019)

Notes: Female-managed farm data reported in two districts for rice and one district for wheat; other data are for male-managed farms. ***significant at 1% level of alpha, **significant at 5%, *significant at 10%. [#]farm activities include land preparation, planting/transplanting, fertiliser application, insecticide/fungicide application, herbicide application, weeding and harvesting saved 29% of total labor use (combining family and hired labor inputs) for the production of kharif rice, 16% for wheat and 27% for rabi maize (Table 22.2) – a major socioeconomic impact of CASI adoption. Often, saved family labor augments livelihoods through use in other farm or off-farm activities. Male-managed farms reported less hired labor use under CASI, notably for kharif rice in five districts, and for wheat and maize each in four out of five districts; and lower family labor use under CASI for maize in all districts, wheat in two districts and kharif rice in three districts. Female-managed farms also reported a lower level of hired labor use under CASI; but did not report any significant change in family labor input for these crops. Of course, family and hired labor are substitutes in many circumstances. The labor-saving effect of CASI is practically universal across regions and crops – even for vegetables, Schneider (2017) found labor savings from some conservation practices in Nepal.

In relation to production costs (Table 22.3), CASI incurred, in general, lower variable costs than CT for both male- and female-managed farms – overall, the savings for kharif rice, wheat and maize were 21%, 8% and 18% respectively. Male-managed farmers reported significant cost savings for kharif rice in five districts, wheat in three districts and maize in four districts. Similarly, female-managed farms using CASI saved costs for kharif rice production in both districts.

In this analysis, net crop income was calculated as harvest value less the variable costs of production, and thus is equivalent to gross margin. On male-managed farms, CASI practices generated greater average net crop income than CT for kharif rice by 50%, and maize by 60% (Table 22.3). Notably, average CASI wheat net income was nearly 2.5 times the CT net income. The adoption of CASI also increased net income compared with CT for spring rice, mungbeans and kidney beans, although not for mustard. On female-managed farms the adoption of CASI practices increased net income for kharif rice and wheat, approximately quadrupling and doubling net income respectively. Similarly, strong economic performance of CASI has been reported in the irrigated Rice-Wheat Farming System in north-west India (Jat et al. 2019; Shyamsundar et al. 2019) and elsewhere in South Asia (Erenstein 2010). Economic benefits from the adoption of CASI have also been observed in many rainfed farming systems in the Middle East, Africa and Latin America.

Considering the growing shortages of rural labor and the role of labor allocation in farm household system management, the estimation of returns to labor is important. Not surprisingly, the CASI boosts returns to labor by factors of 2.4 for kharif rice, 4.9 for wheat and 2.4 for maize compared with CT, largely because of labor savings and increased yield and income (Table 22.3). The increased returns to labor were substantial for both female- and male-managed farms for all crops and all districts except for mustard in one district. Given the substantial labor savings and high returns to labor, the overall effects of CASI adoption on rural labor markets in the Rice-Wheat Farming System is an important question for future investigation.

Overall, the survey results indicate substantial household benefits and strong socioeconomic impacts from CASI adoption, notably improved food security from increased yields and especially increased income, reduced labor requirements and

Table 22.3 Production cost, net income and returns to labor under CASI cf. CT by crop and district

	Product-ion cost (AU$ ha^{-1})			Net income (AU$ ha^{-1})			Return to labor (AU$ hr^{-1})		
Crops/districts	CASI	CT	sig	CASI	CT	sig	CASI	CT	sig
Kharif rice									
Sunsari	678	775		226	348		0.79	0.74	
Dhanusha	728	904	***	369	31	**	1.10	0.07	***
female	*613*	*957*	***	*472*	*14*	**	1.83	0.04	***
Coochbehar	232	327	***	463	234	***	2.55	0.72	***
female	*247*	*340*	***	*374*	*209*	***	1.71	0.65	***
Malda	380	392		344	369		1.09	0.88	*
Rangpur	668	819	***	1343	1189	**	1.56	1.25	***
Spring rice									
Rajshahi	681	920	***	1161	903	***	2.11	1.31	***
Wheat									
Sunsari	565	575		345	131	***	1.85	0.01	**
Dhanusha	626	593		104	30		0.55	0.17	
female	*542*	*618*		*238*	*100*		1.16	0.39	
Malda	399	449		179	112		1.07	0.32	
Rajshahi	846	1019	***	215	65	***	0.47	0.16	***
Rabi maize									
Sunsari	701	917	***	865	692		5.78	2.02	***
Coochbehar	363	462	***	621	348	***	4.24	1.12	***
Malda	497	437	***	402	470		1.85	1.52	
Rajshahi	916	1130	***	3639	1691	***	7.73	2.50	***
Rangpur	797	1052	***	2345	1710	***	2.85	2.16	***
Kharif mung bean									
Rajshahi	787	784		489	380		0.85	0.73	
Mustard									
Malda	249	244		234	344	**	1.18	2.32	***
Kidney bean									
Sunsari	690	832		1631	1183		5.28	2.92	*

Source: Rola-Rubzen et al. (2019)

Notes: Production costs are variable costs. Net crop income is equivalent to gross margin. Female-managed farm data cover two districts for rice and one district for wheat; other data are for male-managed farms. All estimates calculated directly from survey data. ***significant at 1% level of alpha, **significant at 5%, *significant at 10%

increased returns to labor for both female- and male-managed farms. Compared with other studies, the kharif rice yields reported in this research are similar to those described by Jat et al. (2019) in the early years after adoption of CASI, although they documented higher yields during the subsequent years. The net income from kharif rice is also comparable to the results of Jat et al. (2019) in the first two years after CASI adoption. However, Gupta and Sayre (2007) reported greater net crop income, perhaps because their study included land levelling practices.

Rola-Rubzen et al. (2016, 2019) emphasize the positive perceptions of CASI by farm women and men, as well as a variety of indirect benefits. Due to the additional income and saving of time, the benefits include better nutrition for the farm family, reduced drudgery for women, more time for other productive tasks or leisure activities and better education of children (Rola-Rubzen et al. 2016; Brown et al. 2017). In focus group discussions with 1182 female and male participants in the eastern Rice-Wheat Farming System, male farmers overwhelmingly agreed that the key benefits of CASI were less labor, less water, lower cost, and healthy soils (Rola-Rubzen et al. 2017). Farm women voiced similar perceptions, viz, the main benefits were less labor, less drudgery, less irrigation water, timely seeding and decreased costs. Both male and female farmers perceived CASI as a woman-friendly technology.

22.3.2 Farm-Household Resilience and Livelihood Risk Reduction

A large proportion of smallholder women and men are risk averse (Dixon 2003), meaning that many would trade-off less household income for reduced livelihood risk. For most South Asian smallholders, income from crops, whether in kind for home consumption or cash from sales of harvest produce, represents more than half of household livelihoods. Figure 22.2 shows Cumulative Density Functions for cropping system net income for CASI (averaged over partial and full) and CT practices (left quadrant) and for five rice-based cropping systems with CASI (right quadrant) estimated from the two years of on-farm trial data across the eastern Rice-Wheat Farming System, reflecting differences in farm and seasonal conditions. The cumulative density functions for CT and CASI practices represent the probabilities of obtaining particular minimum annual net cropping system incomes, in which higher probabilities (and less uncertainty) are associated with lower returns. CASI practices provided consistently higher net income than CT at all probability levels, suggesting that CASI technologies are likely to be superior to CT for good and poor soils, and for good and poor seasons. At 90% probability level, the annual net income from CT of AU\$ 901 ha^{-1} compared with AU\$ 1334 ha^{-1} for CASI. However, at the 50% probability level, annual net income with CT of AU\$ 1590 compared to AU\$ 2027 with CASI. Taken another way, a target net crop income (say, for escape from poverty) of at least AU\$ 2000 ha^{-1} would be achieved with CASI in more than half of situations (51.6%) but only one-third (34.2%) of situations with CT.

The degree of superiority of CASI technologies over CT depends on the cropping system. For comparison purposes, the rice-wheat system is considered as the benchmark. The cumulative density functions for the cropping systems practiced with CASI showed the probabilities of obtaining minimum annual net crop income ranged widely, with the highest incomes from the rice-maize and rice-wheat-jute systems (Fig. 22.2). At 50% probability, annual net crop income exceeded AU\$

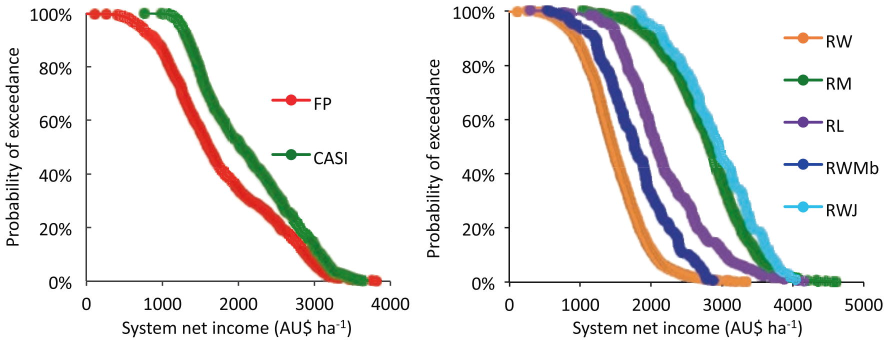

Fig. 22.2 Comparison of risks in obtaining system net income from CASI and CT (referred to as FP in figure). *RW* rice-wheat, *RM* rice-maize, *RL* rice-lentil, *RWMb* rice-wheat-mungbean and *RWJ* rice-wheat-jute. (Modified from Gathala et al. 2018b)

1455 ha^{-1} for the rice-wheat system, AU$ 2826 ha^{-1} for rice-maize and AU$ 2950 ha^{-1} for the rice-wheat-jute system, with intermediate net incomes for the rice-lentil and rice-wheat-mungbean systems. The chances of achieving a target net crop income of AU$ 2000 ha^{-1} was 11.7% from the rice-wheat system, while the probabilities would increase to 90% and 94.5% from the rice-maize and rice-wheat-jute systems, respectively. These results demonstrate the consistently high returns (relative to risk) of practicing CASI for rice-maize and rice-wheat-jute systems in the eastern Rice-Wheat Farming System.

Risk analysis for food productivity revealed that, at all probability levels, CASI practices had consistently higher yields than with CT. The annual food productivity from rice-maize system was about 50% greater than that from rice-wheat, and the rice-maize system was also more resilient to climate stresses (e.g., terminal heat stress or variable rainfall) than rice-wheat or rice-lentil (Islam et al. 2019). These findings suggest that CASI can decrease livelihood risks and increase farm household system resilience for resource-poor smallholder farmers in the Rice-Wheat Farming System. Because the research results span two years and a portion of the variability in the research results would arise from spatial variability in precipitation across the trial locations, the analysis suggests increased resilience to climate change variability. Further evidence of climate resilience could emerge from cropping systems simulations using historic (or projected) rainfall sequences for several decades.

There are limited studies on risk analysis of potential cropping systems comparing CT with CASI in South Asia using cumulative density functions. The consistently higher system productivity and higher net income with CASI compared to CT at all probability levels for the rice-maize system obtained in this study are consistent with findings of Gathala et al. (2015, 2016) for several locations of Bangladesh. Further research is required to estimate the reduced risks of practicing CASI compared to CT in long run.

22.4 Institutions for Scaling and Rural Transformation

22.4.1 Approaches to Scaling

The above results from on-farm trials and household surveys illustrate how adoption of CASI would improve livelihoods and system resilience for smallholders in the eastern Rice-Wheat Farming System, as in many other farming systems around the world. Many socioeconomic factors influence the adoption of CASI practices (Knowler and Bradshaw 2007; Pannell et al. 2014), often of equal importance to biophysical constraints. Institutions have played a key role in the adoption of CASI practices across the Rice-Wheat Farming System (Erenstein et al. 2008; Erenstein 2010; Keil et al. 2016) and in other regions of the world.

Accelerated adoption and scaling of CASI require an in-depth understanding of farming systems, public agricultural agencies, agribusiness, NGOs and the local community institutions which shape the incentives for farmer, business and public agency decisions (Tiwari et al. 2017; Gathala et al. 2018a – see also Fig. 22.1). The knowledge of adoption and scaling processes and the pathways to farming system and institutional change lie at the heart of agricultural and rural transformation. Naturally, many system linkages, feedback loops and uncertainties are embedded in farming systems and institutional change, i.e., it is far from a linear process.

These system approaches to scaling (Sinclair 2017) require broad partnerships and constructive engagement between research, development organizations, business and farmers in order to enable and foster broad system change and rural transformation. There are a variety of tools to assist the process of formulating, targeting and implementing effective scaling strategies (Woltering et al. 2019). In marked contrast to traditional perspectives concerning the dissemination of technologies, systems approaches to scaling call for iterative action research, continuous learning and adaptive management, and increased capacity of farmers, local institutions and value chains.

22.4.2 Value Chains

The provision of inputs and services for effective NT seeding is a critical challenge for CASI in many farming systems, especially in the case of NT drills (Keil et al. 2016). Accordingly, a series of ACIAR projects supported the development of the Happy Seeder NT drill and related machinery in India, Pakistan and Bangladesh – a major technological breakthrough which enabled the successful direct seeding of wheat seed under heavy rice straw. However, until recently, weak institutions and incentive structures slowed the manufacture and uptake of the Happy Seeder and other NT drills, with the consequence that rice straw burning, ploughing and conventional sowing of wheat persisted.

Because the burning of rice straw aggravated the already-critical levels of air pollution across north-west India, a policy study analyzed Happy Seeder value chains for NT (Loch et al. 2018). Despite the clear economic viability of the Happy Seeder (Shyamsundar et al. 2019), the value chain analysis revealed, *inter alia*, a lack of capacity in custom hire centers for effective operation and maintenance of Happy Seeder equipment, and for the business arrangements for effective service provision. Also, manufacturers of the Happy Seeder lacked confidence in farmer demand, especially before subsidies for farm equipment purchase were extended to include the Happy Seeder. Long supply chains for Happy Seeder machinery is another constraint in some areas, particularly in the eastern Rice-Wheat Farming System because the majority of manufacturers are located in north-west India.

The results of the Happy Seeder value chain analysis were valuable input to the policy dialogues leading up to the launching of the Government of India program for the provision of NT planting services. This program resulted in a massive expansion of the number of NT drills on farmers' fields during the 2018/19 wheat season in north-west India and a reduction in the number of districts that routinely burnt rice straw before planting wheat. The strengthening of the value chain for delivery of the Happy Seeder and other NT drills generated substantial additional income and socioeconomic benefits along the Happy Seeder value chain from manufacturers to service providers and farmers.

Of course, successful scaling of CASI depends on the strengthening of many other input and produce value chains. Rural entrepreneurship plays a key role in value chain development, but so too the social capital of farmers' groups and local communities.

22.4.3 Social Capital

Institutional innovations play multiple and diverse roles in farmer-to-farmer learning, irrigation water management, micro-finance, marketing and participatory evaluation of CASI. In West Bengal, farmers' clubs provide outstanding support for CASI, including input acquisition, provision of machinery services, and produce marketing. A notable institutional innovation of one club is the provision of contract services for maize crop establishment under CASI in neighboring villages (Gathala et al. 2018b).

One successful form of social capital for CASI R&D is the innovation platform, which links farmers researchers, extension agents, traders, NGOs, and other development actors to foster co-learning and adaptive innovation (Makini et al. 2013). Underpinned by social network analyses, the Sustainable and Resilient Farming Systems Intensification Project established about 30 innovation platforms in the eastern Rice-Wheat Farming System (Brown et al. 2017). A number of factors were associated with successful Sustainable and Resilient Farming Systems Intensification Project innovation platforms, including consideration of farmers' perceptions, effective NT machinery value chains, an enabling environment for entrepreneurship, and broad engagement of stakeholders including women (Cummins 2018). Table 22.4 compares the relative strength of the innovation platforms and the resulting impacts.

Table 22.4 Innovation platform capacities and impacts

Capacity and impacts	Bangladesh	Nepal	West Bengal	Bihar
Demonstrated changes in crop management	1.75	1.53	2.38	2.05
Financing (savings, loans, self-funding of CASI machinery)	2.44	0.87	2.00	2.07
Crop input retail business services	2.22	1.60	2.50	2.67
Adoption of CASI seeding systems	2.50	1.50	2.17	3.00
Access to CASI machinery	2.00	1.70	1.17	3.00
Knowledge (group awareness of improved farming systems)	1.17	1.90	1.33	2.20
Attitudes (positive attitudes and motivation amongst members to increase profitability and productivity	2.17	2.6	2.00	2.60
Skills (relating to crop production, farm business management)	2.00	2.00	2.00	2.60
Aspirations (farmers being ambitious, future plans for success)	2.00	2.20	1.34	3.00
Social Capital (how well the group and community work together, leadership prominence)	2.83	1.90	1.67	3.00

Source: Cummins (2018)
Notes: Scores range from 0 = nil/poor to 3 = significant/outstanding

22.4.4 *Spillovers*

Several studies have shown that spillovers between states, countries and regions account for a substantial portion of the returns to research in the USA and in developing countries. In South Asia, the Rice-Wheat Consortium generated high payoffs from the coordination of research and sharing of knowledge about resource conserving technologies, including CASI, across the Rice-Wheat Farming System of South Asia (Seth et al. 2003; TAAS 2017). At a regional Happy Seeder Policy project workshop in 2018, National Agricultural Research System leaders from four South Asian countries agreed in principle to the establishment of the South Asian Regional Platform (‘SARP4CASI’) for CASI knowledge sharing. There is scope for further research on the determinants of spillover effectiveness in different contexts and the influence on CASI scaling pathways and socioeconomic impacts.

22.5 Conclusions and Lessons

Considering the expanding demand for food this century, strengthening the underlying natural resource base and Food-Energy-Water securities is an essential foundation for the required sustainable intensification of agriculture. One effective sustainable agricultural development option is CASI, which has been adapted to many types of farming systems around the world, including the Rice-Wheat Farming

System that underpins South Asian food and nutrition security. As an illustration of the nature and magnitude of socioeconomic impacts from CASI, this chapter reviewed the evidence arising from the successful adaptation of CASI to six different farming subsystems of the eastern Rice-Wheat Farming System spanning Bangladesh, eastern India and Nepal. The results were compared with findings in other irrigated and rainfed farming systems.

The research results from the eastern Rice-Wheat Farming System show that CASI can substantially improve smallholder household food security and strengthen the Food-Energy-Water nexus. On-farm trial results showed increases of food energy production from 304 GJ ha^{-1} in the RW cropping system to 540 GJ ha^{-1} in intensified and diversified cropping systems. CASI also increased energy and water use efficiencies by 15% and 24% respectively, and reduced GHG emissions (CO_2 equivalent) from the improved CASI-based cropping systems. These results are similar to those observed in other Asian irrigated farming systems. However, in rainfed farming systems in Africa and the Middle East the increases in food productivity and energy efficiency are often larger than for water use efficiency.

Substantial household benefits and socioeconomic impacts flow from smallholder adoption of CASI in the eastern Rice-Wheat Farming System. Both female- and male-managed farms benefited from increased food crop yields and thus improved household food security. Two further key findings were the major savings in farm labor requirements for rice, wheat and maize production and major increases of net crop income. Consequently, the returns to labor more than doubled for rice and maize, and more than quadrupled for wheat. The research results also confirmed that CASI reduced production risk for smallholders. Both female and male farmers in the eastern Rice-Wheat Farming System perceived CASI as a ‘woman-friendly’ technology. They summarized the major benefits as less labor/drudgery, less irrigation water, timely sowing, decreased production costs and healthier soils. Overall, CASI strengthens system resilience in the irrigated Rice-Wheat Farming System of South Asia. In rainfed farming systems, CASI also increases farm income and reduces labor requirements, and especially reduces seasonal production risk.

The wider rural non-farm economy also benefits from the scaling of CASI adoption. In the eastern Rice-Wheat Farming System increased local employment and business income from expanded input and grain value chain activity were observed. Farmers’ clubs in West Bengal acquired and distributed farm inputs at competitive prices, provided NT machinery services to members and contract services to neighboring communities for CASI crop establishment. Social capital increased, especially through the innovation platforms that brought together farmers, local business, extension workers and researchers for co-learning and capacity development. Such CASI innovation platforms have also been very effective in rainfed farming systems in Africa. In the eastern Rice-Wheat Farming System, the convergence of research activities with national and State livelihoods development programs in West Bengal fosters the scaling of CASI. Active engagement of policy makers is an essential feature of CASI scaling approaches in the Rice-Wheat Farming System in South Asia, as in other regions.

The choice of the CASI approach enabled a win-win-win for intensification along with positive environmental and socioeconomic outcomes. The size of the target population and the severity of poverty, food insecurity, resource degradation and climate stress ensured potentially large socioeconomic impacts from scaling of CASI. Enabling factors for scaling include efficient service delivery and value chains, strengthened social capital and adjusted policy and institutional settings. These various factors interact and so a complex systems approach to further research and scaling would be most effective.

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Chapter 23
No-Till Farming Systems in Resource-Limited Contexts: Understanding Complex Adoption Behavior and Implications for Policy

Jesus Pulido-Castanon and Duncan Knowler

Abstract The literature on no-till (NT) farming systems has typically relied on cross-sectional analyses that apply a binary lens to the adoption decision. There is increasing acknowledgment that such an approach masks the realities of farmers' adoption. In resource-limited contexts, for example, uptake has been documented to regularly happen in a partial or even a periodic manner. Dynamically, this situation becomes even more complex, as most farmers revisit their production decisions with every new cropping season. The promised environmental benefits of NT farming systems (such as conservation agriculture) depend precisely on their continuous application. Thus, beyond promoting uptake, effective policy making should strive towards transforming current patterns of disadoption and periodic adoption into long-term adoption (i.e. 'true' NT). A modern approach to agricultural policy aims to tie incentives to environmental outcomes. In this context, a viable policy tool is payment for ecosystem services where payments are conditional on the farmers' continued use of NT. The benefits that sensitive agricultural management provides to society may justify this type of incentive. Committing policy makers towards this endeavor – not just land managers and development organizations – will be crucial.

Keywords Conservation agriculture · Disadoption · Periodic tillage · Ecosystem services · Agricultural policy · Africa · Latin America

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23.1 Introduction

While no-till (NT) based farming systems are undeniably gaining prominence in the world, the question of what is hindering adoption in some regions still remains critical. Unfortunately, while some catastrophic events receive immediate attention, those that occur more gradually may not be as easily recognized and, therefore, may not receive adequate attention (Kassam et al. 2014). For example, fast-track progress in international law was triggered by the Chernobyl nuclear disaster in 1986 (see Rautenbach et al. 2006). The challenge with an arguably equally disastrous issue – soil degradation – is that it occurs gradually, and in addition, is masked using chemical fertilizers and other non-organic means of boosting yield. One measure to sustainably intensify crop production is the "ecosystem approach" in agricultural management, which uses inputs such as land, water, seed, and fertilizer, to complement the natural processes that support plant growth (Gibbon 2012). Such an approach is underpinned by the principle of minimum soil disturbance or NT (Gibbon 2012), and for this reason conventional extension programs have strived to persuade non-adopters to join the adopter team. Unfortunately, the issue at hand is more complicated. Evidence from countries in Africa and Latin America demonstrates that there exists a spectrum of adopter categories (from partial to full users), some with legitimate reasons for not fully switching to soil conservation practices.

Many studies show that NT farming systems often improve ecosystem service delivery (see Palm et al. 2014). For example, through the widespread uptake of NT, the micro-level changes induced by adoption (such as raising organic matter content in the soil) can be upscaled to macro-level effects such as increases in groundwater recharge, flood prevention, and improved water quality (Palm et al. 2014). There is evidence that where institutional conditions are adequate (e.g. participatory technology development and access to knowledge, machinery, and complementary inputs), agricultural innovations are generally welcomed by farmers, big or small (Roling 2009). Conversely, the vagaries of public funding (and extension programs, by default) may contribute towards the ill-suited application of conservation farming systems (see Martinez-Cruz et al. 2019). In this sense, policy initiatives that foster an appropriate adoption environment are fundamental.

This chapter begins with a review of selected issues in global agriculture, and how NT systems can contribute towards solving these problems. We then illustrate how their adoption has been conceived in theory, and how farmers in resource-limited contexts have adopted them in practice. In view of some clear disconnections between these two, we then argue that the benefits of NT only materialize when these systems are applied on a continuous basis. Understanding this requirement in the face of actual adoption behavior is fundamental for tailoring policy instruments that can promote meaningful adoption. While our interest is NT farming systems in general, we frame the discussion around Conservation Agriculture (CA), which is defined as NT when practiced in combination with stubble retention and a diversification of crop rotations.

23.2 NT Farming Systems: Implications for Sustainable Development

23.2.1 Current Scenario for Global Agriculture

The issue of how to feed a growing population is a recurrent topic of concern as most of the world's soil resources are in a fair, poor, or very poor condition, with the major threats to soil function being erosion, loss of organic carbon, and nutrient imbalance (FAO and ITPS 2015). While regions such as North America, the Southwest Pacific, and Europe show signs of improvement derived from increased adoption of reduce tillage and improved residue management practices, a synthesis of meta-analyses suggests that agricultural productivity globally is being degraded at a mean rate of 0.3% per year through soil erosion (FAO and ITPS 2015). If soil and water management practices remain constant, this sums up to be a yield loss of 10.25% in the period 2015–2050. This number is in stark contrast with the required increase in food supply projected to be of at least 27% or as much as 73% by 2050 (Southgate et al. 2011). In addition, there are uncertainties brought up by climate change. With increased temperatures the suitability and productivity of staple crops (i.e. wheat, maize, and rice) will likely extend to higher latitudes, but reduce at lower latitudes, where agriculture is already marginal (Gornall et al. 2010). Furthermore, extreme temperatures may lower productivity by affecting enzyme reactions and gene expressions in the short term, as well as by affecting soil carbon, and thus growth and yield, in the long term (Wollenweber et al. 2003).

The current scenario is thus one of interlinked issues of food security, soil productivity, and environmental degradation. As part of the Food and Agriculture Organization of the United Nations' (FAO) new paradigm of sustainable crop production intensification (SCPI), NT farming systems have been proposed as a response to these challenges due to their capacity to increase productivity, while enhancing ecosystem services (Gibbon 2012). It is believed that for farmers to embrace the SCPI a number of major changes in agricultural policy and institutions need to take place. These include making agriculture profitable, devising incentives to use natural resources wisely, as well as major investments in research and technology transfer capacity (Gibbon, 2012).

23.2.2 Role of NT in Enhancing the Soil Physical Environment

Despite the many ecosystem benefits attributed to NT, the variety of soil types, topographies, crop rotations, and climates among studies has made understanding of some crucial cause-effect relationships difficult (Palm et al. 2014). While the relevance of NT for climate change mitigation is still under debate, there is a high certainty that NT increases the level of soil organic matter (SOM) in the surface soil versus conventional tillage (Palm et al. 2014; Blanco-Canqui and Ruis, 2018). In a review of SOM dynamics in tropical and temperate regions around the world, Six et al. (2002) assert that there is a relative increase in SOM in the upper 0.4 m of NT soil after 6–8 years when compared with tilled systems under similar cropping regimes. This is important as it links NT management with the delivery of important ecosystem services such as reduced erosion and runoff and enhanced water quality (Palm et al. 2014).

The relevance of SOM build-up for soil ecosystem services can be explained as follows. Palm et al. (2007) assert that the natural capital of soils underlying ecosystem service provision is determined primarily by three core properties: texture, mineralogy, and SOM. While the first two generally remain unchanged, SOM can be subject to dramatic changes through land use management practices (Palm et al. 2007). The contribution of SOM to ecosystem services appears to have two mechanisms. First, increased SOM provides the energy and substrate for soil biota activities and their contributions to soil structure and nutrient cycling, as well as many other processes and ecosystem services (Brussaard 2012). Second, the accumulation of soil organic C in the surface influences soil physical properties by reducing susceptibility of the soil to compaction, enhancing the ability of the soil to capture and retain water and transport heat, and improving soil structural quality and stability (Blanco-Canqui and Ruis 2018). Unfortunately, the SOM threshold levels that drive such changes in soil properties, processes, and related ecosystem services are not well known yet (Palm et al. 2014).

It is worth noting that enhanced quality and structure of soils may be conditional upon the way in which NT systems are practiced. Bolliger et al. (2006) point out that plant biomass input and time are essential factors governing SOM build-up under NT regimes. With regards to the first, a study by Govaerts et al. (2007) suggests that at least 30–50% of crop residues should be left on the surface in order to keep adequate benefits for the soil. The quality and combination of residues may be of importance as well. In a study in tropical Southern Brazil (i.e. a region with high temperatures and decomposition rates), Mielniczuk (2003) postulates that it is only feasible to maintain SOM stocks if both high-biomass cover crops and main crops are planted. With regards to the time issue, Blanco-Canqui and Ruis (2018) conclude that one of the leading factors affecting soil physical properties is the duration of NT management. From a review of relevant studies, they found that soil bulk density and penetration resistance (as measures of soil compaction) were significantly and negatively correlated with NT duration. Also, wet aggregate stability (as a measure of soil structural quality) was moderately and positively correlated with NT duration. Correlations with soil hydraulic properties such as water infiltration, water retention and hydraulic conductivity were not significant in this exercise.

23.3 Adoption Pathways for Conservation Agriculture

23.3.1 Putting 'NT' Farming in the Context of 'CA'

Non-plough farming systems include a variety of production techniques that have as their underpinning the principle of minimum soil disturbance. One way to differentiate them is through their associated relative severity of tillage, ranging from reduced soil disturbance (i.e. minimum tillage, conservation tillage, and strip-till) to virtually nil disturbance rates (i.e. no-tillage, conservation agriculture, and direct seeding mulch-based cropping systems) (Kassam et al. 2009). For clarity, this chapter will focus on no-tillage or NT when it is used within the broader context of the CA system.

NT is a cultivation system in which seeds are placed into otherwise untilled soil by opening a narrow slot, trench, or hole of only sufficient width and depth to obtain proper seed placement and coverage. No other soil tillage is done (Derpsch et al. 2014). A more comprehensive system, CA, follows three interlinked principles: (a) minimum mechanical soil disturbance that is less than 0.15 m wide or less than 25% of the cropped area, and may include NT; (b) permanent organic soil cover of at least 30% ground cover; and, (c) species diversification where a rotation and/or association should involve at least 3 different crops (FAO, 2019). In the last couple of decades, the global spread of CA has been remarkable, partly due to the voluntary uptake of farmers, but especially due to promotion efforts carried out by development organizations such as FAO and CIMMYT. Whereas in 1973/1974, CA was applied to only 2.8 M hectares worldwide, since 2008/2009 the increase in area has averaged 10.5 M hectares per year, raising coverage from 106 to 180 M hectares (Kassam et al. 2019).

23.3.2 Adoption of CA (Theoretical)

Roger's renowned diffusion of innovations theory from 1962 holds that an idea or technology will be adopted by successive categories of "consumers" (i.e. innovators, early adopters, early majority, and laggards) until the saturation level – 100% of potential adopters – is reached (Rogers 2010, 4th ed.). This reasoning can be represented through the standard S-curve, which displays an increasing number of adopters over time for an agricultural innovation (Knowler 2015). Based on this binary logic, various periodic reviews of CA uptake offer encouraging estimates of the global spread of this farming system (see Kassam et al. 2009, 2015, 2019; and Friedrich et al. 2012). While valuable, these estimates do not reflect the realities of adoption, which must also consider the intensity of application as well as variations over time.

Baudron et al. (2007) provide insights into the dynamics of CA adoption. They theorize that farmers embark on a journey of consecutive phases, each characterized

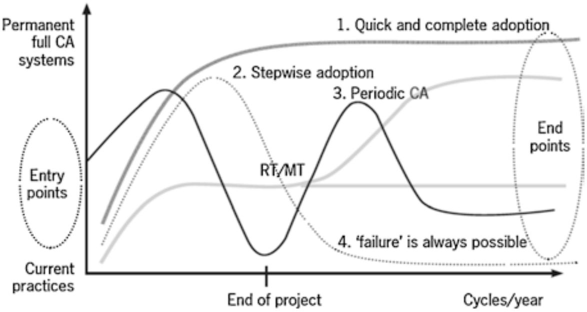

Fig. 23.1 Entry points and four hypothetical pathways towards adopting CA. Reproduced from Baudron et al. 2007, Copyright 2007, with permission from the Food and Agriculture Organization of the United Nations

Note: "End of Project" refers to the termination of training and/or incentives provided as a part of a systematic strategy for technology transfer to farmers. Baudron et al. (**2007**) detail various CA-support projects i**n Africa**

by the use of specific practices that increasingly incorporate practice and mastery of the three CA principles. As illustrated in Fig. 23.1, these "common" pathways of adoption include (a) "quick and complete adoption" of CA in its fullest form; (b) "stepwise adoption" of CA practices, leading (or not) to complete adoption over time; (c) "periodic CA", as in practicing during some cycles but not others; and (d) "failure" or disadoption after the end of a project. What may be the factors that lead to such a convoluted set of uptake routes? Erenstein (2003) notes that adoption (and intensity) decisions are taken in the framework of variable environmental and socio-economic conditions, such as capital available for investments in equipment and inputs, soil conditions, and the farmer's ability to learn new practices and take risks. Another aspect is the political and institutional environment in which decisions are made, such as ease of access to equipment, inputs, and relevant knowledge, links to markets, existence of policies favoring (or discouraging) adoption, among others (Baudron et al. 2007). Knowler (2004) also stresses constraints at the local level, as in the case of innovations that do not apply to a specific context, are less viable than farmers' own solutions, suffer from weak extension practices, are prevented by land tenure regimes, or have a negative social connotation.

Indeed, for farmers that undertake any other pathway below complete CA adoption, it may be that the above factors are making a socially optimal level of soil conservation simply unattainable. Alternatively, it may be that partial CA adoption in some cases is socially optimal. For example, Baumgartner and Cherlet's (2016) analysis of four cases of land degradation in China, Guatemala, Kenya, and Tunisia concluded that beyond the characteristics of land users alone, a whole set of institutional layers modified, altered, or even determined the level of land degradation. This calls for tailored approaches to soil conservation.

23.3.3 Adoption of CA (Case Studies)

As seen above, Rogers' diffusion of innovations theory suggests that, over time, all farmers will adopt CA in its fullest form. While such an outcome may be realized in a few locations, for resource-limited contexts the norm is more limited and modified adoption. Disadoption is another common event, albeit less frequent. In order to demonstrate these assertions, here we present case studies for small and medium-scale farmers in Africa and Latin America (Mexico).

23.3.3.1 Five Countries in Africa

In the last few decades, there have been major investments in the promotion of CA and other NT based farming systems in various parts of the world. This is particularly the case of Sub-Saharan Africa, since it is a region with major issues in soil erosion and food security (FAO and ITPS 2015). One central claim is that partial adoption (i.e. only one or two CA components) and semi-utilization (i.e. use in a limited portion of an individual's farmland) are often the outcome of technology transfer in resource-limited contexts. To justify this assertion, Brown et al. (2017) developed two frameworks that provide insights into the intensity of CA adoption and on user typologies. The first one is the "Conservation Agriculture Appraisal Framework" (CAAF), which is a weighted index of the proportion of CA use and its components for individual land plots with respect to the total farmed area. The second is the "Process of Agricultural Utilization Framework" (PAUF), which provides 10 utilization categories disaggregated by extent of use for adopters, and by abandonment and level of interest/awareness for non-adopters (Fig. 23.2).

For a dataset of five African countries (Ethiopia, Kenya, Tanzania, Malawi, and Mozambique), Brown et al. (2017) show that the conventional binary measure (i.e. where any degree of use of the three CA principles would constitute adoption) provides uptake rates in the upper quintile of the sample for all countries, except for Ethiopia (56.7%). In contrast, under the 0–1 CAAF index Tanzania and Mozambique are the most advanced in terms of aggregate CA use (with mean values of 0.4027

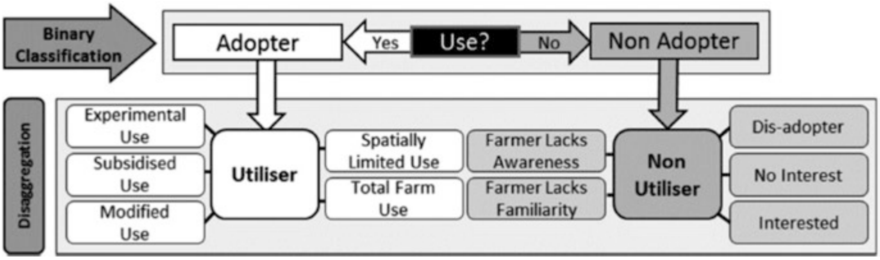

Fig. 23.2 Reconceptualization of the classification of adoption to various sub-uses. Reprinted from Brown et al. 2017, Copyright 2017, with permission from Elsevier

and 0.4023, respectively), followed by Malawi, Kenya, and Ethiopia (mean values of 0.3519, 0.3106, and 0.0601). When analyzed under the PAUF, only Tanzania showed a total utilization rate >0.01% (i.e. 3.1%). Modified use accounted for 56% of farmers in Ethiopia and between 89% and 96% in the remaining four countries. Non-exposure was a key determinant of limited use in the case of Ethiopia (37%) (Brown et al. 2017).

23.3.3.2 Mexico – State of Michoacan and State of Guanajuato

In early 2017, we carried out a farmers' survey to understand what factors influenced the timing and intensity of CA adoption in two states in Mexico. One of the challenges throughout our survey work was that respondents seemed to have different interpretations of what the "CA" concept implied. Indeed, in a study carried out in the same region, Van den Broeck et al. (2013) comment on how difficult it was to identify the extent of farmers' awareness of this production system. A recent paper helps in making sense of this issue. Martinez-Cruz et al. (2019) put together a timeline of the promotion of CA in Mexico. In this evolution, CA has been promoted under various labels ranging from conservation tillage (1994–1999), direct seeding (2000–2009) and conservation agriculture / sustainable intensification (2005–2017), with increasing degrees of farmer involvement at each stage. Martinez-Cruz et al. (2019) note this conceptual and practical transformation has been shaped by the vagaries of political, researcher, and farmer agendas and dependent upon the availability of public funding. In this context, it is only natural that farmers in this region (especially those not in direct contact with soil conservation scientists), experience varying degrees of understanding regarding the CA concept.

We asked our survey participants about their use of the three CA principles, either individually or simultaneously, during the period 1994/1995 to 2015/2016. As shown in Table 23.1, from the data collected we identified three types of farmers: non-adopters, periodic adopters, and full adopters. Non-adopters are those individuals who use conventional tillage, who use the NT seeder in tilled soils (i.e. purely as

Table 23.1 Overview of CA production systems

Production system	Description
CA full adopters	∗ No/reduced tillage, crop residue retention (>30%) and crop rotations over two cropping cycles.
CA periodic adopters	∗ No/reduced tillage, crop residue retention (>30%) and crop rotations over the first cropping cycle. Second cycle: conventional tillage.
Non-CA adopters	∗ Uses NT machine in tilled soils, any residue management. ∗ NT in bare soil (<30% crop stubble cover) ∗ Conventional tillage and no residue retention

Source: author's own data

Note: For full and periodic adopters, the crop-rotation principle has been relaxed to include different cereal species (e.g. maize followed by wheat). But alternation with a legume is preferable over cereals and so that practice was also accounted for under this principle a seeding machine), or who use the NT seeder appropriately but in bare soils (i.e. those with <30% crop stubble cover). Periodic adopters are those that alternate between NT (plus soil cover) and conventional tillage within a rotation of different crops. Full adopters are those that apply the three CA principles together over two cropping cycles.

Our initial sample size included 492 farmers and was not representative of the adoption ratio in the area, as our intention was to analyse a 1:1 ratio of adopting v non-adopting individuals for statistical purposes.[1] After a few adjustments to the data, we ended up with 401 farmers with CA user data available for at least 3 years in a row (i.e. four data points). Using the SPSS software version 24 we applied a double-step clustering procedure (see Hair et al. 2013), and relied on mean cluster values to identify typical adoption pathways for CA. As shown in Fig. 23.3, four farmer clusters were identified from the data. The first cluster consists of "non-adopting" farmers. The second cluster, "eventual disadopters" are farmers who adopt fully or partially, but eventually disadopt by year 3, on average. The third cluster "periodic adopters", are farmers who consistently use periodic CA over time. The fourth cluster, "full-adopters", tend to use CA over two cropping seasons over time. In the case of the full-CA category, however, a few farmers turn to periodic tillage after year 2.

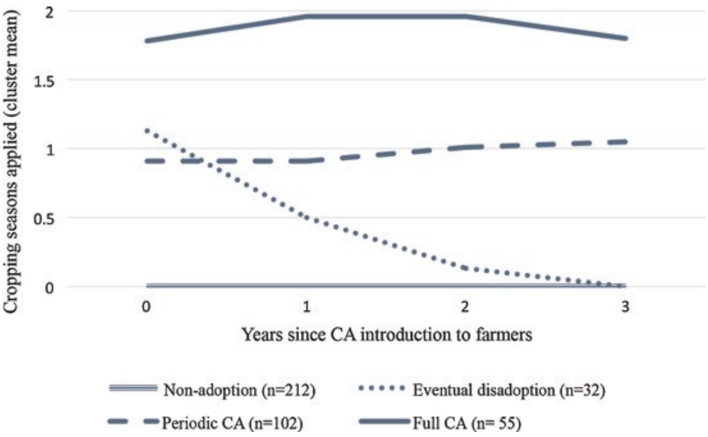

Fig. 23.3 Adoption pathways for CA
Note: A statistically significant difference between clusters was determined through one-way ANOVA test for year **0**, year **1**, year **2**, and year **3** (p = **0.000** for all). This was confirmed by a Tukey post hoc test which also revealed there is no statistically significant difference between non-adopters and eventual disadopters in year **3** (p **= 1.000)**

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[1] Following the identification rule for extreme outliers (>3 x interquartile range), we excluded 39 observations with land holdings greater than 24 hectares each. Further, Grigar et al. (2018) suggest that any field with less than 3 years under NT management should be considered transitional, rather than true NT. This led to a further reduction of the sample size by 52 observations.

needed to mix up small seeds with fertilizer (Helios Escobedo-Cruz, AGRODESA Consulting, personal communication, April 2017).

The use of tillage within an otherwise NT farming system is a practice that conflicts with the philosophical idea of zero disturbance (Conyers et al. 2019). Some authors even assert that soil health improvements gained over years of NT application can be eliminated with a single tillage pass (see Grandy et al. 2006; Grigar et al. 2018). This is not necessarily true, as it has been documented in the case of "strategic" tillage, which is a sporadic (i.e. one-time) practice some farmers apply to combat constraints of NT systems such as the build-up of herbicide resistant weed populations (Dang et al. 2015). Recent evidence demonstrates that strategic tillage generates only minor and short-term impacts on soil structure and productivity, and that these are often exceeded by the agronomic benefits obtained in return (see Dang et al. 2015, 2018; Blanco-Canqui and Ruis 2018; Conyers et al. 2019).

More justifiable concerns exist when NT systems are disrupted on a regular basis, as is the case with periodic and alternate tillage. Few studies have discussed the longer-term impacts of continued infrequent no-tillage. For example, Conant et al. (2007) carried out a related modelling exercise at four diverse sites in the U.S. Although not conclusive, the results suggest that (a) increasing the time between tillage events increases the amount of C in the soil surface; (b) marginal gains in C stocks are greater in the first years of NT management; thus, more than 80% of soil C gains can be achieved with biannual cultivation or ripping of NT soils, compared with an average of 94% soil C gains under 10 years of continuous NT; and c) less soil-disrupting methods (such as non-inversion tillage) average just 6% less soil-C stock losses than continuous NT, compared to 27% less for conventional inversion tillage.

23.4.2 Disadoption

The use of tillage has been traditionally linked to various agronomic benefits such as loosening the soil, eliminating compaction, increased water infiltration, redistribution of nutrients in the soil profile, and the burial of weed seeds (Derpsch 2008). This thinking has underpinned a "tillage mindset", which entails the ignorance and/or disbelief in the agronomic benefits of sustainable production systems that maintain soil surface cover like NT (Derpsch 2008). Thus, the switch to an apparently contradictory production system requires a radical mental change, which in many cases ends up in the conversion of NT users into disadopters (Derpsch 2008). This may have two immediate consequences. First, benefits from the SCPI will be lost since tillage eventually brings soil conditions back to the status quo. Second, farmers who have given up on NT will be more difficult to persuade to re-adopt it in the future. This includes individuals who may already have invested substantial time or money (e.g. as in buying the NT seeder) and still decide not to pursue it anymore.

The disadoption or "failure" to continue with CA is commonly associated with the termination of project incentives such as agricultural input subsidies or technical

23.4 Issues with Current Patterns of CA Adoption

The discussion in Sect. 23.2.2 suggests that SOM usually accumulates under NT in excess of that under plowed land, and that such an effect can be captured by farmers who use appropriate residue and crop rotation practices over sufficient time periods. While major investments in resource-limited regions have concentrated on bringing the non-adopters into the adopting team, our case studies reveal that continuous CA adoption has been importantly constrained by periodic use, as well as by disadoption. Unfortunately, the regression to conventional practices risks forsaking the environmental benefits that such system provides. This poses serious questions with regards to our ability as society to appropriate the celebrated benefits of CA.

23.4.1 Periodic Adoption

"Periodic CA" refers to practicing CA during some cycles but not others (Baudron et al. 2007). Departing from the principle of NT, this behavior pattern may occur in two ways. The first is "rotational tillage", in which NT soils are tilled every second, third, or fourth year and it has been documented in the United States (US) Midwest region as a common practice among farmers that apply a corn-soybean crop rotation (Conant et al. 2007; Kurkalova and Tran 2017; Grigar et al. 2018). The second is "alternate tillage", in which soils are managed under NT in one season followed by intensive tillage the next season (Derpsch et al. 2010, 2014). Farmers in the Mexican Bajio region often apply a variant of this system (locally known as "hybrid tillage"), which consists of alternating CA practices during one farming cycle with the use of conventional tillage and some form of crop residue management during the subsequent cycle (author's own data; Turmel, cited in Speratti et al. 2015). In Brazil's region of Parana, smallholder NT farmers still resort to a range of intermediate-tillage systems by falling back on disc harrowing before-after certain crops (Ribeiro et al. 2005). In addition, about five million hectares are being managed this way in the Indo-Gangetic plains in a rice-wheat rotation, where wheat is the NT crop (Derpsch et al. 2010).

It can be argued that the reasons for rotational tillage in the US are of a more agronomic nature and these include lime incorporation, phosphorus redistribution, and abating soil compaction (Derpsch 2008; Powlson et al. 2014). In the case of alternate tillage, the reasons have been less studied, but they seem to reside in resource constraints of various types. In Mexico, for example, failure to apply NT during the Fall-Winter cropping season may be due to the following reasons (a) lack of access to specialized machinery such as the fine-grain NT seeder; (b) lack of market positioning for the types of winter crops that complement cereal rotations (e.g. chia seeds, beans, chickpeas, and other legumes); and (c) lack of technical knowledge on the use of the fine-grain NT seeder, since a complicated calibration is assistance (Baudron et al. 2007). Some case studies offer complementary insights into why disadoption happens. For example, Brown et al. (2017) documented widespread disadoption of CA in Malawi, Kenya, and Ethiopia as the result of conflict between minimum tillage and the cultural and institutional contexts of African smallholder farming, an issue further compounded by national policies that incentivize ploughing. In the Mexican states of Mexico and Hidalgo, Ramirez-Lopez et al.'s (2013) semi-structured farmer interviews show that disadoption often occurs right after the first cycle of use. The main reason for abandonment was the lack of technical assistance, followed by the establishment of CA in rented land plots, farmer disinterest, and the competing uses for crop stubble. In the states of Guanajuato and Michoacan, disadoption initiated within the first year of uptake, but full abandonment was not completed until year 3, on average (author's own data). From our observations, the disenchantment with the CA system in this region might be related to low or weak yields that farmers obtain in the first few applications versus the results of conventional farming. As described by some authors, it takes between 3 and 7 years of continuous NT before soil physical and biological properties improve enough to be reflected in higher yield levels (Hobbs 2007; Grigar et al. 2018).

23.5 Adoption of No-Till Farming Systems: Policy Considerations

23.5.1 Agricultural Policy Trends Across Countries

In the case of numerous adoption pathways, how can we help direct farmers' resource use, production, and investment strategies toward routes compatible with the "SCPI"? Here, policy instruments represent a leverage point that governments can use to alter the incentives faced by producers and other actors, and thus direct them towards more sustainable agri-food production systems (OECD 2019). For a sample of countries including OECD members, non-OECD European Union (EU) member states, and 12 emerging economies, average transfers to individual producers in the early 2000s represented just over 20% of gross farm receipts, compared to about 12% (USD 440–442 billion) in 2017–2018 (OECD 2019). This marks a declining but still important use of monetary incentives worldwide as a tool to pursue agricultural sector objectives.

Even more informative is the structure of these payments. In 2016–2018, close to 70% of all transfers to and from agriculture originated from measures that potentially distort farm business decisions. These include market price supports, payments based on output, and payments based on unconstrained variable input use (OECD 2019). Unfortunately, such measures do not seem to align with the much-needed paradigm of sustainable intensification. For example, a study relying on five indicators including green house gas (GHG) emissions, water quality, biodiversity, and nitrogen and phosphorus balances, concluded that such instruments often cause negative impacts on the environment through incentives to expand and intensify land use (Henderson and Lankoski 2019). Alternatively, other (tax-financed) support instruments exist that are less coupled with production decisions and, as a result, may produce lower environmental impacts (OECD 2019). These include payments relating to other inputs (e.g. support for on-farm investments) or variable input constraints, and payments based on area, animal numbers, and historical farm receipts or farm income. Although their use is not as widespread, these instruments represent an important share of producer support in the EU (67%), Australia (52%), Switzerland (44%), Norway (38%), the US(38%), and Canada (32%) (OECD 2019).

A modern approach to agricultural policy makes incentives conditional on environmental or animal-welfare outcomes. This works in consideration of the link between agriculture and some areas of growing societal concern, as well as in the expectation that the sector will provide various public goods (OECD 2019). These include (a) payments conditional on the adoption of specific production practices; (b) voluntary opt-in programs for the investment in facilities for environmental or animal welfare friendly production; and (c) payments for voluntary agri-environmental constraints – such as input subsidies conditional on use constraints (OECD 2019). In the period 2016–2018, Switzerland, Norway, the EU, and the US championed this approach by applying it to at least five percent of their farmer payments (OECD 2019). Interesting examples include the 'Programa ABC' (Low Carbon Agriculture Program) in Brazil, which provides preferential interest credit lines to farmers implementing pasture and forest restoration projects or who adopt GHG emission-reduction technologies (MAPA 2012). Another instance is the Emissions Reduction Fund (ERF) in Australia, where actors in the economy (including small farmers) can participate in eligible projects that bring effective reductions in GHGs emissions. The carbon credits generated by these actors are subject to a bidding (auction) process, mediated by the Clean Energy Regulator authority, and credits with the lowest cost abatement are paid out to the generators (Commonwealth of Australia 2019).

23.5.2 Policy Rationale in the Case of CA Adoption

Perhaps tied to a classic view on the role of agriculture, various countries still focus on rewarding the maintenance of landscapes and conservation of biodiversity (OECD 2019). In many cases, the diffusion of 'environmentally profitable' (Pampel and van Es 1977) technologies has been expected to occur spontaneously among farmers. These approaches are short sighted, and governments need to recognize the public value of the environmental benefits generated through the widespread adoption of CA and other conservation technologies (Kassam et al. 2014). In this context, the improved delivery of ecosystem services provided by CA justifies the articulation of policies and incentives so that monetary, risk, and other costs incurred by adopting farmers can be shared with society at large.

Recent experiences demonstrate that policy and institutional support are crucial in creating necessary conditions for the introduction and accelerated adoption of agricultural technologies. For instance, the swift and mass-scale adoption of high-yielding seed varieties in India during the 1960s was heavily influenced by conditions created by the government via political commitment, incentives, access to inputs, and so on, which in turn allowed farmers to adopt and use the technology (Roling 2009). In contrast, the experience of 20+ years for the spread of CA in Brazil and Argentina shows that, unless farmers' initiative is matched by support mechanisms provided by the public and private sectors, it may take a long time to reach significant adoption levels (Kassam et al. 2014). Furthermore, in central Mexico the promotion of CA technologies has been carried out over the last 30 years. However, support and funding have been subject to numerous changes in political priorities and except for the current "Masagro" program, none of the other projects had life cycles greater than five years. This naturally led to discontinuities in the agendas of researchers and technicians, who needed more time to configure CA to local contexts (Martinez-Cruz et al. 2019).

There are several necessary conditions that build up an enabling environment for the transformation of tillage-based systems into CA. These include achieving a dynamic institutional capacity to support CA, engagement with farmers, interlinkage of farmers' networks, provision of knowledge, education and learning services, mobilization of input supply and output marketing sectors for CA, accessibility of required inputs, and financing and enablement of initial stages (Kassam et al. 2014). The relevance of each condition may be case-specific, but it can be argued that whenever efforts on a crucial component have not been diligent enough then issues of non-adoption or incomplete adoption may arise. In this context, disadoption and periodic adoption represent special cases, as these suggest that introductory conditions were met, but conditions needed tosecure farmers' commitment over longer periods were not.

23.5.3 Towards the Adoption of Continuous CA Systems: Policy Recommendations

Farmer decisions to partially adopt or disadopt NT systems are made in the transition from one cropping season to another. In our case studies we also noted these decisions are made early on in the adoption process. One crucial issue here is that resource-poor farmers have short planning horizons and face difficulties in adopting a long-term view (Shiferaw et al. 2014). In this context, it is necessary to identify what policy measures can support the adoption of NT farming systems on a progressive and continuous basis.

A first policy objective is to improve well-being and the level of natural resources available to farm-households so as to enable adoption. Shiferaw et al. (2014) point out that a policy environment that enhances the stock of livelihood assets for production, consumption, and investment decisions in the current period (t) will in turn determine natural resource outcomes in the next period (t+1). Initially, a farm-household's endowment with assets and resources determines its production and investment decisions – such decisions constitute the household's attempt to maximize livelihood benefits in consideration of expected shocks (Shiferaw et al. 2009). The role of policy and institutional measures here is to push initial resource constraints outwards by offering enhanced trade and market participation opportunities (Shiferaw et al. 2009). Thus, enabling policies (e.g. secure rights to land and water), and access to market and institutional arrangements (e.g. credit and extension services), should provide farmers with opportunities to diversify livelihood strategies through the adoption of conservation technologies. A second policy objective is to establish a mechanism that supports adoption continuity in the crucial stage between cropping seasons. Here, incentives can be provided to farmers conditional on their continuation with CA practices. These incentives can be monetary (as direct payments, access to low-interest credits, or support for irrigation/drainage infrastructure), but also in-kind support in the form of machinery and seeds. These two policy measures may just get at the very nature of inter-cropping decision making that otherwise can result in truncated patterns of adoption.

Importantly, it is now widely acknowledged that CA is a complex system to use, especially over time (Kassam et al. 2014). This was also evident as we spoke to farmers in our case study in Mexico. In order to be sustainable, the above policy recommendations must be coupled with institutional capacity (i.e. training and extension services) that permanently supports farmers in the dynamic challenges that CA carries with it. In consideration of limited state resources (monetary, institutional, or otherwise), discriminatory provision mechanisms may apply. For example, Bopp et al. (2019) has found that subsidies may effectively persuade less environmentally conscious farmers into the adoption of sustainable agricultural practices, whereas those more environmentally motivated do not depend on incentives as much.

23.6 Conclusion

From a set of case studies, we showed how the farmers' uptake of CA in resource-limited contexts differs from the theory that applies a binary lens on the adoption decision. Albeit from a limited sample of Mexican farmers, we identified a spectrum of adoption choices, including non-adopters, periodic adopters and full CA adopters, but we believe this situation likely describes CA adoption more generally. The problem with some of these behaviors is that they are short-lived and thus prevent society from capturing the ecosystem service benefits that widespread CA adoption can provide, in part from SOM build-up.

Discontinued or periodic CA adoption may signal that farmer support mechanisms are not in place or, alternatively, have not been up to the task. Governments need to acknowledge the public good value of soil and water conservation technologies and provide measures that effectively support their uptake, up to a socially optimal level. This suggests that society should share the costs of adoption with farmers. A modern approach to agricultural policy involves paying farmers for environmental outcomes. This must be accompanied by training and extension services throughout. Where resources – monetary or institutional – are limited, discriminatory mechanisms may apply, as for example, in directing support preferentially towards those individuals where incentives have greater potential to increase adoption.

As important, perhaps, is to make soil and water conservation a national priority and law, to prevent its use as a convenient excuse to aid political agendas. At present, the use of conditional environmental payments may sound far-fetched in developing economies, but it is already happening with success in many regions of the world and may provide crucial leverage to help alleviate the wicked issue of rural poverty.

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Part V
Regional Strategies in No-Till Farming Systems

Chapter 24
Lessons Learnt from Long-Term Experiments on No-Till Systems in Semi-arid Regions

Mahesh K. Gathala and Alison M. Laing

Abstract Healthy soil is a vital component of sustainable crop production. While it is challenging to describe or measure soil health directly, it can be quantified by measuring indicators of soil physical, chemical, and biological health. Traditional crop management practices rely on tillage operations to prepare the soil for sowing and, in part, to manage weeds and crop residues, however tillage is deleterious to soil health. Over time, the negative effects of tillage on soil health can be seen in declining yields or the need to increase inputs such as fertilizers or irrigation water to maintain productivity. We use two case studies of long-term agronomic experiments in semi-arid cropping regions of India to demonstrate the value of no-till systems to improving soil health and thus contributing to the sustainable production of cereal-based cropping systems. The results summarized here have applications and relevance in other semi-arid cropping systems globally.

Keywords No-till · Residue retention · Soil health · Cropping system productivity · Low-rainfall

24.1 Introduction

Soils have both inherent and dynamic properties: inherent soil properties change little over time and reflect soil-forming factors such as the parent material, climate, topography and age of the soil. Dynamic soil properties reflect current and recent

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land use practices. Changes in dynamic soil properties are generally slow and can indicate a soil declining or improving in health, generally as a result of land management practices.

Healthy agronomic soils are important both to ensure the sustainable production of food and other crop products, and to ensure that the food and feed produced are healthy and not harmful to humans or animals (e.g. livestock, poultry, fish). While ‘soil health’ is simple conceptually, it can be difficult to identify a healthy soil. However, we can deduce information about a soil’s health from measurable properties in both the soil and in the plants it supports.

Soil health may be considered in terms of three key, interdependent factors: physical, chemical, and biological condition (Fig. 24.1). Physically, soil provides a physical support for plants and mediates the retention and movement of water. Chemical processes in the soil relate to nutrient retention and release, chemical reactions within the soil, and the storage of energy (as carbon). Soil biological processes catalyze the presence and growth of microbial populations, which contribute to weed and pest suppression, N mineralization, and the decomposition of organic matter. All three factors influence soil health and thus plant growth, and sustainable agronomic production requires soils that are physically, chemically, and biologically healthy. Improving the health of agronomic soils improves cropping system

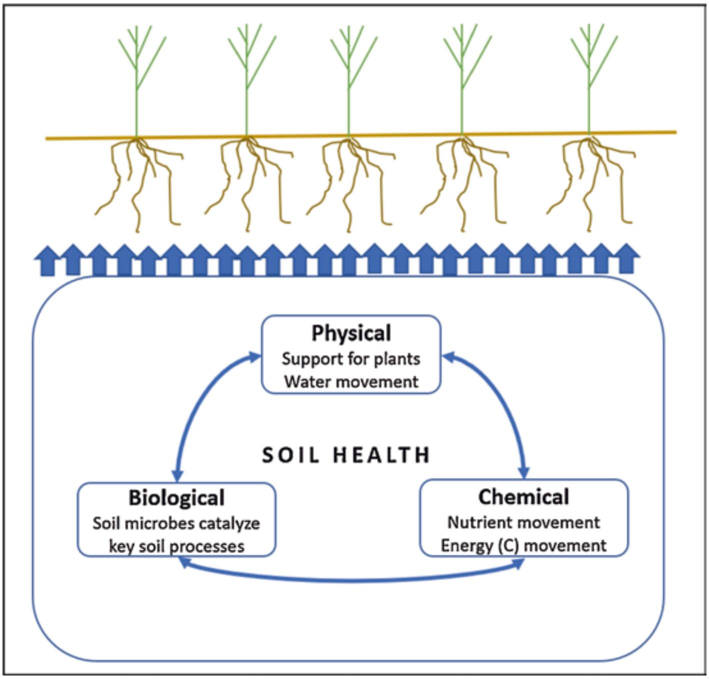

Fig. 24.1 Soil physical, chemical, and biological factors influence soil health and plant productivity

productivity: healthy soils produce higher yields of more nutritious plants, and this productivity is more sustainable.

Semi-arid cropping systems in South Asia are characterized by sandy to sandy-loam soils with low organic matter and low fertility. Precipitation is also low, while variations in both diurnal and seasonal temperatures are large. As a consequence of these challenging edaphic and climatic conditions, cropping intensity is low and crop productivity poor. In rainfed areas, typically only one wet season crop is grown, while if irrigation water is available, a second dry season crop is also planted (Aryal et al. 2019).

Traditional conventional (CT) crop management practices in the semi-arid Indo Gangetic Plains region of South Asia require the soil to be tilled, generally between two and five times, before sowing. As well, in traditional rice production the soil is compacted (puddled) to facilitate the retention of standing water through the growing season. After harvest, crop residues are traditionally removed (either manually by humans or grazed by animals) or burned to facilitate a rapid establishment of the subsequent crop. In contrast, modern agronomic management practices recommend the establishment of crops into untilled, fields (in the case of rice) fields from which residues have *not* been removed. Generally, crops are established mechanically using planters attached to tractors. For smallholder subsistence farmers for whom these new methods differ substantially from established practice, a reduction in tillage, with the aim of transitioning to no-till (NT) in time, is recommended.

In this chapter we summarize results from two long-term experiments conducted in semi-arid regions of the Indo Gangetic Plains: the first, at Modipuram in Uttar Pradesh, India, examined over seven years from 2002 the effects of different establishment methods and tillage practices in rice-wheat cropping systems (Gathala et al. 2011a, b). The second experiment is ongoing and has been conducted at Karnal, Haryana, India, since 2009; at least four years' data were used in analyses reported here (Jat et al. 2018, 2019a, b; Choudhary et al. 2018a, b). In the Karnal experiment, the performance of a conventional rice-wheat system was compared against rice-wheat-mungbean and maize-wheat-mungbean systems under different tillage and crop establishment practices. We focus here on longer-term experiments as soil health changes relatively slowly and the effects of altered management practices may not be observable in shorter experiments. First, we use results from these experiments to illustrate that NT practices improved the physical characteristics of soils. We also show that the chemical and biological characteristics of theses soils improved under NT management. Next, we discuss how tillage-based crop establishment creates a 'downward spiral' of decreasing soil health, while NT systems break this cycle of soil degradation. Lastly, through a comprehensive review of long-term rice-based cropping system experiments in the Indo Gangetic Plains, we demonstrate that the NT practices which improve soil health also contribute to improved plant growth and cropping system productivity. While we have constrained our review to research within the semi-arid Indo Gangetic Plains region of South Asia, the results summarized here are likely to be relevant for other semi-arid crop producing regions globally.

24.2 Improving Soil Physical Health under No-Till Crop Establishment

24.2.1 Physical Support for Plants

Over the longer-term experiments considered here, NT cropping systems generally decreased subsurface soil penetration resistance and bulk density, improving the physical structure of the soil relative to CT cropping systems (Gathala et al. 2011a, 2017; Kumar et al. 2019). 'Bulk density' indicates the amount of a given total volume of soil that is occupied by dry soil particles. 'Soil penetration resistance' is a measure of the potential for water and plant movements through the soil: soils with higher penetration resistance or higher bulk density restrict the movement of water and plant roots. Tilling and puddling soils as part of traditional rice management practices reduces soil health by destroying the soil structure and restricting water movement through the creation of a hard pan layer at approximately 0.15–0.25 m depth. Once established, this hard pan layer is removed only slowly under improved crop management practices. Both soil penetration resistance and bulk density increase with compaction and depth. These measures are inversely related to soil water content. At the soil surface, NT management contributed to increased moisture retention and higher organic matter in the topsoil, both of which improved soil health by reducing the amplitude of diurnal temperature and by moderating soil topsoil temperature.

Gathala et al. (2011a) observed soil penetration resistance in topsoil (0–0.05 m) in standard NT treatments to be significantly higher than raised-bed NT or CT treatments after seven years (Fig. 24.2). However, below the surface at 0.15 m and 0.25 m depths the opposite was observed: soil penetration resistance was significantly higher in the tilled treatments than in any NT treatments; this was the result of puddling at these depths. Below 0.3 m there were no differences between treatments in terms of soil penetration resistance. Jat et al. (2018) observed the highest soil penetration resistance under CT crop management with lower soil penetration resistance under NT systems. Differences between tilled and NT systems were significant in the top layers (0–0.10 m) and again below 0.3 m. Soil penetration resistance values were beneath the critical 2–3 MPa value limiting wheat root growth in the Jat et al. (2018) study, however Gathala et al. (2011a) observed values above 2.0 MPa, particularly between 0.1 and 0.3 m. They note, however, that generally soil penetration resistance values were lower under NT management than under tilled systems, suggesting that wheat root growth was likely to be less impeded under NT management.

Averaging experimental data over four years, Gathala et al. (2011a) found that bulk density at the soil surface (0–0.05 m) was significantly higher, by around 4%, under standard NT treatments than under CT treatments or under raised-bed NT treatments; the authors suggest the lower bulk density under raised-beds may be associated with regular bed reshaping. With increasing depth, however, the tilled treatments had significantly higher bulk density, again by around 4–5%, than any of

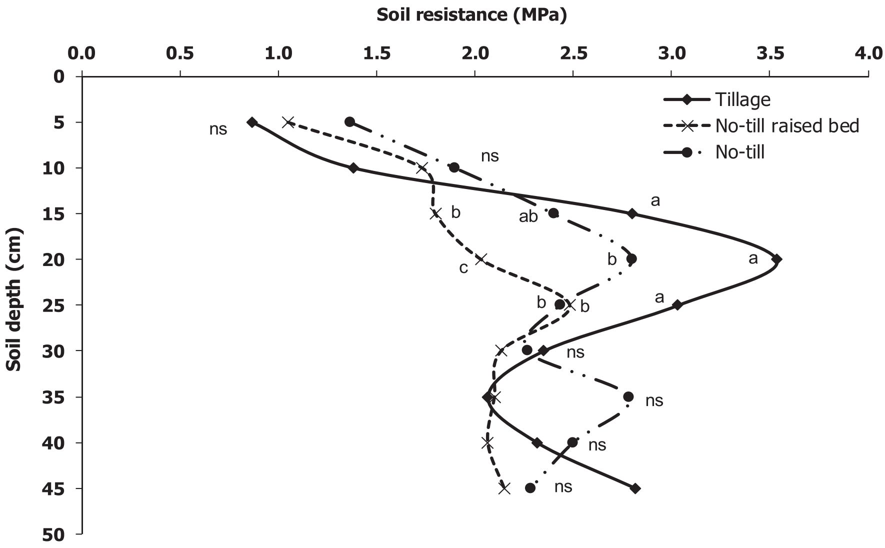

Fig. 24.2 Soil penetration resistance (MPa) under conventional tillage, raised bed no-till, and standard no-till treatments in a rice-wheat system. Across a depth, means followed by the same letter are not different at the 0.05 probability level (Tukey's HST test). (Derived from Gathala et al. 2011a)

the NT treatments at both 0.11–0.15 m and 0.16–0.2 m depths. This increase in bulk density below the soil surface in CT treatments was attributed to puddling, which physically compacted the soil, destroyed soil particles, infilled spaces between soil pores with finer matter, and destroyed the soil structure (Sharma et al. 2003). Jat et al. (2018) found decreases after four years in bulk density under NT treatments compared to a CT baseline at 0–0.15 m and 0.15–0.3 m depths. While the differences between treatments were not significant, the authors suggest that a significant difference is likely to be observed following a longer timeframe under NT crop management.

As a consequence of the higher bulk density observed on the soil surface in standard NT treatments than in raised-bed NT or CT treatments, Gathala et al. (2011a) found that the topsoil (0–0.05 m) layer had higher thermal conductivity and capacity under standard NT management (Fig. 24.3). Soils under standard NT management had average topsoil temperatures significantly higher (in 16 out of 20 weeks) in the morning (7 am) and significantly lower (again in 16 out of 20 weeks) in the afternoon (3 pm) than CT soils or, generally, than raised-bed NT soils. NT treatments increased organic matter in the topsoil, and also (often in conjunction with residue retention) reduced evaporation and increased soil moisture. These factors buffered thermal transfer within the soil. In contrast, tillage increased the soil volume and facilitated heat exchange between the topsoil and atmosphere (Gathala et al. 2011a, b). Thus, the standard NT management better insulated the topsoil against temperature fluctuations than other treatments and also exposed the topsoil

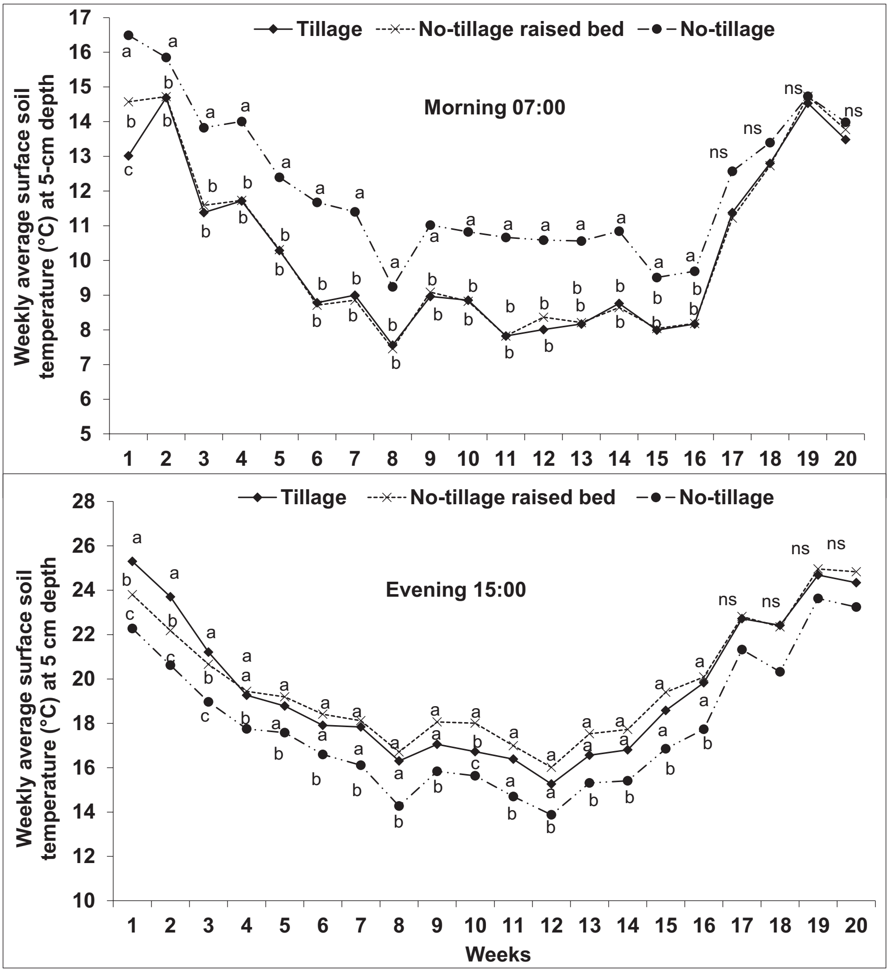

Fig. 24.3 Average weekly soil temperature (°C) at 0.05 m soil depth under conventional tillage, raised-bed no-till, and standard no-till treatments in a rice-wheat system at 7 am (top) and 3 pm (bottom). Within a week, means followed by the same letter are not different at the 0.05 probability level (Tukey's HST test). (Derived from Gathala et al. 2011a)

to less thermal heat stress. These outcomes are likely to lead to improved soil chemical and biological factors, and to improved plant growth.

24.2.2 Regulation of Soil Water

Over the longer term in the experiments considered here, NT crop management increased the diversity of aggregates within the soil structure compared to CT practices, and improved infiltration rates (Gathala et al. 2011a; Kumari et al. 2011). Healthy soils consist of a matrix made up of different sized particles that facilitate the ready movement and retention of water within the soil. Both the stability and the number of water-stable aggregates indicate the health of a soil: healthier more productive soils have a greater quantum of, and more stable, aggregates. Both tillage and puddling destroy soil aggregates; additionally, tillage promotes the decomposition of soil organic carbon while puddling decreases infiltration rates. In contrast, the reduction in soil disturbance under NT crop establishment increases soil aggregation and infiltration rates. Increasing infiltration rates facilitates the cultivation of waterlogging-sensitive crops, such as legumes and maize, and contributes to the recharging of aquifers. Combined with stable aggregates, higher infiltration rates also contribute to the free movement of water within soils, providing the necessary conditions to facilitate both upward water flux through capillary rise, and increased soil water storage. The improved regulation of soil water is particularly important in rainfed semi-arid cropping systems.

Gathala et al. (2011a) showed that the percentage of water-stable aggregates greater than 0.25 mm within the soil differed between NT and tillage management practices after two years, and that this difference continued to increase over time, with more aggregates present in NT treatments. They did not observe a difference in water-stable aggregates between standard and raised-bed NT treatments. In the same study, after seven experimental years the authors observed differences in the distribution of aggregates between NT and CT treatments: under CT the presence of macroaggregates decreased and that of microaggregates increased as a consequence of puddling. In contrast, NT management increased the presence of macroaggregates. Gathala et al. suggest that this is likely due to NT practices both protecting aggregates against destruction and binding microaggregates.

Over the seven-year experiment, Jat et al. (2018) found that NT systems had significantly (70%) higher infiltration rates than CT or partial NT cropping systems (Fig. 24.4). A similar result was observed by Gathala et al. (2011a) where, after seven years, the (puddled) CT treatments had lower infiltration rates than the NT treatments; additionally, the differences in infiltration rates between tilled and NT treatments continued to increase over time (Fig. 24.5). Gathala et al. also found that raised-bed NT systems had higher infiltration rates than standard NT systems, although the difference between NT treatments was smaller than between NT and CT treatments.

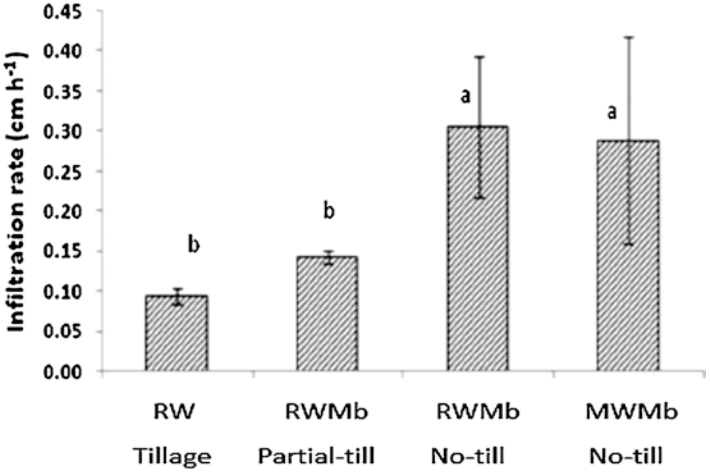

Fig. 24.4 Change in infiltration rate between tillage, partial-tillage and no-till cropping systems. Treatments with the same letter are not significantly different at the $p < 0.05$ level. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *MWMb* maize-wheat-mungbean. (Derived from Jat et al. 2018)

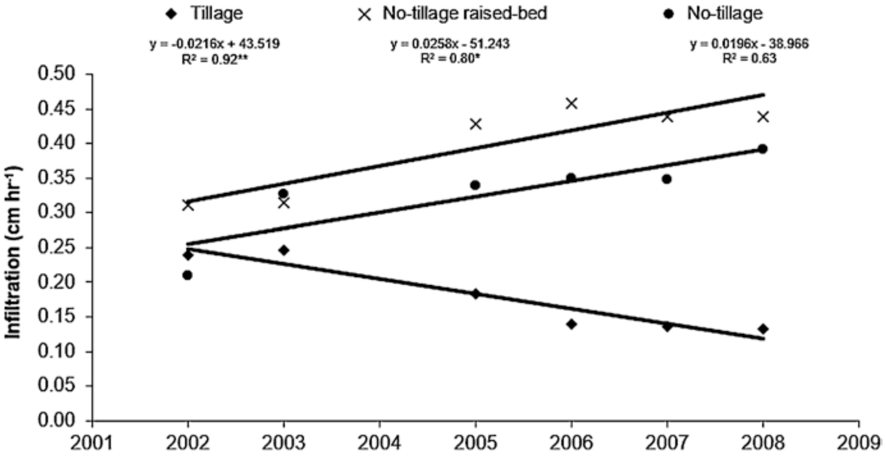

Fig. 24.5 Infiltration rates over 7 years in conventional tilled, raised-bed no-till and standard no-till rice-wheat systems. (Data from Gathala et al. 2011a)

The retention of residues, which is generally practiced concurrently with NT crop establishment, also improves soil water storage and increases plant water-use efficiency. Soil matric potential quantifies the soil moisture available to plants (Yadvinder-Singh et al. 2014). Gathala et al. (2017) used two years' data from the longer rice-wheat experiment at Modipuram to show that tillage and crop establishment method do not affect soil matric potential. However, the authors demonstrated that residue retention in wheat significantly decreased the pressure of the soil matric

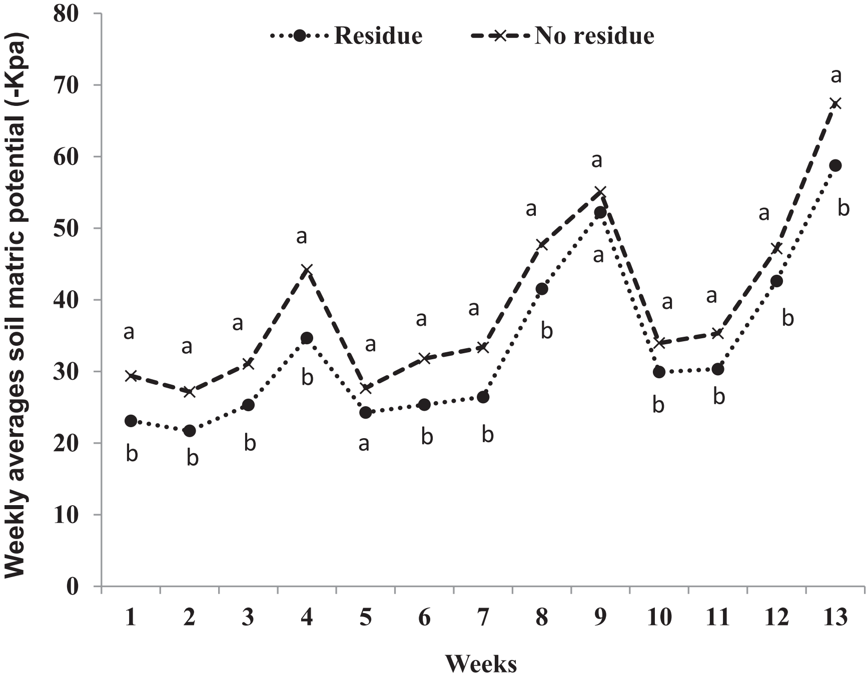

Fig. 24.6 Average soil matric potential in wheat with residue retained and removed. (From Gathala et al. 2017)

potential (at the 0.15–0.19 m root-zone depth) by an average of −5.7 MPa in the 14 weeks after crop establishment, compared to wheat grown without retained residues, thus significantly increasing the plant-available soil water (Fig. 24.6). The effects of residue retention on soil matric potential are likely to be observed not only in wheat but in other dry-season crops, although this requires further research. Gathala et al. did not observe a difference in matric potential with residue retention in the wet-season rice crop; this is unsurprising as water stress is much higher in the dry-season crops than in the wet-season rice crop.

24.3 Improving Soil Chemical Health Under No-Till Crop Establishment

24.3.1 Nutrient Retention

Jat et al. (2018) observed that one of the major effects of NT practices was greater accumulation of total nitrogen in the topsoil compared to the CT baseline. After seven years they observed increases in soil nitrogen and potassium under full NT

Table 24.1 Available nitrogen, phosphorus and potassium (0–0.3 m) in tilled, partially-tilled and no-till cropping systems after a seven-year cropping system experiment

Treatment	Available nitrogen	Available phosphorus	Available potassium
	(kg ha^{-1})		
Rice-wheat; tillage	251 ± 3.22	29.5 ± 2.23	389.4 ± 9.1
Rice-wheat-mungbean; partial no-till	270 ± 3.71	28.5 ± 1.58	393 ± 6.7
Rice-wheat-mungbean; no-till	287 ± 3.51	32.9 ± 1.18	459 ± 5.8
Maize-wheat-mungbean; no-till	306 ± 4.04	29.8 ± 2.04	534 ± 1.52

Derived from Jat et al. (2018)

treatments relative to partial NT and CT treatments, while soil phosphorus levels under NT were comparable to, or slightly higher than, under CT (Table 24.1). Jat et al. observed that higher biomass loads (i.e. roots in the soil and retained crop residues) combined with slower decomposition in the minimally-disturbed NT treatments were likely to have increased total nitrogen concentrations in the NT systems. They also attributed the higher levels of potassium under NT treatments to additions over time from crop residues.

Jat et al. (2018) found the presence of micronutrients in the soil was significantly affected by soil tillage practice. In the topsoil (0–0.15 m) available zinc concentrations were significantly and considerably (51–93%) higher under full and partial NT systems than under the CT system. Similar results were observed for manganese; the authors suggest that the presence of these elements in the topsoil may be enhanced under NT due to the retention of residues and the subsequent accumulation of micronutrients in the surface layer. In contrast, concentrations of iron were significantly highest under the partial NT system, and lowest in the full NT systems. Jat et al. suggest that puddled rice (which was part of both the partial NT and the CT systems) provides conditions which are conducive to the conversion in the soil of iron into forms readily accessible to crops.

24.3.2 Energy (Carbon) Retention

Soil organic carbon is the basis of soil fertility; soils with higher organic carbon levels are healthier and better able to support sustainable crop production (Gathala et al. 2011a). Tillage operations expose soil organic carbon to decomposition, while NT management facilitates the retention of soil organic carbon within plant-available soil layers (Gathala et al. 2011a).

Gathala et al. (2011a) observed a positive relationship between soil aggregation and soil organic carbon: fresh organic carbon enters into macroaggregates within the soil and over time degrades into the core of new microaggregates. They observed an increase in soil organic carbon over the seven-year experiment in the 0–0.15 m layer. Compared to the CT baseline, soil organic carbon was 22% higher under

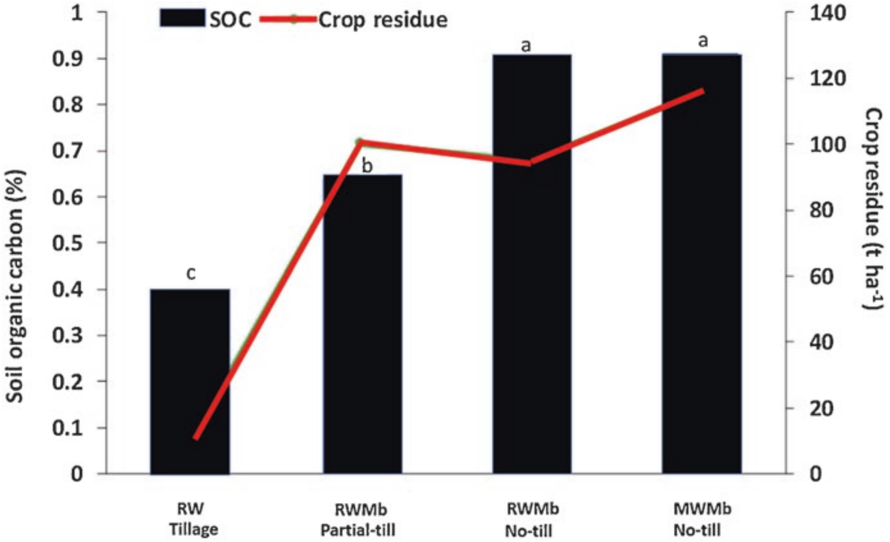

Fig. 24.7 Soil organic carbon (SOC) and crop residue under tillage, partial-tillage and no-till cropping systems. Treatments with the same letter are not significantly different at the $p < 0.05$ level. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *MWMb* maize-wheat-mungbean. (Data from Jat et al. 2019a)

standard NT and 7% higher under the raised-bed NT: increases in soil organic carbon contributed to higher soil aggregation in NT systems. Similarly, Jat et al. (2018, 2019a) found that soil organic carbon was strongly associated with residue retention and reduction in soil disturbance (Fig. 24.7). Compared to an initial value of 0.45%, Jat et al. observed that soil organic carbon in the partial-till system increased over seven years to 0.65%, while soil organic carbon in NT systems increased to over 0.90%. In the NT systems there was no effect of different crops in rotation on soil organic carbon level. Jat et al. suggest that the increase in slow-decaying residues (on the soil surface and as root matter) in NT systems may increase the soil organic carbon concentrations in NT systems.

24.4 Improving Soil Biological Health Under No-Till Crop Establishment

24.4.1 Soil Microbes Mediate Key Soil Processes

Edaphic microbes play an important role in maintaining the health and functionality of soils (Choudhary et al. 2018). The type and magnitude of microbial populations are influenced by cropping system, available organic matter, and crop establishment practices including tillage and residue retention (Choudhary et al. 2018). Soil

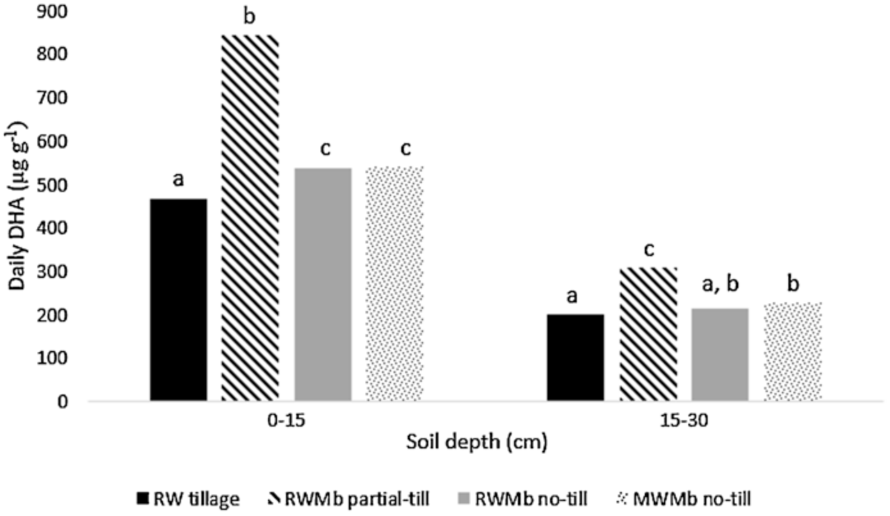

Fig. 24.8 Daily dehydrogenase activity (DHA) under tillage, partial-tillage and no-till cropping systems. Treatments with the same letter are not significantly different at the $p < 0.05$ level. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *MWMb* maize-wheat-mungbean. (Data from Jat et al. 2019a)

organic carbon is linked to soil biological properties: greater organic carbon in the soil indicates greater and more robust communities of microorganisms (Jat et al. 2019a). Soil microbes are critical to facilitate the availability of nutrients to plants. Dehydrogenase activity (DHA) is a key biological measure of soil fertility; it is also important for the decomposition of organic matter within the soil (Jarvan et al. 2014). NT practices increase the presence and diversity of soil microbes in cereal-based systems, resulting in greater stability of microbial ecosystems within the soil, and leading to improved soil health (Choudhary et al. 2018b).

Jat et al. (2019a) observed highest DHA values under partial-tillage and lowest under tilled systems (Fig. 24.8). They suggest that the highest values occurring in the partial-tillage cropping system were as a consequence of incorporation (through tilling) of dry season crop residues before rice, leading to a greater availability of carbon and nitrogen for microbes as crop residues break down faster when incorporated into very wet soil, as in this treatment. These findings were supported by Choudhary et al. (2018), who observed higher DHA under NT in both rice-based and maize-based cropping systems. Choudhary et al. suggest that, under NT, greater amounts of organic matter (from crop residues and roots) in the topsoil than under CT practice contributed to the significantly higher activity of microbial populations.

Soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) both varied considerably under different tillage and residue retention practices. Jat et al. (2019a) observed MBC and MBN were both highest under partial-tillage, followed by NT systems, with the CT system having the lowest MBC and MBN

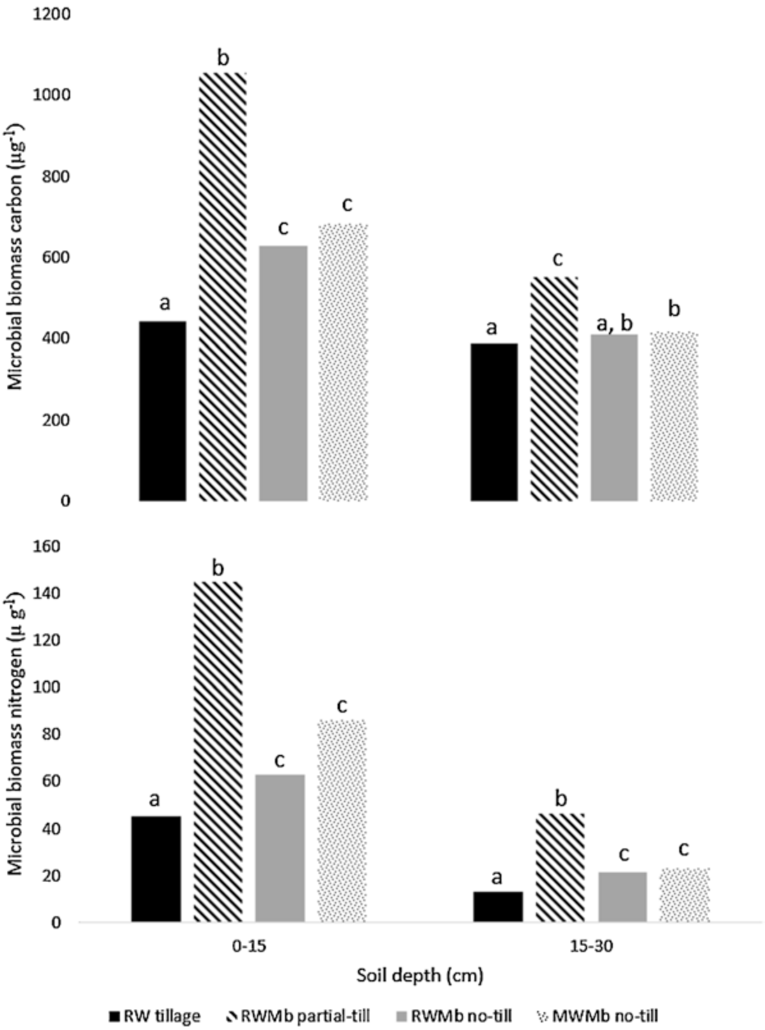

Fig. 24.9 Microbial biomass carbon (top) and microbial biomass nitrogen (bottom) under tillage, partial-tillage and no-till cropping systems. Treatments with the same letter are not significantly different at the $p < 0.05$ level. *RW* rice-wheat, *RWMb* rice-wheat-mungbean, *MWMb* maize-wheat-mungbean. (Data from Jat et al. 2019a)

(Fig. 24.9). Similar results were observed by Choudhary et al. (2018), who found also that cropping systems with legumes in the rotation had higher soil organic carbon, MBC and MBN than those without, regardless of tillage system or residue retention practice. The higher MBC and MBN under partial-till and NT systems are likely due to greater amounts of residues: MBC in particular strongly depends on soil organic carbon inputs from plant biomass (Choudhary et al. 2018).

Table 24.2 Rates of change of key microbial populations under no-till relative to tillage systems

Microbial population	Rice based cropping systems	Maize based cropping systems
Bacteria	+ 26%	+ 28%
Fungi	+ 61%	+ 68%
Actinomycetes	+ 92%	+ 98%

Choudhary et al. (2018) observed increases in the populations of three key classes of soil microbes under NT treatments relative to a traditional CT baseline (Table 24.2). Bacterial populations increased by over a quarter in both rice- and maize-based cropping systems; fungi populations by almost two-thirds, and populations of actinomycetes almost doubled under NT. These increased populations indicate improvement in the biological health of soil. Changes in indicators of soil biological health can be early signals of the direction and rate of change of overall soil health.

24.5 No-Till Crop Establishment Breaks the Cycle of Soil Degradation

The negative effects of tillage practices on soil physical health lead to a downwards spiral of overall soil health. Tillage destroys soil structure and compacts the soil. This reduces water movement through the soil, decreases topsoil thermal conductivity and reduces the availability of inter-pore spaces in which plant roots grow. To overcome these practices, farmers have traditionally maintained a regular tillage regime before sowing each crop, often interspersed every few years with deep-tilling events, in an effort to maintain productivity. However, ongoing tillage only exacerbates the physical problems it was intended to overcome. Tillage also reduces soil chemical and biological health and reduces overall health in soils under agronomic management. Introducing NT practices, either alone or as part of larger management practices focused on conservation agriculture and/or sustainable crop production, improves soil health and over time breaks the downward cycle of soil degradation.

The initial benefits observed by farmers following the introduction of NT practices are generally in terms of increased cropping system productivity and water use efficiency (Islam et al. 2019), or increased energy use efficiency (Gathala et al. 2019). As well, reductions in CO_2-equivalent greenhouse gas emissions are likely to occur with the introduction of NT management (Gathala et al. 2019). Improvements in soil health will take longer to be observed in terms of changes in soil physical, chemical, and biological factors. Of these, it is likely that soil microbial populations, available carbon, and available nitrogen will respond earliest to innovations in crop management, with metrics of soil physical health taking longest to respond.

24.6 Effects of Improved Soil Health on Crops and Cropping Systems

For key crops and cropping systems in the Indo Gangetic Plains, improved soil health under NT systems directly improves average crop (except rice) and cropping system productivity and water usage. We examined the yield performance and change in irrigation water usage reported in the literature from long term experiments in semi-arid regions of South Asia. These experiments compared NT to a tilled CT baseline, sometimes in combination with other improved management practices including residue retention, mechanized crop establishment, and good agricultural management. The cropping systems reflect those common in drier regions of South Asia; rice-wheat, rice-maize, maize-wheat, rice-lentil, and soybean-wheat. Over 70 studies have been published in the last 15 years; a bibliography of supplementary references is presented at the end of the chapter.

Compared to CT management, at the crop level under NT management the average yield of all crops except that of rice increased: gains were greatest in wheat (10.2%) and smallest in lentil (5.37%; Table 24.3). Rice production was 4.23% higher in CT systems: this is likely due to the anaerobic conditions created under puddling that enhance nutrient availability (Gathala et al. 2011a). However, at the cropping system level yields were higher in all instances, indicating that yield gains under non-rice crops under NT more than ameliorated the yield penalty from rice grown without tillage. Improvements in yield were highest in the maize-wheat (10.28%) and rice-wheat (10.22%) systems and least in the soybean-wheat system (1.22%).

Jat et al. (2019a) showed that in NT systems, the retention of residues significantly lowered canopy temperature below air temperature by up to 4 °C in wheat crops towards the end of the growing season (i.e. from approximately 130 days after sowing until harvest). This reduction from ambient temperature was not observed when residue was removed (Fig. 24.10). Similarly, Jat et al. (2019b) demonstrated

Table 24.3 Synthesis of over 70 studies showing change in average yield and water use under no-till relative to a conventional tilled system

Crop	**Yield change (%)**	**Water use change (%)**
Rice	−4.23 (−8.53 to −1.73)	−14.20 (−17.24 to −10.38)
Wheat	10.16 (9.80 to 11.51)	−12.55 (−15.34 to −10.04)
Maize	7.81 (3.27 to 10.54)	−18.45 (−23.68 to −16.56)
Soybean	6.61 (−2.25 to 14.56)	−4.84 (−7.22 to −2.94)
Lentil	5.37 (−1.34 to 15.24)	−4.14 (−6.23 to 2.40)
Cropping system	**Yield change (%)**	**Water use change (%)**
Rice-wheat	10.22 (9.88 to 11.98)	−13.22 (−15.46 to −10.20)
Rice-maize	5.21 (2.27 to 6.37)	−6.84 (−8.64 to −3.28)
Maize-wheat	10.28 (8.74 to 12.78)	−15.53 (−18.55 to −13.83)
Rice-lentil	3.66 (1.62 to 6.33)	−7.44 (−10.52 to −1.20)
Soybean-wheat	1.22 (−8.32 to 9.66)	−9.02 (−14.55 to −4.24)

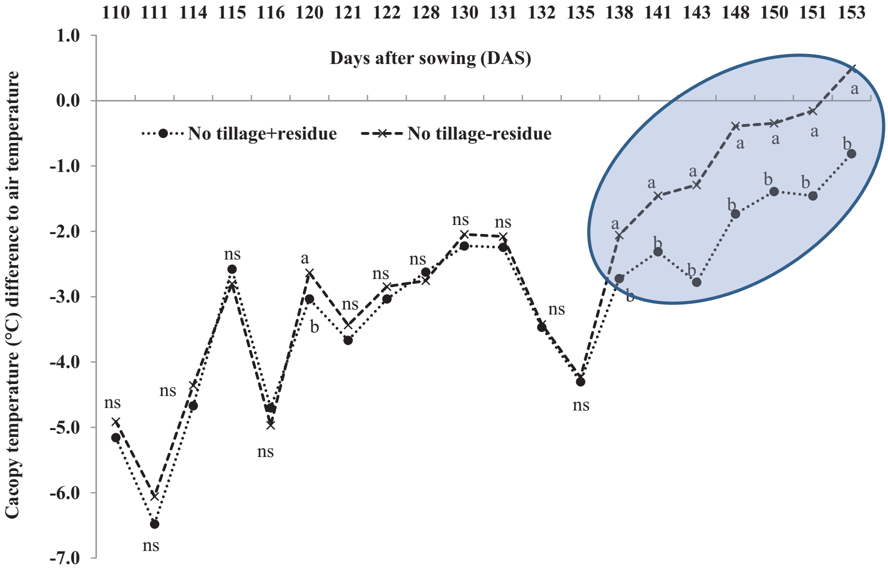

Fig. 24.10 Crop canopy temperature difference from ambient air temperature (°C) under no-till wheat, with residues retained and removed. Treatments with the same letter are not significantly different at the $p < 0.05$ level. (From Jat et al. 2019b)

that photosynthesis rate and leaf water potential were improved under NT systems with residue retention compared to CT systems. Terminal heat stress is a critical issue in the Indo Gangetic Plains and reduces yields in wheat especially.

In terms of water use, crops in NT systems are significantly more water efficient than traditional CT systems (Islam et al. 2019; Jat et al. 2019b). Our analysis of long-term studies examining NT systems in semi-arid regions in South Asia (Table 24.3) demonstrates that, for every crop and cropping system, NT practices reduced average irrigation water usage. Water savings were greatest in maize (−18.45%) and rice (−14.20%) crops; at the cropping system level savings were greatest at the maize-wheat (−15.53%) and rice-wheat (−13.22%) systems. Extrapolating from these results, rainfed cropping systems in semi-arid regions will also benefit from NT as the improved soil water storage and crop water availability resulting from improvements in soil structure, aggregation and overall physical health are likely to reduce variability in crop yields and may also increase cropping system productivity (Gathala et al. 2011a; Kumari et al. 2011).

24.7 Conclusion

Soil health is critical to the sustainable production of food and resource crops. Agronomic management practices that improve soil health will contribute to the sustainability and productivity of cropping systems. While it is challenging to directly quantify soil health, we can use indicators of soil physical, chemical, and biological health to infer the overall health of a soil. We have used case studies from long-term experiments at two sites in semi-arid regions of the Indo Gangetic Plains, Modipuram in Uttar Pradesh and Karnal in Haryana, to demonstrate that NT systems improve soils across all three key indicators relative to traditional CT practices.

While some aspects of sustainable crop production, such as system productivity or water or energy use efficiency, will begin to show signs of improvement under NT fairly rapidly (e.g. over one to three cropping seasons), indicators of improvements in soil health under NT will be observed more slowly. This is particularly true for changes in soil physical factors.

Besides NT, other characteristics of cropping system management may also contribute to improved soil health and thus to crop productivity: these include retaining soil residues; diversifying crops in rotation and including legumes; targeted applications of water and nutrients; and using satellite image mapping, real-time weather forecasting and other digital tools to ensure farm management is timely and appropriate. These management practices have not been examined here but they are by no means unimportant, and will likely to continue to increase in relevance in future. Under NT weeds are generally managed differently than under CT, often with an increased reliance on herbicides: we have not discussed this here due to lack of space.

There are clear benefits provided by NT systems in semi-arid regions in South Asia to improve overall soil health by improving soil physical, chemical, and biological indicators relative to CT systems. These benefits of NT are likely to also be achieved in other semi-arid regions. NT systems are an effective and appropriate management tool for farmers in semi-arid regions globally to sustainably improve their soil health, thus contributing to improved cropping system productivity and profitability.

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Chapter 25

Lessons Learnt from Long-term No-till Systems Regarding Soil Management in Humid Tropical and Subtropical Regions

Cimélio Bayer and Jeferson Dieckow

Abstract Based on the thermodynamic principle of minimum entropy production, we propose that the two fundamentals of soil management in the sunny, warm and rainy ecosystems of humid tropical and subtropical regions are non-disturbance of soil and high input of crop residues. The positive results of ordering soil processes surpassing dissipative ones are clearly enabled by no-till (NT), but not totally. High input cropping systems, adding at least 10 Mg DM ha^{-1} $year^{-1}$ of phytomass to soil, must be properly coupled to NT in those regions as well. Soil organic matter (SOM) is the nexus between a conservation management system, like high input NT, and the resulting improvement of soil quality that leads to sustained crop production and environmental conservation. Particularly in the tropics and subtropics, SOM plays crucial roles in soil aggregation, water holding capacity, CEC, nutrient storage, biological activity, and many other soil processes. In the first 5–10 year of a conservation management system, SOM accumulates mainly in the top 0.2 m soil, but in the long term (>20 years) accumulation also extends to layers as deep as 0.20–1 m, thus prolonging the period of accumulation to more than the 20–30 years that were initially expected for conservation managements in temperate regions. With substantial soil carbon accumulation, and in many cases mitigation of soil nitrous oxide emissions, conservation management has also helped to curb greenhouse gases emissions. Yet NT has a number of critical challenges in tropics and subtropics, many of them associated just with cropping system. Autumn and or winter fallow, for instance, prevent the achievement of the minimum 10 Mg DM ha^{-1} $year^{-1}$ of phytomass addition, besides leaving the soil prone to the heavy and erosive rain-

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falls. Cultivation of cover crops is a feasible strategy to close these fallow gaps, including the cultivation of legumes, which are also advantageous to nitrogen input and even to SOM accumulation. New insights on the increased efficiency of soil microorganisms to metabolize carbon from labile residues such as legumes and on the stabilization of this carbon in organo-mineral interactions are crucially supportive to the recommendation of these species in sustainable NT cropping systems. Other challenges of NT relate to soil compaction and the low adoption of support practices such as contouring and terracing. Our key message is that NT is an outstanding farming system in tropical and subtropical regions that enables the non-disturbance of soil and the many other benefits that follow, but its successful outcomes in terms of organic matter accumulation and therefore minimum entropy production are only attainable in cropping systems with a high input of crop residues; an input that is ecologically achievable, given the favorable conditions and resources of humid tropical and subtropical regions.

Keywords Entropy · Organic matter · Sustainability · Cropping system · Cover crops · Phytomass

25.1 Humid Tropical and Subtropical Environments

Humid tropical and subtropical regions are characterized by the incidence of intense solar radiation and by the occurrence of high rainfall volume and erosivity (Table 25.1). On general averages, tropical and subtropical regions receive

Table 25.1 General and average characteristics of climate and soil in humid tropical and subtropical regions and in temperate regions

Characteristic		Tropical and subtropical	Temperate
Climate			
Solar radiation, cal cm^{-2} day^{-1}		400	200
Rainfall volume, mm year^{-1}		1500	750
Rainfall erosivity, MJ mm ha^{-1} h^{-1} year^{-1}		> 5000	200–400
Soils			
Main classes, % area	Oxisols	23	–
	Ultisols	20	7
	Alfisols	15	13
Variable charge soils, % area		60	10
Main minerals in clay fraction		Kaolinite, iron and aluminum oxides	2:1 minerals

Sources: McGregor and Nieuwolt (1998), Panagos et al. (2017), Sanchez and Logan (1992) and Uehara and Gillman (1981)

400 cal cm^{-2} day^{-1} of solar energy and 1500 mm of annual precipitation, which is twice as high the 200 cal cm^{-2} day^{-1} and the 750 mm $year^{-1}$ that temperate regions receive (Sanchez 1976; Greenland et al. 1992; van Wambeke 1992). The rainfall erosivity varies from less than 400 MJ mm ha^{-1} h^{-1} $year^{-1}$ in temperate region to more than 5000 MJ mm ha^{-1} h^{-1} $year^{-1}$ in tropical/subtropical regions (Panagos et al. 2017).

Because of heat and humidity, the soils of those regions are generally highly weathered, deep and with a physical structure that allows free drainage. The Oxisols are a typical example of soils commonly found in this region. Due to the high degree of weathering, many chemical, physical, and biological attributes of these soils are dependent on organic matter, which plays a vital role in their functioning (Sanchez 1976; van Wambeke 1992). These highly weathered soils are commonly regarded as poor in organic matter relative to temperate soils, but Greenland et al. (1992) and Sanchez and Logan (1992) argued this was a myth and that science shows that because of the higher net primary production and soil carbon stabilization in humid tropics and subtropics, the range of soil organic matter (SOM) content is variable and comparable to temperate regions under native vegetation. However, the higher turnover of organic matter and the difficulty of maintaining its levels in cultivated soils in humid tropical and subtropical ecosystems due to the potentially higher activity of soil decomposer microorganisms is not a myth (Greenland et al. 1992), and is a challenge that must be addressed with much more attention to soil management than perhaps in temperate regions.

The exceptional biological activity in humid tropical and subtropical ecosystems, like higher net primary production of vegetation and greater activity of soil fauna and microorganisms (van Wambeke 1992; Mielniczuk et al. 2003), represents an ecological condition that is extremely favourable agronomically in terms of food, fiber, and energy production. In some regions it is possible to grow two or more high yielding crops per year provided the natural chemical limitations of soil are removed (Mielniczuk et al. 2003). However, it also represents an ecological condition that requires more attention to environmental conservation practices, as the same heat and humidity can also be highly damaging in terms of land degradation via organic matter depletion and soil erosion if management and conservation practices are not duly adopted (Ogle et al. 2005; Blanco-Canqui and Lal 2010). The best management of soil cover, soil structure, and SOM with crop rotation and cover crops, as well as the adoption of support conservation practices like contouring and terracing are mandatory to minimize the risks of soil degradation in the tropics and subtropics, even in no-till (NT) systems (Mielniczuk et al. 2003; Blanco-Canqui and Lal 2010; Merten and Minella 2013).

25.2 The Thermodynamics of the Soil System and the Fundamentals of Soil Management

Thermodynamically, the soil is an open and complex system that exchanges energy and matter with its surroundings and can reach different levels of organization depending on its flows of energy and matter (Addiscott 1995). The complexity of the soil system derives from the interaction between its physical, chemical, and biological subsystems and from the interactive response of those subsystems to soil management practices (Vezzani and Mielniczuk 2009; Delgado and Gómez 2017).

The main source of energy in natural and agro ecosystems is the sun, whose radiation can directly reach the soil surface, raise the soil temperature, and thus intensify dissipative processes such as the decomposition of organic matter and the breakdown of aggregates, ie, increases entropy and decreases enthalpy. On the other hand, the solar energy can prompt ordering processes by being converted into chemical energy and incorporated into organic compounds through photosynthesis, being latter transferred into the soil, mainly as decomposition products of above or belowground phytomass, through microbially mediated flows. Starting with photosynthesis, ordering processes end up reducing entropy and increasing enthalpy of soil by promoting the accumulation of organic matter and its complex and supramolecular structure, as well as by increasing microbial biomass and by improving soil aggregation (Addiscott 1995).

We argue that a sustainable soil management system for humid tropical and subtropical regions must be based on what Addiscott (1995) developed and called the principle of minimum entropy production, which results from ordering processes being greater than dissipative processes. Therefore, the balance between dissipative and ordering processes, which are highly influenced by management practices, will determine whether the soil is losing quality (dissipative > ordering) or gaining quality (dissipative < ordering) over the time a given management is being adopted.

Intensive soil tillage operations coupled with poor cropping systems that include fallow periods, monoculture, or even burning of crop residues advance dissipative processes and decrease ordering ones. In this case, soil degradation is therefore severe and rapid, since the climatic conditions of high precipitation and temperature are highly favourable to the biological activity of SOM decomposition (Mielniczuk et al. 2003) and to the physical process of soil erosion (El-Swaify et al. 1982; Lal 1990; Labriere et al. 2015).

The fundamentals of soil management must be conceived from the premises that they are vital for maintaining or improving soil quality, that they lead to environmental protection coupled with high productivity in the long-term, and that through the flows of energy and matter in the soil-plant-atmosphere system they promote ordering processes and attenuate dissipative processes, bringing the dissipative/ordering ratio to <1 (Addiscott 1995). Attenuation of dissipative processes can be accomplished by eliminating or minimizing mechanical soil disturbance, thus increasing soil cover, preserving soil structure and reducing organic matter decomposition (Fig. 25.1). Promotion of ordering processes can be accomplished by

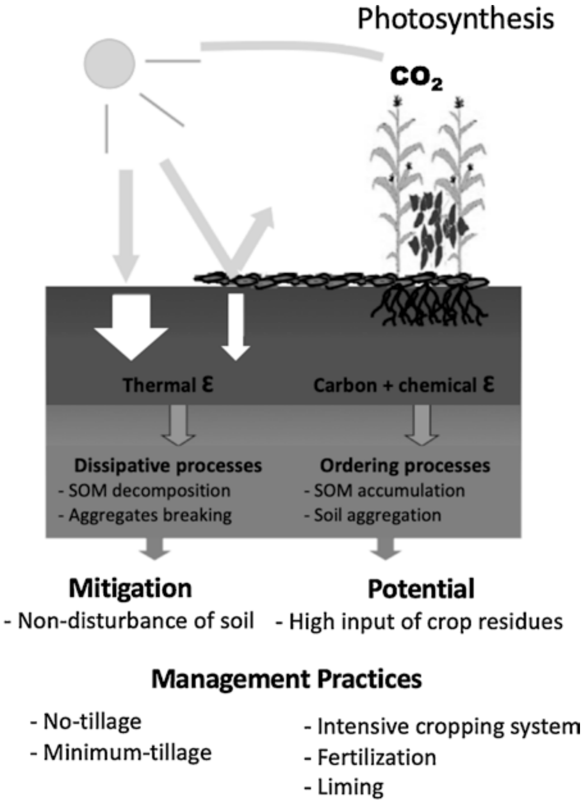


Fig. 25.1 Conceptual framework of energy flows in the soil system and its effect on dissipative and ordering processes, and related agricultural practices

increasing photosynthesis and the net primary production, thus increasing the beneficial effects of plants in terms of soil cover by canopy, soil aggregation by roots, and input of organic material into the soil to fuel biological activity and the organic matter accumulation that follows (Fig. 25.1).

Therefore, based on the thermodynamics of the soil system, we propose that the two fundamentals of soil management in humid tropical and subtropical regions are the **(i) non-disturbance of soil** and the **(ii) high input of crop residues**. Only in compliance with those two fundamentals is possible to achieve a predominance of ordering relative to dissipative processes and, therefore, an improved soil quality and sustainable production in humid tropical and subtropical croplands. And we argue that the way to turn these fundamentals into practical reality is essentially by adopting NT and cropping systems with high net primary production, not overlooking complementary strategies that also contribute to phytomass production like fertilization, liming, cover crops, or integrated crop-livestock. These two fundamentals are consonant to the three main principles of conservation agriculture: minimum mechanical soil disturbance, permanent soil organic cover, and species diversification (FAO 2019).

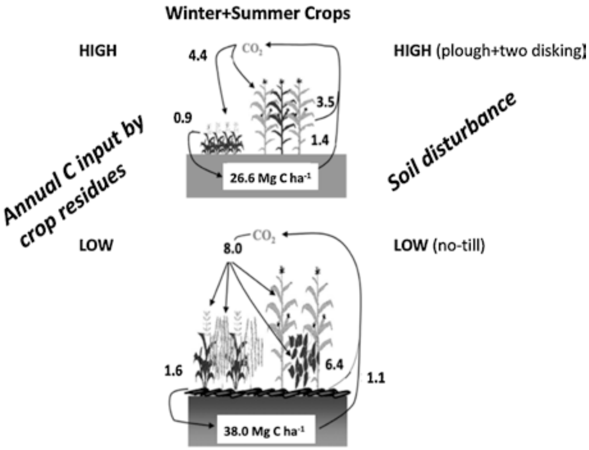


Fig. 25.2 Carbon flows as a proxy for the energy flows in a subtropical soil subjected to traditional (top) and conservation (bottom) management systems. (Source: Adapted from Bayer et al. (2006))

Figure 25.2 shows carbon flows as a proxy for energy flows in the soil-plant-atmosphere system and their effects on ordering and dissipative processes in a long-term experiment conducted in the Brazilian subtropics. Here the soil was under traditional management based on conventional tillage (CT) and low-input cropping systems, or under conservation management based on NT and high-input cropping system.

Under traditional management, 0.9 Mg C ha^{-1} year^{-1} was effectively incorporated into the SOM pool, assuming that the overall addition of 4.4 Mg C ha^{-1} year^{-1} by winter and summer crops was converted into the organic matter pool at a rate of 20% (humification coefficient); while 1.4 Mg C ha^{-1} year^{-1} was emitted to the atmosphere by the microbial decomposition of SOM. Therefore, in the traditional management, the dissipative process that represents the carbon originally in a supramolecular organic matter structure flowing into the atmosphere as individual CO_2 molecules was greater than the ordering process that represents the carbon effectively incorporated into the complex nature of organic matter, at a net dissipative rate of 0.5 Mg C ha^{-1} year^{-1} (1.4 minus 0.9).

However, when the two fundamentals were applied via conservation management, the ordering process was quantified as 1.6 Mg C ha^{-1} year^{-1} effectively incorporated into the SOM, from an overall addition of 8.0 Mg C ha^{-1} year^{-1} by crops, and it was greater than the dissipative processes represented by a loss of 1.1 Mg C ha^{-1} year^{-1}, at a net ordering rate of 0.5 Mg C ha^{-1} year^{-1}.

Greater dissipative than ordering processes increased the entropy and led the soil system to a lower level of order, as illustrated theoretically in the Fig. 25.3a redrawn from Prigogine (1997) and evidenced experimentally in soil carbon depletion in Fig. 25.3b. In contrast, soil management based on two fundamentals became organized into a higher level of order (Fig. 25.3a), according to the accrual of soil carbon pool (Fig. 25.3b). It is interesting to note the equivalence between the theory illustrated in Fig. 25.3a and the observation in a long-term experiment conducted in Brazilian subtropics (Fig. 25.3b).

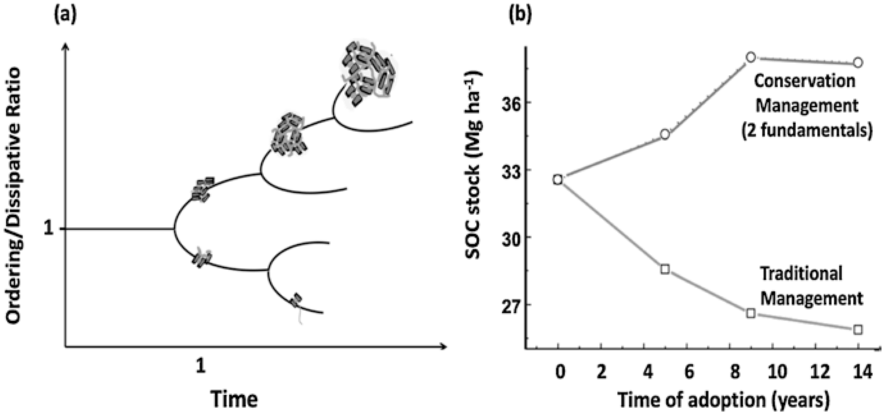


Fig. 25.3 (**a**) Conceptual framework of changes in soil order levels and (**b**) equivalent changes in soil carbon pools under traditional and conservation management in Brazilian subtropics. (Source: Adapted from (**a**) Prigogine (1997) and from (**b**) Bayer et al. (2006))

Nonetheless, in our synthetic analysis it is necessary to emphasize that improvement of soil quality towards a higher level of order by conservation management is essentially of biological nature, since all processes of soil ordering are governed by the input of energy and matter via plants and by all microbial transformations that follow (Addiscott 1995). In principle that means that plants are essential for ordering processes, minimum entropy, and soil quality; and ultimately this underlines the practical importance of high-input and diversified cropping systems, even in NT (Conceição et al. 2013).

It is not our goal here to revisit the concepts of soil quality, which are clearly explained elsewhere (Doran and Parkin 1994; Vezzani and Mielniczuk 2009), but only to address the interrelationship between soil physical, chemical, and biological subsystems and their interactive response to soil management practices, and the central role of soil organic matter in the soil amelioration process. An essential aspect is that the feedback between increased crop productivity and amount of crop residues returned to the soil has a positive and gradual impact on soil characteristics over time.

The soil organic matter is an essential soil component and the nexus between soil management and soil quality in humid tropical and subtropical environments. In the soils of these regions, organic matter is a determining factor of soil CEC (>70% of CEC coming from organic matter), Al toxicity, nutrient availability after mineralization, decreased P retention on oxide surfaces, aggregation, porosity and resistance to compaction, and water infiltration and availability, with strong corresponding effects on the productive capacity of soil (Doran and Parkin 1994; Lovato et al. 2004; Fließbach et al. 2007).

25.3 Soil Organic Matter, its Dynamics and Stabilization in Management Systems

The rate of change in SOC stocks (dC/dt) is a balance between the amount of carbon effectively added by crops into the SOM pool (k_1A) and the amount of carbon that is lost from the SOM pool via mineralization (k_2C), expressed in the equation (Henin and Dupuis 1945; Mielniczuk et al. 2003):

$$dC/dt = k_1A - K_2C \tag{25.1}$$

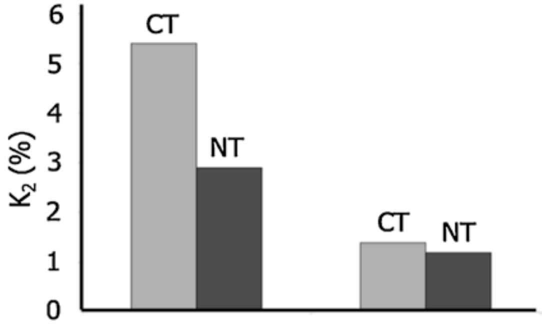
The input flow is controlled by the annual amount of carbon added by the cropping system onto or into the soil as above or belowground phytomass (A), and by the humification coefficient (k_1), which represents the ratio of the added carbon that is effectively incorporated into the SOM pool after 1 year. The output flow is controlled by the SOM mineralization rate (k_2), ultimately controlled by the degree of soil disturbance that is caused by the tillage system.

Although the composition of the crop residue in cropping systems may influence the k_1 coefficient, more attention has been given to the amount of phytomass carbon (A) added. In addition, most of the studies focuses on the aboveground carbon, and less emphasis has been given so far to the carbon addition by roots, although roots have a great potential to promote soil carbon accumulation (Balesdent and Balabane 1992; Balesdent and Balabane 1996), especially in deep soil layers where higher deficits of carbon saturation occur (Rumpel et al. 2015; Poirier et al. 2018).

Regarding the carbon output flow, soils managed under NT generally have a much lower mineralization rate, k_2, than soils under CT, as seen for the Ultisol in Fig. 25.4. Under no or minimal disturbance of soil, the lower turnover rate of macroaggregates in NT soil increases the physical protection by occlusion of the particulate organic matter and thus offers it a time to mature, to be stabilized in microaggregates, and ultimately to become chemically stabilized on mineral surfaces via organo-mineral interactions (Six et al. 2000; Balabane and Plante 2004). However, the magnitude of the effect of tillage system on the mineralization rate depends on soil texture and mineralogy. Figure 25.4 shows that the impact of NT at reducing the mineralization rate k_2 was more noticeable in the medium textured Ultisol than in the clayey Oxisol. Due to the higher chemical stability of the SOM associated with surfaces of iron and aluminium oxides, the SOM mineralization rate in the clayey Oxisols was much lower and less responsive to tillage system (Fig. X4).

The combined effect of non-disturbance by NT (lower k_2) and high-input of carbon by cropping system (higher A) can be seen in Fig. 25.5. Eliminating soil disturbance by the adoption of NT reduced the SOM decomposition rate k_2 from 0.040 per year (4%) to 0.019 per year (1.9%), which increased the SOM mean residence time (MRT = $1/k_2$) from 25 to 53 years. At the same time, the increase of the annual input of plant biomass by cropping systems led to a linear increase in the SOC stock in both CT and NT systems.

The relationship between the annual change of the SOC stock relative to the initial stock (dashed line) also allows us to analyse the ratio between ordering and



	Ultisol	Oxisol
Mean annual temperature (°C)	19.4	21.2
Mean anual precipitation (mm year^{-1})	1440	1713
Clay content (g kg^{-1} soil)	220	680
Fe-low cristalinity (g kg^{-1} clay)	11.8	87.6
Fe-high cristalinity (g kg^{-1} clay)	0.9	2.5

Fig. 25.4 Annual mineralization rate (k_2) of soil organic matter in an Ultisol and Oxisol and the relationship with climate characteristics, clay content and mineralogy (NT = no-till and CT = conventional tillage). (Source: Bayer, C. (data not published))

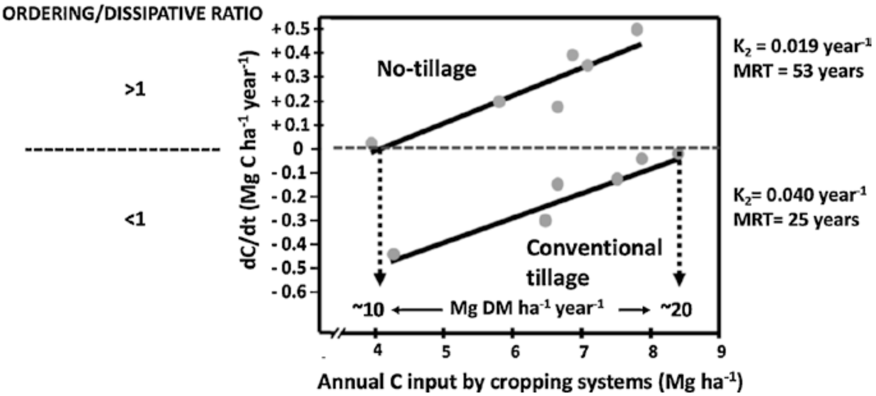


Fig. 25.5 Change in soil organic carbon stock as affected by annual carbon input and by tillage system (no-till vs. conventional), and related mineralization rate k_2, mean residence time (MRT), and amount of biomass needed to keep the initial soil carbon level (dashed line). (Source: Adapted from Bayer et al. (2006))

dissipative processes in soil (Fig. 25.5). When the SOC stock is in a steady state (unchanged, dC/dt = zero), we can assume that the dissipative and ordering processes are in balance, and to keep that balance an amount of approximately 4 Mg C ha^{-1} are necessary to be added annually in NT system, while under CT that necessity rises to approximately 8 Mg C ha^{-1}. Assuming that phytomass has a carbon concentration of 400 g C kg^{-1}, it means that at least 10 Mg DM ha^{-1} of crop residue must be added annually in NT soils to attain a dissipative/ordering ratio <1 in tropical and subtropical ecosystems. Although it is potentially feasible to reach those levels of biomass input considering the favourable environmental conditions for two to three crops per year in tropics and subtropics, many traditional cropping systems adopted for grain production in those regions, especially those with high frequency of winter and fall fallows and soybean monoculture, do not reach the minimum requirement.

Soil organic matter accrual under conservation management reaches its maximum accumulation rates in the approximately first 5–10 years of the management adoption, while afterwards those rates tend to decrease towards zero (Fig. 25.6). That decrease in SOM accumulation rates occurs because the difference between the effective addition of carbon to the soil (k_1A) and the loss of carbon by mineralization (k_2C) narrows as the SOC stock increases. Eventually, after a long period under the same management, the addition (k_1A) and loss of carbon (k_2C) tend to be similar and the SOC stock enters a new steady state. Many estimates of carbon accrual under NT management have concluded that a period of 20–30 years is required before a soil enters a new steady state under NT management (West and Post 2002; West and Six 2007). However, it was observed in the subtropical Ultisol that even at the 30th year of NT adoption the annual rates of SOC were still significant, especially under high-input cropping system (Veloso et al. 2018). This indicates that the potential of NT soil to accumulate carbon may be much longer than the 20–30 years initially indicated, at least in variable charge soils of tropical and subtropical regions.

The period over which conservation management can make the soil a net sink of atmospheric CO_2 is also influenced by soil depth. In conservation management

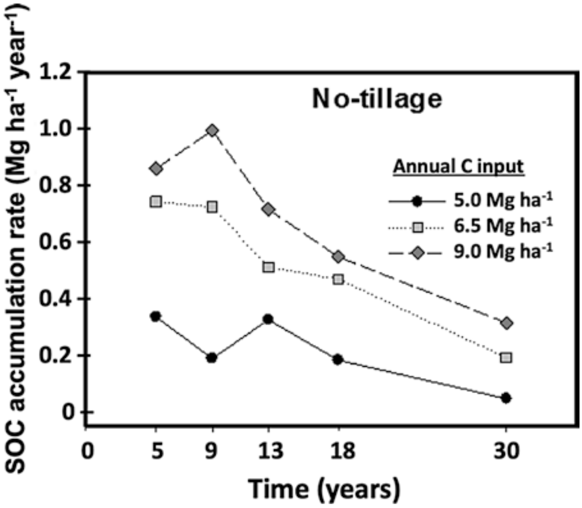


Fig. 25.6 Annual rates of soil organic carbon (SOC) accumulation in the 0.2 m top layer of a subtropical Ultisol under no-till combined with cropping systems with different potential of carbon input. (Source: Adapted from Veloso et al. (2018))

systems in temperate soils, the accumulation of SOC occurs mainly in surface layers (Angers and Eriksen-Hamel 2008; Dimassi et al. 2014), but in tropical and subtropical soils significant accumulation has also been observed in subsurface layers. Early studies showed some evidence of deep SOC accumulation in soils of the Brazilian Cerrado (Corazza et al. 1999), which was confirmed with the study of Boddey et al. (2010). They found that more than half of the overall SOC accumulation to 1 m depth occurred below 0.3 m depth in three long-term experiments (>20 years) on subtropical Oxisols. Other studies followed and confirmed this deep SOC accumulation in NT soils (Alburquerque et al. 2015; Veloso et al. 2018), but the underlying mechanisms of this accumulation are still unclear and should be a key research topic in the near future. Hypotheses range from migration of organic compounds from top to deeper layers, to direct deposition of root residues, to stabilization of the accumulated SOC by organo-mineral interaction with oxidic mineral surfaces having a high carbon saturation deficit.

The effect of deep SOC accumulation on the duration of the effective contribution of NT system to the retention of atmospheric CO_2 in a subtropical Ultisol is shown in Fig. 25.7. After 30 years under NT, the SOC accumulation rates were 0.18–0.50 Mg C ha^{-1} $year^{-1}$ in the top 0.3 m layer, while when considering the whole 0–1 m layer, the accumulation rates increased considerably to 0.80–1.15 Mg C ha^{-1} $year^{-1}$. In the early years, the SOC accumulation possibly occurred mainly in the top layers (0–0.2 m), reaching maximum rates over a period of 5–10 years and then rapidly decreasing over the coming years, as already seen in Fig. 25.6. However, as the SOC accumulation rate decreases in top layers, possibly the accumulation process moves to subsurface layers, thus explaining why subtropical and tropical soils under NT accumulate carbon beyond the 20–30 years initially expected.

Regarding the quality of the added crop residue, we are observing a paradigm shift from the traditional view that recalcitrant residues with high lignin contents and high C:N ratio are those that contribute most to the SOM pool (Marschner et al. 2008). In fact, residues with low C:N ratio and low lignin content, like those rich in

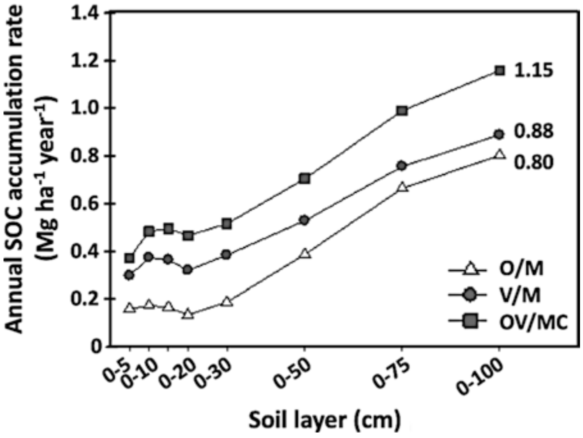


Fig. 25.7 Annual accumulation rate of organic carbon in a subtropical Ultisol after 30 years of the adoption of no-till combined with three cropping systems (oat/maize, vetch/maize, oat+vetch/maize+cowpea). Annual rates were calculated in relation to conventionally-tilled paired plot. (Source: Adapted from Veloso et al. (2018))

cellulose, other carbohydrates, and nitrogenous compounds that are metabolized rapidly (weeks to months), are also metabolized more efficiently by microorganisms and the resulting microbial products are then stabilized through organo-mineral interactions on clay surfaces (Cotrufo et al. 2013; Cotrufo et al. 2015). This is contrary to the rather common view that these residues are easily decomposed and make only a small contribution to the SOM pool.

Recent studies have corroborated the similar or higher efficiency of carbon derived from crop residues of low C:N ratio or lignin content to accumulate in soil (Bird et al. 2008; Rubino et al. 2010; Throckmorton et al. 2015). This result is relevant on practical grounds because it revives the comprehension that legume cover crops have a great potential to improve soil quality under NT. The misconception that legume residues have a low contribution to the SOM pool has led many producers and agronomists stop using them in crop rotation systems, in preference to grass species with higher biomass production. Figure 25.8 schematically shows what happen with crop residues of different quality after their addition into the soil, ie that in the long-term (1 year) there is a greater stabilization of carbon derived from residues of low C:N ratio and low lignin content (Cotrufo et al. 2015). In the same figure, this theoretical model is confirmed by results obtained in the Brazilian Cerrado, where carbon added by the black velvet bean, a legume cover-crop, had a conversion rate into SOC almost as twice of that added by millet, a grass.

In addition to SOM stocks, conservation management that includes NT and high carbon input cropping systems increase SOM lability due to the proportionately higher accumulation of labile fractions like particulate organic matter (Diekow et al. 2005; Vieira et al. 2007). Particulate organic matter is one of the main substrates for soil microorganisms, it improves soil macroaggregation, and is an important reservoir of nutrients (Gregorich et al. 1994). The carbon lability index, originally proposed by Blair et al. (1995), is an index in which the particulate organic matter fraction can be considered as the labile fraction (Vieira et al. 2007), and thus be used

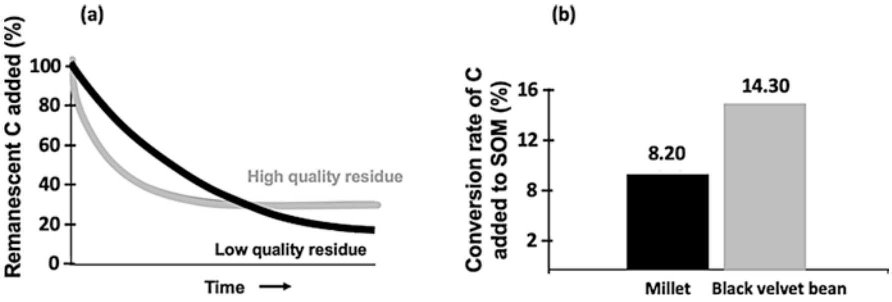


Fig. 25.8 (**a**) Conceptual illustration of carbon stabilization from high and low quality crop residues in soil and (**b**) observed data in Cerrado region showing the higher efficiency of conversion of carbon added by summer legume (Black velvet bean) than grass specie (millet) in a tropical Oxisol in Brazilian Cerrado region. (Source: Redraw from (**a**) Cotrufo et al. (2013) and from (**b**) Nunes et al. (2011))

in the evaluation of management systems. In this respect, in a long term experiment in subtropical Brazil, Zanatta et al. (2019) found lability indexes for the top 0.2 m soil of 0.9–1.4 under CT but higher values of 1.1–1.8 under NT.

Additionally, studies based on spectroscopic techniques like solid state CPMAS-^{13}C-NMR, electron spin resonance or laser induced fluorescence, showed that the conversion of CT to NT system generally increased the proportions of O-alkyl (carbohydrates) and decreased the proportions of aromatics and semiquinone free radicals, and the fluorescence signals (Bayer et al. 2000; Milori et al. 2006; Dieckow et al. 2009). The fact that in NT soil the proportion of potentially labile structures like O-alkyl increases and the proportion of more recalcitrant ones like aromatics decreases suggests that physical protection of SOM into soil aggregates and by organo-mineral interactions are playing a major role, compared with recalcitrance, in promoting soil carbon accumulation.

25.4 Evolution of Crop Yields in Long-term No-till

Crop yields respond to NT in both the short- and long-term. In the short-term, yields improve due the effect of the surface mulch increasing water availability and regulating soil temperature. In the long-term, improvements in chemical and physical soil properties have an additional impact on water availability, and improve plant development because increases in SOM alleviate aluminium toxicity, increase CEC and have positive impacts on cation availability, and lead to a higher availability of phosphorous (Bayer and Mielniczuk 1997; Ciotta et al. 2002; Ciotta et al. 2004; Silva et al. 2016).

Figure 25.9 shows the evolution of soybean yield in NT compared to CT in the Brazilian subtropic. The early years are regarded as a transitional period in which improvements in soil attributes are slow and yields may be even lower than in CT. Afterwards, the NT reaches maturity, improvements in soil attributes are consolidated and are reflected in crop yield increments that may exceed 1.5 Mg ha^{-1}. The length of the transition period depends, among several factors, on the cropping system. Under monoculture, the transition period lasted for 11 years, but under crop rotation with maize every 4 years and a legume cover crop (lupine) in winter it was reduced to 7 years; showing that improved cropping systems probably accelerate soil improvements and bring forward the related yield gains. In addition to soil quality improvement, high-input crop rotations have relevant and positive impacts on other technical aspects of the farming system, such as weed, pest and disease control, and rational use of machinery and work.

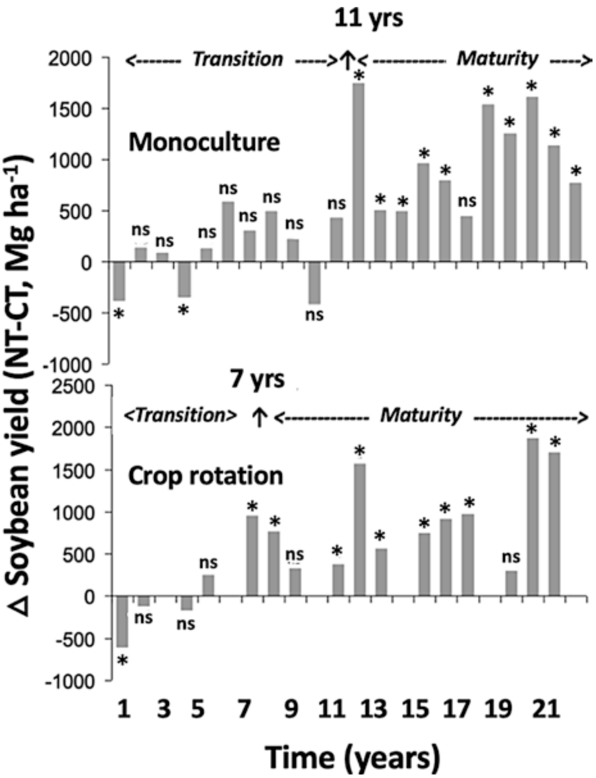


Fig. 25.9 Net increment (Δ) of soybean yield in no-till in comparison to conventional tillage combined with monoculture (wheat-soybean) or crop rotation (wheat-soybean/lupinus-maize/wheat-soybean/black oat-soybean) in a subtropical Oxisol of Southern Brazil. ∗ difference significant by Tukey test 5%. ns = not significant. (Source: Adapted from Bayer et al. (2019). Original data from Embrapa (Franchini, J. C.))

25.5 Greenhouse Gas Balance in Soil Management Systems

One of the great environmental benefits of NT by promoting soil carbon accumulation is the mitigation of CO_2 emissions, contributing therefore to decreased global greenhouse gas (GHG) emissions. However, this environmental benefit should be considered along with the potential impact of NT on the emission of non-CO_2 gases, namely methane (CH_4) and nitrous oxide (N_2O), which have a global warming potential 25 and 298 times bigger than CO_2, respectively (IPCC 2013). Additionally, the CO_2 equivalent costs from inputs and farm operations must be also properly accounted (Lal 2004; Zanatta et al. 2007).

Early GHG results obtained mainly in temperate regions showed an increase in soil N_2O emissions under NT, attributed mainly to soil compaction, would partially offset the environmental benefit of soil carbon sequestration (Ball et al. 1999; Baggs et al. 2003; Gregorich et al. 2005). However, as GHG research advanced in tropical and subtropical regions, those early results from temperate regions have not been confirmed. In tropics and subtropics, N_2O emissions in NT soils have usually been lower than those found in conventionally tilled soils, possibly due to the lower mineralization rates of SOM and plant residues under NT, and thus lower availability of ammonium and nitrate for N_2O production through soil nitrification and

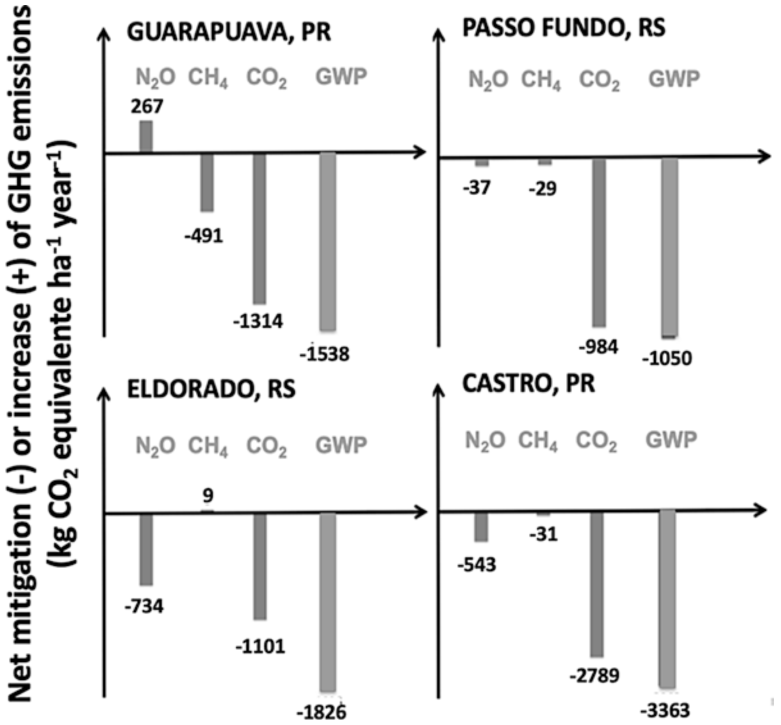


Fig. 25.10 Net greenhouse gas emissions (N_2O, CH_4 and CO_2) and mitigation of global warming potential in subtropical no-till soils in four sites of Southern Brazil [three Oxisols (Guarapuava, Passo Fundo and Castro) and one Ultisol (Eldorado)]. (Source: Bayer, C. (data not published))

denitrification processes (Jantalia et al. 2008; Escobar et al. 2010; Piva et al. 2012; Bayer et al. 2015).

In spite of that mitigation of N_2O emissions, the main determining factor for the overall mitigation of GHG emissions in NT compared to CT is the accumulation of soil organic carbon. Figure 25.10 shows the GHG balance in four NT soils in southern Brazil, where about 75% of the overall mitigation of ~2000 kg CO_2 eq ha^{-1} $year^{-1}$ was due to soil carbon accumulation. However, according with previous discussions, this GHG balance in NT system is highly dependent on the adopted cropping system and its effect on soil organic carbon stocks, so that the higher the annual biomass input, the greater the environmental benefits (Piva et al. 2012; Bayer et al. 2016).

25.6 Current Context on Cropping Systems and Main Strategies to High Biomass Input

In this section we discuss what is currently occurring in terms of cropping systems in NT farming, with emphasis on the humid subtropics of Southern Brazil. Crop diversification with plants of high yielding biomass like maize rotating with soybean in summer is a very well recognized practice that coupled with NT can better control weed, reduce the incidence of pests and diseases, and increase the input of crop residue to soil. However, the inclusion of maize in rotation with soybean in many cases is not so easily accepted by farmers, in part due to the higher costs of cultivation, higher risks of yield drop due to short periods of water deficit, and lower profitability of maize compared to soybean. Despite the many benefits of crop rotation relative to monoculture, crop rotation still has very limited adoption by farmers.

In order to improve the quality of cropping systems in terms of residue input, one strategy is to use the lands that currently are under winter fallow, a practice that unfortunately is usual in subtropical Brazil. Estimates are that over 30% of the summer acreage remains fallow in winter, due to the low economic return of winter crops like wheat, white oat, rapeseed, and barley compared to summer crops like soybean. The practice of winter fallow is very negative, especially considering the climatic conditions highly favourable to biological activity in the soil and which requires soil cover all year round to counteract dissipative processes. Cultivation of cover crops is one option to fallow, and among the several winter cover crop species we highlight black oats (*Avena strigosa* Schreb.), oilseed radish (*Raphanus sativus* L.), and vetch (*Vicia sativa* L. or *Vicia villosa* Roth); which have a biomass production of approximately 4–5 Mg DM ha^{-1} and have an important impact on nutrient cycling, especially on those nutrients susceptible to leaching such as nitrogen and potassium. Legumes such as vetch also have a strong impact on nitrogen input by symbiotic fixation, being capable of fixing more than 100 kg N ha^{-1}.

Another concern in the Brazilian subtropics is the increase of the acreage under fallow during autumn. Traditionally, autumn fallow was restricted to lands where maize grown in summer was harvested in mid-February and then a period of approximately 4 months followed until the sowing of winter crops. However, autumn fallow is now moving even into areas where soybean is grown. With the increasing use of short maturity groups of soybean cultivars, harvest is anticipated and the fallow interval until the next winter sowing has also expanded. That means that the acreage under autumn fallow has expanded four to five times over the past years and it is estimated that about 50% of croplands of the Brazilian humid tropics and subtropics are under autumn or winter fallow. This is alarming, because it is unlikely that under this scenario the required amount of biomass input of 10 Mg DM ha^{-1} $year^{-1}$ will be achieved to promote a positive balance between the dissipative and ordering processes, leading the soil into a degradation process, despite being under NT.

One alternative to eliminate or reduce the autumn fallow is a second cultivation of summer crop, like the cultivation of maize after the short maturity soybean is harvested, or even the cultivation of cover crops. For cover crops, the options vary from winter C3 species such as black oats or oilseed radish, to C4 species such as millet or Sudan grass, with those C4 plants having a higher biomass production and a more abundant root system. C4 cash crops like maize or sorghum, cultivated in high plant densities, have also presented good results in terms of mulch production and soil cover. More emphasis has been given to the importance of the root system of those C4 species in the formation and stabilization of soil structure, including the resistance to compaction and reducing their impacts on crop yields by increasing soil biopores in NT.

Recently the intercropping of two species or the intercropping "cocktails" of three or more species have shown promising results for biomass production and soil quality improvement. The causes of such benefits are many and their analysis are complex, but it involves the addition of residues of different quality that impact different microbial groups in the soil, nutrient mineralization at varying rates and over a longer period of time, soil cover also for a longer period, and distinct root systems with different soil effects. For example, fibrous root systems influenc aggregation, while taproot systems leave biopores that influence water flow and serve as a pathway to new roots (Kautz 2015).

25.7 Some Regional and Global Challenges in Soil Management Under No-till

In addition to the required improvements of cropping systems, which include crop rotation schemes and that shorten the undesirable fallow periods, NT in humid tropical and subtropical environments faces two other challenges. One relates to the degradation of soil structure by soil compaction, and that requires a proper management of machinery including the right type, pressure, and dimension of tires; a better control of soil moisture before carrying out operations; controlled traffic; and also a cropping system that incorporate species with an abundant root system capable of increasing soil elasticity and loading support (Rainbow and Derpsch 2011; Nunes et al. 2015). In integrated crop-livestock systems where animal or pasture management are inadequate due to high grazing pressure, soil compaction may also become a serious problem, particularly in clayey soils. A correct adjustment of grazing pressure to the forage allowance is the strategy to be adopted to avoid compaction and earn the multitude of benefits that integrated crop-livestock offers when properly managed (Carassai et al. 2011; Conte et al. 2011).

The second challenge relates to support practices like contouring and terracing, because many farmers are still resistant to the adoption of such practices on grounds that they hinder mechanization. But when proper management practices of soil cover and soil structure are adopted, which includes crop rotation with high biomass input, the horizontal spacing between terraces can be larger and thus mechanization difficulties minimized. The fact is that, in practical terms, there is not complete infiltration of water under high volume rainfalls, even with best management practices, and so the adoption of such support practices to control surface runoff are necessary for conservation not only of soil but also of water (Merten and Minella 2013; Deuschle et al. 2019).

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Chapter 26
No-Till Farming Systems in South Asia

Somasundaram Jayaraman, Anandkumar Naorem, Rattan Lal, Ram C. Dalal, and Ashok K. Patra

Abstract Among the resource conservation technologies, no-till (NT) farming systems have been in limelight since the 1980s around the globe. The potential of NT may be questionable for South Asian countries because the majority of the farmers are small land holders who practice rainfed farming, are resource-poor, and are faced with the shrinking cultivable land area. However, rice-wheat rotations, a predominant cropping system in South Asia, is benefitted by NT systems due to a faster turnover time that allows early planting of wheat, increases water use efficiency, and enhances crop yield. Compared to conventional tillage (CT), NT enhances soil organic carbon (SOC) sequestration, reduces emission of greenhouse gases (GHG), causes minimal disruption of soil, retains residue on the soil surface, and reduces fuel use and energy consumption. Despite an increase in the adoption rate of NT in South Asian countries, there exists a need for stronger diffusion of NT. Barriers to the adoption of NT are a lack of practical knowledge, unavailability of NT seed drills, poor performance of existing tools and technology, restricted access to inputs, and other biophysical constraints. The successful adoption of NT in these eco-regions with predominantly small land holder farmers requires that the net returns from its use are more than those from the conventional system through carbon market and/or payments for ecosystem services.

Keywords Resource conservation technology · No-till · Conservation tillage · Soil properties · Carbon sequestration · Ecosystem services

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26.1 Introduction

South Asia (SA) covers less than 3% of the world's total land area but 14% of agricultural land (Gathala et al. 2011a; Jat et al. 2014). Due to urbanization and a rapidly increasing population, expansion of agriculture is a major challenge in SA countries as more than 94% of the cultivable land is already utilized (Jat et al. 2011). Although dramatic improvements have been made in agricultural productivity and poverty reduction during the past decades, millions of people are still suffering since predominantly rainfed agriculture is subjected to environmental constraints, such as uncertain rainfall, severe land degradation, and poor soil health and quality (Hayashi et al. 2018). Converting the present farming system in SA to a more profitable and sustainable system is an unavoidable addition to the present challenges in food production. This is particularly important given the increasing prices of food and energy and climate change (Ahmed and Suphachalasai 2014).

The production variables of modern agriculture have changed enormously compared to traditional agriculture, with most of the improved practices focused on tillage, input of chemicals, and labor intensive agriculture (Abro et al. 2018). Keeping all these in priority in a quest to find alternative technological approaches, many resource conservation technologies (RCTs) have been advocated, especially for small and marginal farmers. Under the umbrella term of RCTs/conservation agriculture (CA) or the no-till (NT) system is one of the promising low external input and sustainable agriculture approaches introduced by National Agricultural Research and Extension Systems around the late 1990s (CIMMYT 2002; Abrol et al. 2005). As the name suggests, NT is regarded as a simpler technology for resource-limited farmers in SA countries because of the elimination of seedbed preparation for crop establishment. The NT system is often claimed to allow higher precision in seeding, more timely sowing, and lower production costs than those needed for the conventional tillage (CT) system (Saharawat et al. 2010; Jat et al. 2011). It also, improves soil quality and health (Sapkota et al. 2012; Somasundaram et al. 2018, 2019) while maintaining environmental sustainability and, in many cases, even increasing crop yield (Keil et al. 2015).

26.2 Key Pillars of NT Farming Systems

NT farming and CA comprise of three main pillars (Fig. 26.1) (i) minimal soil disturbances or NT; (ii) permanent soil cover using cover crops and crop residue as mulch; and (iii) diversified crop rotations and intercropping (FAO 2019). However, other components such as integrated nutrient management (INM) for resource poor farmers (Lal 2015a) and location specific water conservation practices can also be incorporated into the NT system. The NT system/CA has been promoted, especially to small land holders, to intensify sustainable agriculture (FAO 2011). However, adoption especially by small land holders, remains limited (Andersson and D'Souza

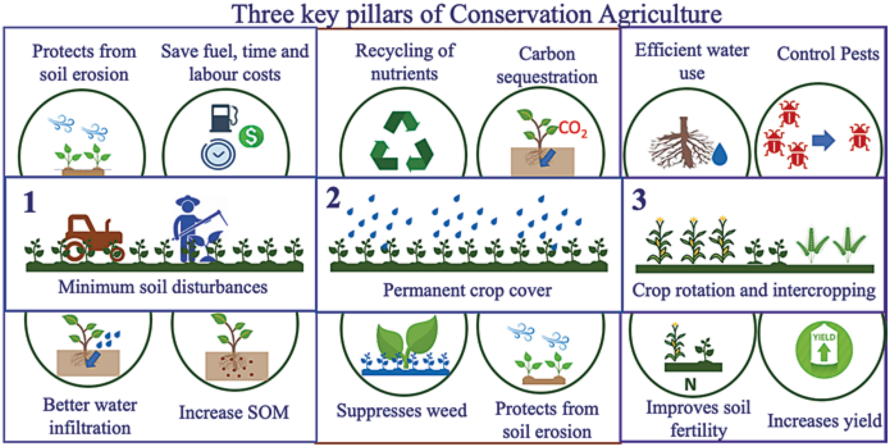

Fig. 26.1 Key pillars of NT systems farming/Conservation Agriculture

2014), often due to insufficient organic resources. Therefore, Vanlauwe et al. (2014) have suggested another fourth principle i.e. using appropriate fertilizer or integrated nutrient management (INM) (Lal 2015b) to ensure an increase in productivity and small-farm holder adoption.

26.3 CT V NT: The On-Going Debate of Benefits

26.3.1 Yield and Profitability

There is always speculation on the yield advantage or penalty when adopting NT. Krishna et al. (2017) reviewed 25 published studies to analyze the impacts of NT on wheat (*Triticum aestivum* L.) productivity across SA. Thirteen out of 25 studies reported significantly higher grain yield in NT than CT, while the rest indicated no significant difference. In addition, adoption of NT wheat (with partial residue retention) in the north-western part of Indo-Gangetic Plains (IGP), and in Bihar increased annual income by 6% compared to CT wheat (Keil et al. 2015). The benefits of NT systems in SA for yield and profitability thus seem clear. The real question lies in the fact that expansion of NT system (with residue retention and crop rotation) is a big challenge in SA smallholder farming systems where a majority of farmers are resource-poor and highly vulnerable to climatic extremes. Therefore, further analysis of both environmental and socio-economic benefits in adopting NT systems by smallholding farmers must be considered.

26.3.2 Carbon Sequestration

CT involves repeated soil disturbance that inverts, mixes and breaks down soil aggregates (Somasundaram et al. 2012, 2017; Kushwah et al. 2016). This disturbance, along with residue removal and unbalanced fertilizer application, causes depletion of soil organic carbon (SOC), especially in the surface layer (0–0.15 m depth) (Ghimire et al. 2017). Lal (2007) estimated the loss of SOC due to long-term use of CT on an erosion-prone landscape can be up to 75% of the native SOC. Such reduction of SOC in agricultural soils of SA is leading to considerable decrease in crop production (Hobbs et al. 2008). In fact, 1 Mg ha^{-1} year^{-1} increase in SOC, especially in developing countries, can lead to increase in food grain productivity by 32 million Mg year^{-1} (Lal 2006; 2004b).

In conventional rice-based cropping systems, low concentrations of SOC are often observed due to a reduction in stable aggregates in intensively puddled soil (Hobbs et al. 2008). In cotton (*Gossypium hirsutum* L.) cultivated areas, NT has been shown to increase SOC by 86–130% over five years as compared to CT, and could sequester relatively more carbon than that under CT within 0–0.24 m soil depth (Das et al. 2014). West and Post (2002) studied 67 long term experiments in different cropping systems in both tropical and temperate regions, and reported that the conversion from CT to NT could result in SOC sequestration of 0.57 ± 0.14 Mg C ha^{-1} year^{-1}. However, the carbon sequestration rate is affected by climatic conditions, ranging from 0.10 to 0.50 Mg ha^{-1} year^{-1} for humid temperate regions and from 0.05 to 0.20 Mg ha^{-1} year^{-1} for semiarid and tropical regions (Lal 2004b; Lal et al. 2007). A brief review on the effect of NT farming on SOC v CT in the different cropping systems of SA is given in Table 26.1.

26.3.3 Potential of NT in Rice-Wheat System of South Asia

One of the most dominant cropping systems found in SA is the rice-wheat cropping system, which covers 13.5 million hectares (M ha) (Gupta et al. 2003), 85% of which is practiced in the IGP (Chauhan et al. 2012). The IGP covers parts of India, Nepal, Bangladesh and Pakistan. In these four countries, the rice-wheat system produces more than 40% of wheat and 30% of rice (Gathala et al. 2011a; Sinha et al. 2019). Short duration rice (in summer) and wheat (in winter) are cultivated in a double cropping system over one calendar year, which is favored by a wet monsoon summer followed by a dry and cool winter (Gianessi 2014). The traditional method of rice cultivation followed by wheat after intensive tillage has led to soil and water degradation, jeopardizing the sustainability of the ecosystem in the region. Therefore, the NT system was introduced in IGP around 1996–1997 (Gianessi 2014).

The adoption rate of the NT system in the IGP is the highest in the north-western part of IGP (25%) and lowest (2%) in the eastern IGP (Singh et al. 2012). The lower rates of adoption in the eastern region may be attributed to the shorter time since the

Table 26.1 Effect of NT farming on SOC under different cropping systems in South Asia

Location	Soil type	Cropping system	Forms of carbon	Increase in NT over CT (%)	References
Patna, India	Silty-clay (Fluvisol); Sampling depth:0–0.2 m	Rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.); Rice- winter maize (*Zea mays* L.)	SOC	13	Nandan et al. (2019)
		Rice-wheat, rice-winter maize	Labile C	16	
		Rice-wheat, rice-winter maize	Less labile C	7	
		Rice-wheat, rice-winter maize	Non-labile C	13	
		Rice-wheat, rice-winter maize	SOC	14	
Punjab, India	Sandy loam soil (Typic Ustochrept); Sampling depth: 0–0.075 m	Rice	SOC	6.2	Bera et al. (2018)
		Wheat	SOC	9.9	
Tripura, India	Clay loam (Typic Kandihumults); Sampling depth:0–0.2 m	Rice	SOC	2.78	Yadav et al. (2017)
		Rice	SOC	5.89	
Rajshahi, Bangladesh	Calcareous silty loam; Sampling depth: 0–0.3 m	Wheat-green gram (*Vigna radiata* L) -rice	SOC	0.22	Hossain (2009)
Gazipur, Bangladesh	Clay loam (Grey terrace soils) Sampling depth: 0–0.25 m	Wheat-green gram-rice	SOC	32	Alam et al. (2014)
Chitwan, Nepal	Sandy loam Sampling depth: 0–0.2 m	Rice-wheat	SOC	6.43	Paudel et al. (2014)
Chitwean, Nepal	Sandy clay loam (Typic Haplustoll) Sampling depth: 0–0.05 m	Rice	SOC	28	Ghimire et al. (2012)
Varanasi, India	Sandy loam (Inceptisol) Sampling depth: 0–0.3 m	Rice-wheat	SOC	9	Pandey et al. (2014)

(continued)

Table 26.1 (continued)

Location	Soil type	Cropping system	Forms of carbon	Increase in NT over CT (%)	References
Uttarkhand,India	Sandy clay loam(Typic Haplaquept) Sampling depth: 0–0.05 m	Rice-wheat	SOC	11	Bhattacharyya et al. (2012)
Bhopal, India	Deep clayey vertisol (Isohyperthermic Typic Haplustert) Sampling depth: 0–0.05 m depth	Soybean (*Glycine max* L) + pigeonpea (*Cajanus cajan* L), soybean-wheat, maize+ pigeonpea, maize-chickpea (*Cicer arietinum* L.)	Very labile-C	−12.18	Somasundaram et al. (2018)
			Labile-C	8.34	
			Non-labile-C	22.72	

SOC Soil organic carbon, *C* Carbon

introduction of NT, the higher poverty rate, the need of farmers to rely on custom-hiring services to access NT drills, and decreased awareness of NT technology (Erenstein and Laxmi 2008; Singh et al. 2012; Keil et al. 2015). Despite its low adoption rates, the NT system has many potential benefits for agriculture in the IGP (Gathala et al. 2011b; Jat 2014; Jat et al. 2014). For example, declining groundwater resources and competition for water between different sectors has decreased the productivity of the rice-wheat cropping system (Gupta et al. 2002). However, the NT system can successfully reduce requirements for irrigation by increasing WUE due to its reduction of water requirement in wheat and more effective utilization of residual soil water of rice (Gupta et al. 2002). Due to less soil disturbance, NT also improves soil structure (Lal 2015b), which increases water infiltration and lead to higher soil water storage (Fig. 26.2). The faster turnaround time in NT also reduces the number of irrigations required compared to CT (Chandra et al. 2007).

To properly implement NT practices in the field, tractor-drawn NT seed drills are required that allow the planting of wheat seeds directly into the unploughed soil (Mehla et al. 2000). This allows the multiple tillage operations of the CT system to be reduced to only one tillage operation in NT. This, it minimizes the system's environmental footprint by reducing the number of tractor passes, and thus energy costs (Erenstein and Laxmi 2008; Gathala et al. 2013a). The reduced land preparation requirements also increase the timeliness of wheat establishment. A 1–1.5% yield loss can occur for each day of late seeding (Hobbs and Gupta 2003), and large yield penalties have been observed in Pakistan due to late planting, where 80% of wheat can be planted late (Gill et al. 2013). Indeed, 2 weeks advanced sowing time could produce an additional two million tons of wheat in Pakistan (Gill et al. 2013). The shorter growing period along with late planting also coincides with high

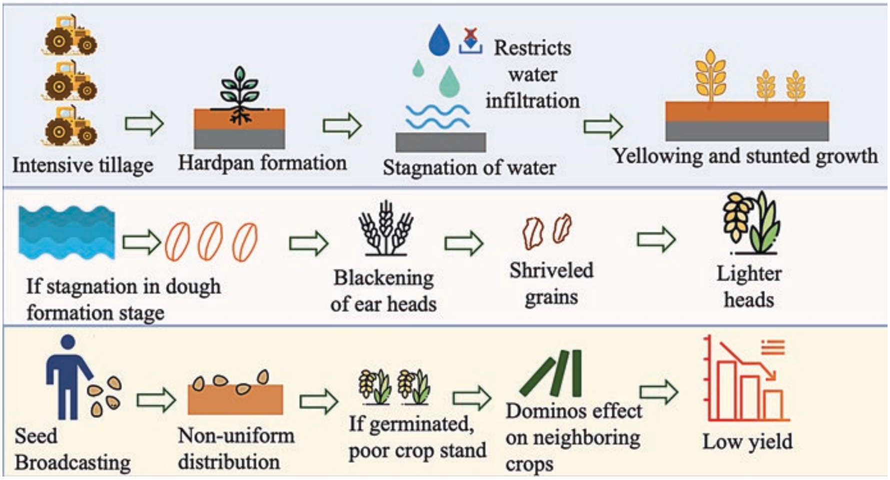

Fig. 26.2 Intensive conventional tillage affects soil system and crop yields

temperatures during grain filling, which reduces wheat productivity (Jat et al. 2014). Earlier timely planting also allows the wheat crop to take immediate advantage of the residual moisture available from the rice crop, thus reducing the number of irrigation frequencies and ultimately minimizing the water use (Erenstein 2009). Erenstein (2009) calculated increased wheat productivity (5–7%) and reduced fuel consumption (36 L ha^{-1}) in NT systems, resulting in 15–16% savings on operational costs and US$100 ha^{-1} greater farm income.

26.3.4 Hypothesis on "Why NT Is Perfect for South Asian Wheat"

There are two main attributes of NT wheat that might reduce yield loss due to unseasonal rains in SA production systems (Fig. 26.2). First, due to intensive tillage in CT system, hardpans are formed that restrict water infiltration and retention and may lead to stagnation of water (Khan et al. 2016). Long periods of stagnant water in wheat fields are detrimental to the crop and cause yellowing of leaves, stunted growth, and poor yield (Fig. 26.2) Therefore, NT systems, which retain crop residues and enhance water infiltration, reduce the period of water stagnation in the field (Khan et al. 2016). Second, CT systems may result in non-uniform placement of seeds at the required depth. The seeds exposed on the surface are less likely to germinate and develop a strong root system, and those seeds that do germinate are susceptible to lodging, which hampers photosynthesis by causing plants to shade one another (Fig. 26.2) (Ishimaru et al. 2008). In NT systems, seeds are placed into the soil at a proper depth via a NT seed drill and, therefore, can withstand unseasonal rainfall and wind (Khan et al. 2016).

26.4 Herbicide Application as a Component of NT Systems: To Avoid or to Use?

The main reason for intensive tillage and continuous submergence in rice cultivation on the IGP is to control weeds (Gianessi 2014). Weed control is more difficult in dry-seeded NT rice as there is no standing water at crop emergence to control weed growth and more competition occurs between rice seedlings and weeds for nutrient and space (Chauhan and Opeña 2012). In addition, high levels of weed infestation in dry-seeded rice can cause yield losses of up to 98% (Kumar and Ladha 2011). However, Gathala et al. (2013b) suggested that with effective weed control, dry seeded rice could be as productive as puddled transplanted rice, but intensive herbicide use is requried (Chauhan et al. 2012). Kumar and Ladha (2011) screened a variety of pre-emergence and post emergence herbicides for weed control in dry direct seeded rice, including NT systems. For weeds with higher dormancy, a broad spectrum of post-emergence herbicides are advocated 4–6 weeks after sowing (Chauhan 2012), and can result in a 25% increase in yield under continuous NT rice wheat system in India (Mishra and Singh 2012). Similarly, Usman et al. (2009) observed a doubling of wheat yield in NT systems with herbicide use compared to those without. Thus, the reported benefits of NT for rice-wheat systems in IGP areas will only reach their full potential when effective herbicides that are screened for use in specific conditions have been identified and registered for widespread farmer application (Chauhan and Opeña 2012).

However, problems can emerge with the extensive use of herbicides. For example, Canary grass *(Phalaris minor)* is one of the most problematic and dominant weeds found in Indian wheat production. Isoproturon had been used as an effective herbicide to control *P. minor* until overuse resulted in resistant varieties, which led to 30–80% yield loss and stagnation of wheat yield in the IGP during 1990s (Chauhan et al. 2012). However, in NT wheat, early planting during high temperatures reduces *P. minor* intensity by 30–40% (Chauhan et al. 2012), which could boost the confidence of other farmers in adopting NT in the rice-wheat system.

26.5 NT in Cotton-Wheat of South Asia: Its Applicability

Another well-established cropping system in SA is cotton- wheat covering 4.5 M ha (Das et al. 2014). With a view to diversifying the present unsustainable rice-wheat system and to reduce irrigation requirements, cotton-wheat cropping system are being encouraged in North-western India and other parts of SA (Yadvinder-Singh et al. 2014)

In conventional cotton-wheat systems, 4–5 tillage operations are conducted for each crop. Compared to NT systems, under CT the sowing time of the wheat is delayed by 20–30 days due to late harvesting of cotton and the time required for seedbed preparation. Delays in wheat sowing after cotton harvest can reduce wheat yield by 1.5–2.0 Mg ha^{-1} as compared to that of the timely sown wheat (Buttar et al. 2013). Naudin et al. (2010) conducted an experiment involving a 2–year rotation of cotton cultivation at two sites and reported 12 and 24% lower cotton yield under CT and NT, respectively, as compared to NT with surface mulch. At another site, no significant differences were observed in cotton yield under the three different tillage treatments. The incorporation of crop residues in NT system increased the soil water content, root growth, and yield of cotton as compared to CT (Karamanos et al. 2004). In contrast to these findings, Jalota et al. (2008) reported significantly lower cotton and wheat yield in NT as compared to that under CT. However, in terms of energy consumption, about 77% lower fuel consumption was reported in NT cotton–wheat compared with that for the CT cotton–wheat system (Afzalinia et al. 2011).

26.6 Adoption of NT in South Asia

26.6.1 Adoption of NT in the IGP

The state of Haryana ranks first in adoption of NT in India (Birthal 2013). Out of all the rice-wheat growing areas in Haryana, 36.5% of farmers adopted NT on 35% of their wheat area in 2015 (Khan et al. 2016). Erenstein et al. (2007) concluded that for the adoption of NT in India and Punjab (Pakistan), the main drivers for rapid adoption were the combined yield increases and the magnitude of cost saving. However, despite the rich economic gains of NT over CT, there is still a need for further diffusion of NT due to its non-uniform geographic distribution and community penetration. Although adoption of NT has increased in wheat cropping system in IGP over past few decades (Erenstein and Laxmi 2008), diffusion of NT in Punjab and Haryana (India) has stagnated, and there are specific issues for a low adoption of NT in these areas (~10%) (Erenstein et al. 2007). This may be due to the interaction of many factors, including knowledge blockages (false perception/mind-set of farmers), high cost and unavailability of NT drills, low technology performance, difficulties in technology access, resource constraints, and seasonal difficulties. However, significant adoption of NT has occurred with large scale farmers who often rely on contracted NT drill services (Sidhu et al. 2010; Keil et al. 2018).

Keil et al. (2018) studied the diffusion behavior of NT technology in Bihar over 3 years to determine the changes in NT adoption rate after the introduction of NT technology in the eastern part of the IGP. At the nascent stage of NT, adoption by the largest landholding tercile, who belong to higher educated and higher caste groups, was 152% greater than that for the smallest tercile. However, the adoption rates between large and small landholder farmers narrowed to 41% over the subsequent 3 years due to increased awareness of NT technology among smaller landholders and less educated farmers.

In Nepal, the Terai region supplies 75% of the country's total food demand. The rice-wheat cropping systems are one of the most important production systems occupying one-fourth of total cropped area and ~1.5 and 0.67 M ha of land is cultivated to rice and wheat, respectively (Tripathi et al. 2002). Farmers in Nepal found NT to be more suitable for growing wheat, especially in low lying wet lands with heavier soil texture and higher soil moisture where they are compelled to keep their field fallow after rice cultivation. In addition, the Nepal Agricultural Research Council (NARC) evaluated NT systems for lentil, pea and kidney bean production and found higher yield and lower carbon dioxide flux under NT compared with that under CT (61 mg m^{-2} h^{-1} versus 90 mg m^{-2} h^{-1}) (Jat et al. 2011).

Overall, reliable measurement of NT adoption in SA is a challenge because it is considered as a cultural practice and is sparsely reported in agricultural statistics and studies. Over-estimation of NT adoption can occur as sometimes adoption rates are estimated via use of the NT seed drill, which can also be used by farmers practicing minimum tillage and conservation tillage. Furthermore, its variation as a practice over seasons and within farms is also problematic as some farmers practice NT in one part of the farm, while the rest is intensively cultivated (Erenstein 2009). Imperfect credit markets and resource constraints in developing countries of SA are the bottlenecks in adoption of new technology by the farmers. Until incentives such as payment for ecosystem services are provided to farmers, the availability of technology alone could not drive the adoption of NT in SA countries (Smith et al. 2007).

26.6.2 Status of NT as a Part of CA Approach in Some Other South Asian Countries

No-till systems and CA are at an early stage of development and thus not widely practiced in many other regions of SA. For example, CA only started in Cambodia during 2004 (Castella and Kibler 2015). Under the 'Project for the Development of Agriculture in Cambodia', experiments based on maize, cassava, soybean and rice were conducted between 2008–2012, after which the adoption of CA practices accelerated (CIRAD 2011; Castella and Kibler 2015).

In Laos, CA-based programs were initiated under PRODESSA when a rural development project was integrated with CA practices in 2001 in the Kenthao district. However, most of the CA practices examined were limited to NT and crop residue management in maize cropping system without any legume crops and ultimately, led to the discontinuance of adoption after the end of the projects (Coudray 2013).

Myanmar has an age-old practice of mulching and intercropping in dry areas, mainly to conserve soil moisture. From 1996–2002 a watershed project in Southern Shan State was conducted, and about 2500 households in Northern Shan State adopted the NT system and used crop residues from previous crops to cover the maize plots and planted the next season crop without any soil disturbances

.Thereafter, the NT system started to diffuse in different agro-ecological zones of Myanmar. Farmers also used edible cover crops to reduce soil crusting and minimize risks of soil erosion (Castella and Kibler 2015). The method of 'Trash Blanketing' in NT commonly followed by the Australian sugar industry to utilize the sugarcane crop residues has also inspired sugar industries in Thailand, followed by those in Myanmar in 2005.

26.7 NT as a Climate-Smart Technology in South Asia

In an attempt to assess the impact of NT on farmers in Haryana, Khan et al. (2016) collected data from 717 farmers in 50 villages within 10 districts and revealed significant lower productivity in CT than NT wheat. In addition, during the study period (2015), farmers suffered a yield loss of 0.37–0.45 Mg ha^{-1} due to unseasonal rains. This yield loss was 24–28% less in NT plots, which is equivalent to approximately US$22.5 ha^{-1}. Climate models suggest that the incidence of short duration and unseasonal rains and other hydro meteorological events will increase in future (Kalra et al. 2007; Ahmed and Suphachalasai 2014). Therefore, adoption of NT could be an alternative climate–smart technology to reduce the potential yield loss from such extreme weather events (Khan et al. 2016).

Agriculture is not only a victim of climate change but also a contributor towards it through emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) (Lal 2004a). According to an IPCC (2007) report, agriculture directly contributes 12% of total anthropogenic emissions of GHGs and may be as high as 35% when indirect emissions from fertilizer industry and land conversion from forest to cultivable land are considered. However, agriculture has the potential to mitigate climate change through SOC sequestration (Lal et al. 2007; Lal 2015a). Sequestration of SOC has the highest potential, around 89% of the total technical potential worldwide, in mitigating emission of GHGs within agricultural systems (Lal 2015a, 2016). Climate plays an important role in increasing or decreasing the mitigation potential of tillage and residue management (IPCC 2007). Many researchers reported higher SOC sequestration in NT than CT systems and ultimately decreased CO_2 (Almaraz et al. 2009; Lal 2015a; Somasundaram et al. 2017; Reeves et al. 2019) and N_2O concentration in the atmosphere (Ussiri et al. 2009). Conversion of the rice-wheat system from CT to NT could sequester approximately 44 Tg (teragram = million metric ton) of carbon over 20 years (Grace et al. 2012). However, an adequate institutional frameworks for carbon trading would be necessary to assist the successful adoption of NT system among the small landholder farmers in SA (Milder et al. 2011; Keil et al. 2018) and to realize the technical potential of SOC sequestration in countries such as India (Lal 2004b). The constraints to adoption of NT by resource-poor small landholder farmers must be removed (Lal 2016) to promote adoption of a system based CA (Lal 2015b). Therefore, the prevailing carbon markets should also focus on reduction of GHGs emissions from agricultural sector in addition to industrial and energy sectors

(Grace et al. 2012). In addition, payments to farmers for ecosystem services, based on the societal value of SOC (Lal 2014), would promote the adoption of this promising technology. Although NT is regarded as a better alternative to CT in SOC sequestration, it is important to consider all aspects of the farming system when calculating sequestration rates (Lal 2015a). For example, NT systems depend heavily on herbicides and pesticides for weed control, and when the C emissions that occur during the manufacturing of these chemicals are considered, this can reduce the benefit of SOC sequestration for greenhouse gas reduction (Lal 2004a). In addition, there can be methodological problems with studies that compare SOC sequestration in NT v CT systems. Baker et al. (2007) noted that many samples used to calculate SOC sequestration have been collected within 0–0.3 m or less. However, when the entire soil profile is considered no advantages of NT over CT may occur in terms of SOC sequestration.

26.8 NT Machinery in South Asia

The prevailing NT technology in rice-wheat cropping systems is the tractor-drawn seed drill with 6–11 inverted T tines to place the wheat seed directly into unploughed soil with a single pass. The challenging task of developing such machinery has been a crucial factor in the diffusion of NT technology in SA. During the mid 1980s, adaptive research to enhance the suitability of NT methods for local conditions was started in Pakistan, resulting in the importation of a prototype drill with inverted-T openers from Aitcheson Industries, New Zealand (Erenstein 2009). The drill was introduced in India in 1989 by CIMMYT and G.B. Pant University of Agriculture and Technology, Pantnagar, developed the first prototype of a NT seed drill for Indian conditions in 1991. In order to further develop and commercialize NT seed drills in both countries, collaborative programs were started by the National Agricultural Research System in cooperation with CIMMYT (Erenstein and Laxmi 2008; Harrington and Hobbs 2009). Another method used in NT without the employment of seed drills is the method of surface seeding (Tripathi et al. 2002), but this technique is limited to low-lying areas with the problems of poor drainage, as is the case in the Eastern Gangetic Plains. Therefore, a wider adoption of NT technology depends upon the availability of location-specific machinery such as no-till seed drill and turbo happy seeder through a strong network of institutions both state and central organizations with active participation of the farming community.

With a view to procure socially inclusive outcomes, deployment of a capital-intensive mechanization technology, such as NT, can be done through private-sector service providers. However, the process of diffusion must be strengthened by strong support from Agricultural Departments and Universities to boost awareness and knowledge of NT by farmers.

26.9 Conclusions

Worldwide, CA practices are adopted on more than 180 million ha, however, the adoption rates in SA countries remain low (<3% area or < 5 M ha). Conversion of the rice-wheat system from CT to NT could sequester approximately 44 Tg of carbon over 20 years. However, an institutional frameworks for carbon trading would be a necessary pre-requisite to assist the widespread adoption of NT system among the small landholder farmers in the South Asia. Ensuring more returns from the newly introduced technology compared to that from the traditional system would be the primary driver in adopting new technology. Therefore, the prevailing carbon markets should also focus on reduction of GHGs emissions from agricultural sector in addition to industrial and energy sectors. Payments for ecosystem services based on societal value of soil carbon would be an important strategy to promote adoption of NT system in SA.

In addition, the accessibility of the small-scale farmers to NT drill service providers must be improved to help drive adoption. These services must also be reliable and available to farmers when required for farm operations. Policies to increase NT adoption must also increase education around NT practices. Converting from intensive tillage-based agriculture to NT based CA systems eliminates unsustainable elements in conventional farming system and substitutes them with CA elements that make the production systems sustainable and ecologically compatible. Therefore, there is an urgent need for simultaneous application of NT and retention of crop residues to provide soil cover, crop diversification for better nutrient cycling, incorporation of a cover crop in the rotation cycle, integrated weed control, and balanced nutrient management to enhance and sustain soil health and crop productivity in the SA region.

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Chapter 27
No-Till Farming Systems in Rain-Fed Areas of China

Zheng-Rong Kan, Jian-Ying Qi, Xin Zhao, Xiang-Qian Zhang, Zhan-Yuan Lu, Yu-Chen Cheng, and Hai-Lin Zhang

Abstract In China, rain-fed (dryland) agriculture is practiced in the North China Plain as well as parts of northeast and northwest China, accounting for 51% of the total arable land. However, this region is facing an increasing rate of environmental degradation, soil erosion, and water shortage. To combat this environmental degradation, no-till (NT), as the primary principle of conservation agriculture, has been widely adopted as a sustainable agriculture practice due to its ability to control land degradation, sequester soil organic carbon (SOC), and mitigate climate change. Thus, NT offers an option to improve soil water conservation and soil quality in rain-fed areas of China. The objective of this chapter is to re-evaluate the current performances of NT farming management and describe the positives and negatives of NT for the control of soil erosion and the increase of crop production in rain-fed agricultural regions of China. Based on this review, NT can reduce wind-blown sediment, save water due to less soil disturbance, maintain a higher proportion of retention and continuous pores, enhance the infiltration rate, and decrease water evaporation, especially by mulching with crop residues. In addition, NT can eventually realize the potential to improve grain yield and the local economy. An 11-year case study conducted in Inner Mongolia showed an obvious increase by 7.4%, 17.9%, and 4.0% in SOC concentration in the NT treatment compared to subsoiling with residue retained (ST), rotary tillage with residue retained (RT), and plow tillage with residue retained (PT), respectively. In addition, the greatest biomass yield was observed for NT, which was 1.9%, 10.5%, and 9.1% higher than that under ST, RT, and PT, respectively. Although NT has the potential to solve problems that the rain-fed agricultural area faces, there are many barriers to its widespread adoption,

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such as the lack of standard technology and suitable equipment compared to traditional agricultural practices. In addition, various and complex crop rotations, intercropping systems, and crop species require corresponding strategies. These barriers constrain the rates of adaptation of NT by farmers in this rain-fed region. Therefore, developing suitable technologies are necessary to popularize NT practices among farmers in rain-fed agricultural areas of China.

Keywords North China · Conservation agriculture · Soil erosion · Crop production

27.1 Introduction

In China, dryland farming is dominated by monocropping systems composed primarily of maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.), and farms are managed with plow tillage to a depth of 0.16–0.18 m (Wang et al. 2007). In dryland farming regions of China, including the North China Plain as well as parts of northeast and northwest China, precipitation limits crop yield, with the precipitation from June to September accounting for 50–60% of the limited annual precipitation (Zhang et al. 2009). Moreover, the dryland farming region has adverse topography and weather conditions (Wang et al. 2007).

Rain-fed agriculture relies solely on natural precipitation as a source of water for crop growth. The concepts of dryland farming and rain-fed agriculture have often been used interchangeably, however, while both of these concepts refer to agriculture conducted without the use of irrigation water, dryland farming is specific to agriculture conducted in arid and semi-arid regions where annual precipitation is 20–35% of potential evapotranspiration. Thus, the area of rain-fed agriculture in China is greater than the area of dryland agriculture (Li 2004). Although excluded from most maps, rain-fed agriculture in dryland areas is pivotal to enhancing the resilience of human communities and understanding land–atmosphere interactions in many parts of the world. Thus, rain-fed agriculture has a larger potential for sustainable development in China (Biagetti et al. 2018).

With the ongoing growth of the population, the demand for agricultural products in China is also increasing (Chen et al. 2014). Developing rain-fed agriculture in dryland regions can maintain and increase grain production capacity and ensure food security. Additionally, water shortage is a very serious challenge that China's agricultural sector is currently facing. Water resources are relatively limited in China, only approximately 67% of the world average, and are distributed unevenly (Wang et al. 2016). Reasonable adjustment of the cropping system and improvement of infrastructure can effectively increase the utilization rate of natural precipitation and irrigation water. This can also help increase the proportion of water available for ecological use, provide conditions for ecological restoration, and improve watershed ecology (Wang et al. 2016).

There is a higher potential for agricultural structural adjustment to enhance water use efficiency and water saving due to the abundant resources of light, heat, and crop species in rain fed areas of China. However, due to the lack of water resources and insufficient investment in technology and infrastructure, low crop yields have led to less-developed agriculture and poverty in the dryland agriculture region of China. Therefore, it is necessary to alleviate the threat of drought and encourage farmers with strong competitive advantages through developing rain-fed agriculture, rationally allocating agricultural resources, and establishing a water-saving planting structure (Wang et al. 2016; Biagetti et al. 2018).

However, the development of rain-fed agriculture in China is facing prominent problems. Conventional soil management practices (eg plow tillage, low fertilizer and manure inputs, and crop residue burning) have contributed to soil, water, and nutrient losses as well as degraded soils by decreasing stored organic matter and creating a fragile physical structure (Wang et al. 2007). This in turn has led to low and unstable crop yields. For example, from 2000 to 2013, the lowest yield of spring corn in Shaanxi Province was 3510 kg ha^{-1}, and the highest was only 4856 kg ha^{-1}; the coefficient of variation was more than 9.5%, which is higher than the coefficient of variation for the national maize yield (1.35%) in the same period (National Bureau of Statistics of China 2001).

The ecosystem of rain-fed agricultural areas is fragile and the ecological balance is threatened. Under the changing climate, rain-fed agricultural production is vulnerable, and its ability to tolerate extreme weather is poor, which is likely to lead to low productivity in the region (Wang et al. 2016). Thus, appropriate strategies that could alleviate limitations and harness the benefits of rain-fed agriculture are needed. For example, rainwater harvesting irrigation (collecting local rainfall and water-saving irrigation methods), full-film covering technology, and water and fertilizer integration technology have been adopted to solve these problems; however, they are time consuming and can be expensive. Therefore, it is urgent to adopt a time-saving and cost-effective method to improve agriculture in this region.

The degradation of soil fertility and labor shortages in conventional plow tillage systems are common problems encountered in different regions of China (Zhang et al. 2014). Conservation tillage or NT systems are the main component of conservation agriculture, which includes four principles: minimum or no tillage, permanent residue mulch, diverse cropping systems, and integrated nutrient management (Zhang et al. 2014). According to long-term filed experiments, NT systems considered a viable option to: (i) guarantee food security and mitigate climate change, (ii) sequester soil organic carbon (SOC) and restore soil quality, (iii) conserve soil and water, (iv) save labor, and (v) reduce inputs of chemical fertilizers and energy (Lal 2004; Zhang et al. 2014; Islam et al. 2015; Vanhie et al. 2015; Zhao et al. 2017). At present, conservation tillage has been adopted on 122–215 Mha around the world, 9–15% of the global arable land area, and has the potential to be adopted on 533–1130 Mha in the future (Prestele et al. 2018). In addition, Zhang et al. (2014)

reported that conversion of plow tillage to no-till (NT) for winter wheat can save \$35 ha^{-1} in northern China.

Wang et al. (2007) summarized the development of NT in rain-fed regions in China, and indicated that NT covered 0.13 million ha in 2003, only accounting for 0.2% of the area worldwide. However, according to the work done by the Ministry of Agriculture and Rural Affairs of the People's Republic of China, the practices of NT has been applied widely throughout dryland regions of northern China.

Water is a limiting factor in the dryland region of China and intensive ploughing has contributed to increasing risks of soil erosion by wind and water, and also to soil compaction and the formation of hard pans in the subsoil layer in this region. However, NT has positive effects on retaining water and preventing the formation of tillage pans. Therefore, adopting NT in rain-fed agricultural regions is conducive to the sustainable development of agriculture. Global warming has caused concern among scientists and policy makers; therefore, technologies that could alleviate greenhouse gas emissions and improve SOC sequestration are widely recognized and of interest for development. NT can decrease greenhouse gas emissions indirectly by saving machinery inputs and has the potential to sequester SOC and mitigate climate change.

The purpose of this chapter is to assess the performances of NT in soil properties and yield production in rain-fed agricultural regions of China and describe positives and negatives of NT for building sustainable agriculture in the context of food security and climate change mitigation.

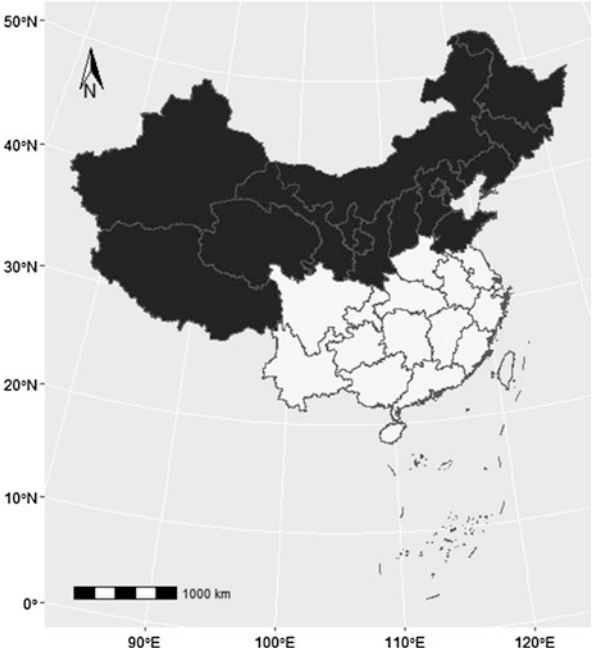
27.2 Characteristics of NT Practices in Rain-Fed Agricultural Regions of China

27.2.1 NT in Rain-Fed Agricultural Regions of China

In China, conservation tillage has been researched since the late 1970s due to the increasing challenges associated with changing weather, drought, low soil quality, and adverse effects from improper agricultural management (Wang et al. 2007). Mechanized technology for the popularization of conservation tillage started in the 1990s. Beginning in 1992, China Agricultural University, in cooperation with the University of Queensland and Shanxi Farm Machinery Bureau, trialed conservation tillage for the first time. The Ministry of Agriculture contributed to the extension of the farming area practicing NT and provided constructive suggestions for on-farm problems. In the past few years, the Ministry of Agriculture has also initiated a set of projects to promote NT farming (He et al. 2010). These projects provide basic training to farmers, who are important to the successful adoption of NT programs.

Developing suitable agricultural management in the rain-fed region of China is difficult but important. Dryland farming accounts for 51% of the total arable land in China and 39% of that globally (Li et al. 2015). In China, the dryland region extends

Fig. 27.1 The possible areas (black shading) for no-till in rain-fed regions of China. (Source: Hailin Zhang)



from the North China Plain to parts of northeast and northwest China (Li 2004; Wang et al. 2007). Recently, it has been predicted that the dryland region will increase due to climate change (Xin and Wang 1998; Tan et al. 2017). The possible areas for NT in rain-fed region of China can be found in Fig. 27.1. Promotion and extension of NT farming in this region have been actively stimulated by the Chinese government since 2002 (Zhang et al. 2004; Wang et al. 2012), following the increasing rate of degradation of the environment due to soil erosion and the shortage of soil water content, especially in North China. NT in the rain-fed region has the potential to conserve soil water and improve the soil quality. Therefore, it is an appropriate tillage practice for sustainable agriculture.

In arid areas of China, the effects of long-term conservation tillage (NT with residue cover) and conventional tillage (CT) (moldboard plowing with residue removal) practices on local income and environmental pollution have been already assessed by the Conservation Tillage Research Centre of USA. However, in the dryland area, the characteristics of NT systems and its effects on crop production and environment are poorly understood. This chapter reviewed related references to understand these effects.

27.2.2 Effects of NT on Soil Properties and Crop Yield in the Rain-Fed Region of China

NT is most effective when used in combination with residue mulching, and this is the predominant method for conservation tillage in the rain-fed area in China (Zhang et al. 2016). The NT farming system has the potential to decrease soil evaporation and store more soil water (Li et al. 2007), which is beneficial for crop growth especially when the rainfall is insufficient. Additionally, other soil properties can also be affected by the NT farming system, including soil organic matter, soil aggregates, and soil nutrient content. These soil properties are important for sustainable agriculture.

The adoption of NT can save water because there is less soil disturbance, a higher proportion and retention of continuous pores, a higher infiltration rate, and low evaporation under the cover provided by mulching with crop residue (Zhang et al. 2014). In addition, NT can increase soil water storage and improve water use efficiency compared to that under plow tillage. Soil water storage can be increased by 10% with adoption of NT when compared with plow tillage (Zhang et al. 2014). Thus, water available to crops is favorable under NT, which promotes crop growth and increases agronomic yield in drought-prone soils. Zhang et al. (2015) reported that long-term average yields (2002–2013) were higher in NT (4.4%) than in plow tillage primarily ascribed to the favorable soil nutrients and soil water content. Data from a 16-year-long field experiment conducted in Shanxi, on the Chinese Loess Plateau, showed that long-term NT farming (NT with straw cover) increased soil organic matter by 21.7% and soil total nitrogen by 51.0% at a depth of 0–0.1 m and available phosphorous by 97.3% at a depth of 0–0.05 m compared to CT (Wang et al. 2008). The NT farming system can induce serious soil compaction; however, this can be resolved by a combination with other tillage practices, such as subsoiling (Jin et al. 2007).

A report from the Conservation Tillage Research Centre suggested that conservation tillage was effective in increasing crop yield in arid areas of China (Li et al. 2007). Wang (2006) reported that yield under reduced tillage was increased by 22% compared to that observed for CT. However, according to previous research, the potential for wheat production of the arid and semi-arid areas in northwest China is approximately 3–4.5 Mg ha^{-1}, and the corn yield is over 7.5 Mg ha^{-1} (Shangguan and Shao 1999). However, a statistical data analysis showed that the potential agricultural production of the arid and semi-arid areas is less than 50% of the total. According to a long-term experiment conducted in Shaanxi Province, the grain yield of wheat was improved by 72.6% and maize by 75.6% under NT compared to plow tillage under rain-fed conditions because of soil water retention (Mo 2002). Therefore, adopting NT in rain-fed areas has the potential to increase grain yield. However, opposite results were found in the North China Plain (Guan et al. 2015), which was mainly due to various amounts of precipitation over the period of the study, and sufficient rain so that the water storage advantage under NT provided no yield advantage.

27.2.3 *Effects of NT on Soil Erosion*

In northern China, wind erosion is monitored by the China Ministry of Agriculture using the Big Spring Number Eight (Li et al. 2005). The results showed that the NT farming system reduced the spread of wind-blown sediment. For instance, at one of the experimental sites in Hebei Province, the conventional farming system produced 42.46 g of wind-blown sediment per sample, whereas the NT system produced only 12.72 g per sample, which is approximately a 70% reduction. Similarly, at the other experimental sites, (e.g., Wuchuan, Lingyuan, and Changping) the NT farming system produced 12.1–61.6% less dust than other tillage practices. These results indicate that the NT farming system effectively protected the soil surface and reduced wind erosion by decreasing the exposure of the soil to wind and slowing the wind owing to the increased roughness of the surface, which is similar to the findings presented by Wang et al. (2006).

NT systems also have the potential to reduce water erosion. Water erosion was studied in Shouyang, Shanxi Province from 2003 to 2007 by measuring and monitoring runoff, which is a significant indicator to evaluate the effects of conservation tillage on water erosion (Wang et al. 2005). In the NT farming system, annual runoff in heavy storm years (2004 and 2006) was reported to be less than that under CT by about 238.5%, and during normal years (without heavy storm), the annual runoff was similar between NT and conventional farming systems. During all experimental years from 2003 to 2007, the cumulative runoff in NT was 88 mm, while in conventional farming system it was 153 mm. These results indicated the benefit of NT systems to control water erosion.

27.3 A Case Study on NT in Rain-Fed Areas in China

An example of some of the improvements in soil properties and yield that can be observed with the introduction of NT systems in Chinese dryland cropping regions can be illustrated in the case study below.

27.3.1 *Experimental Site and Field Management*

A long-term field experiment examining different tillage practices was conducted in Wuchuan, Inner Mongolia, China, commencing in 2003. The experiment was designed with four tillage treatments including NT with residue retained (NT), subsoiling with residue retained (ST), rotary tillage with residue retained (RT), and plow tillage with residue retained (PT). Each treatment was replicated three times. Different tillage practices were implemented after the harvest of oat, and the residue was cut into lengths less than 0.08 m. For NT, no extra tillage practices were performed before sowing oat the following year. For ST, an interval of 0.4 m and a depth with 0.25–0.30 m of subsoiling was conducted followed by rotary tillage to a depth of 0.05–0.08 m to prepare the seedbed. For RT, rotary tillage was conducted to a depth of 0.08–0.01 m. For PT, moldboard ploughing was done to a depth of 0.20–0.23 m. Sowing of oat was done in the spring for all treatments. All plots received the same rate and type of chemical fertilizers (225 kg ha^{-1} of diammonium phosphate, 60 kg ha^{-1} of urea, and 75 kg ha^{-1} of potassium sulfate) at the time of sowing. Soil samples (0–0.05, 0.05–0.1, 0.1–0.2, and 0.2–0.4 m) and crop yield samples were collected in 2014 before harvest.

27.3.2 Effects of NT Farming Systems

27.3.2.1 Effects of NT on Soil Bulk Density

Soil bulk density increased with depth under all treatments (Fig. 27.2). An obviously higher soil bulk density (1.32 g cm^{-3}) could be observed under NT at 0–0.05 m soil depth compared to the other tillage practices. Decreases of 2.3%, 3.0%, and 10.6% in soil bulk density were observed under ST, RT, and PT when compared to NT at a soil depth of 0–0.05 m, respectively. The highest soil bulk density at 0.05–0.10 m soil depth was also observed under NT, which was 4.3%, 4.3%, and 9.4% higher than that under ST, RT, and PT, respectively. However, at a soil depth of 0.1–0.2 and 0.2–0.4 m the highest soil bulk density was observed under RT; it

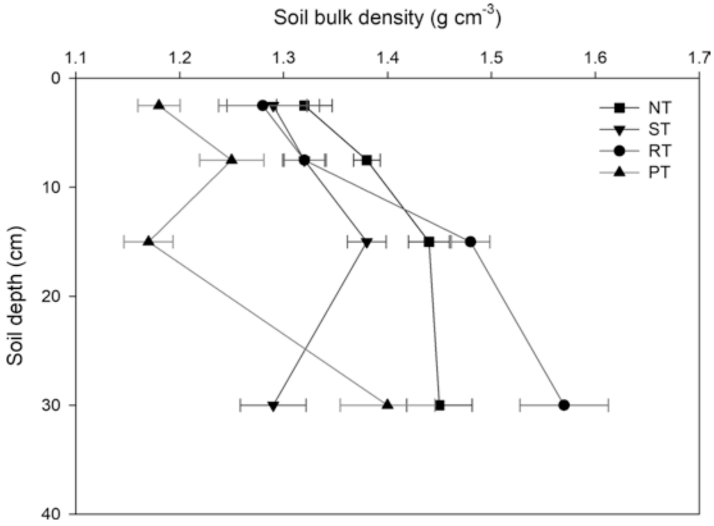


Fig. 27.2 Soil bulk density (g cm^{-3}) under different tillage practices. *NT* no-till, *ST* subsoiling, *RT* rotary tillage, *PT* plow tillage. Error bars show standard deviation (SD)

was 2.8% and 8.3% higher than that under NT, respectively. Thus, the results indicated that NT could increase the soil bulk density at the soil surface, but improved the soil structure deeper in the profile compared to tilled treatments.

27.3.2.2 Effects of NT on SOC

SOC is one of the key indicators of soil quality, carbon sequestration capacity, and soil productivity. It also links the assessments of soil sustainability, climate change mitigation, and food security. After 11 years, NT was observed to increase soil organic carbon concentration for all soil depths between 0 and 0.3 m (Fig. 27.3), specifically, an obvious increase by 7.4%, 4.0%, or 17.9% in soil organic carbon concentration was observed under NT when compared with that under ST, RT, or PT, respectively ($P < 0.05$) in the 0–0.05 m depth due to residue retained in the surface. However, the difference in SOC concentration under NT compared to PT and ST appeared to decline with the increase in soil depth. For ST, decreases in soil organic carbon of 6.0%, 5.8%, and 3.9% were observed when compared with NT at 0.05–0.1, 0.1–0.2, and 0.2–0.4 m soil depth, respectively. The same trend was found under PT for soil depths of 0.05–0.1 and 0.1–0.2 m. However, the reverse was observed under RT where greater differences in SOC of 3.5%, 9.7%, and 17.2% at soil depths of 0.05–0.1, 0.1–0.2, and 0.2–0.4 m, respectively were observed. These results suggested that NT was an effective practice to enhance soil organic carbon concentration for 0–0.4 m deep soil in this region.

According to the changes in soil bulk density, the equivalent soil mass method was used to calculate the SOC stock under different tillage practices. The results indicated that NT was an effective practice to enhance SOC stock at ~0.4 m soil

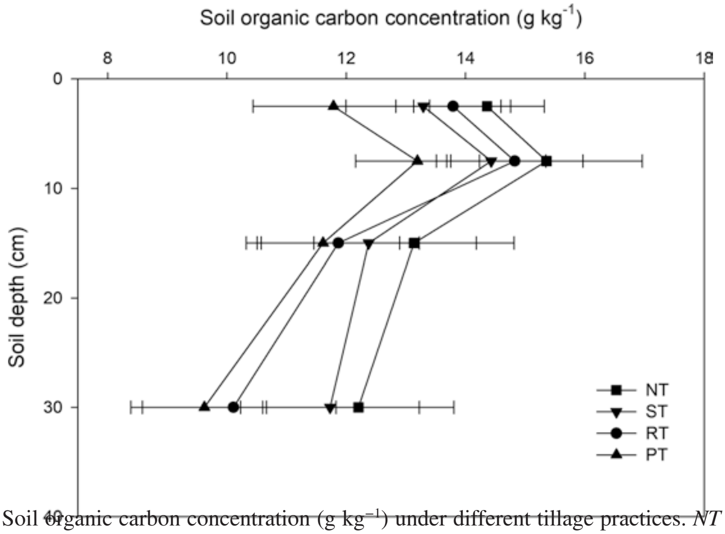


Fig. 27.3 Soil organic carbon concentration (g kg^{-1}) under different tillage practices. *NT* no-till, *ST* subsoiling, *RT* rotary tillage, *PT* plow tillage. Error bars show standard deviation (SD)

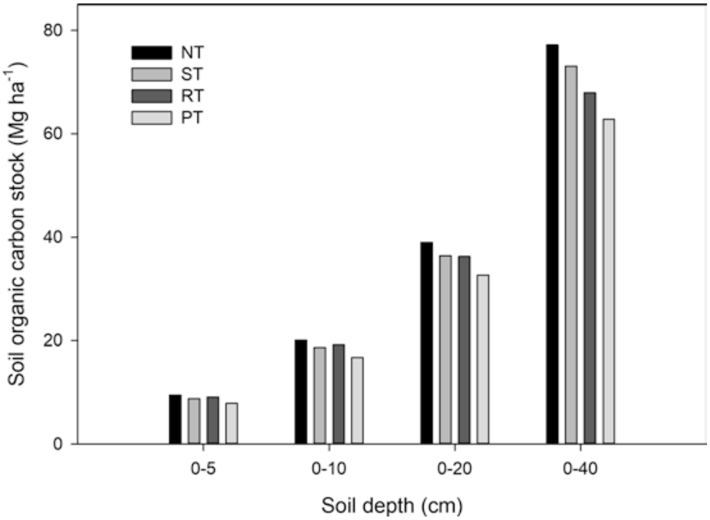


Fig. 27.4 Soil organic carbon stock (Mg ha^{-1}) under different tillage practices. *NT* no-till, *ST* subsoiling, *RT* rotary tillage, *PT* plow tillage

depth (Fig. 27.4). Specifically, SOC stock increased obviously with increases in soil depth. At 0–0.05 m soil depth, NT enhanced SOC stock by 7.3%, 3.7%, and 16.9% when compared with ST, RT, and PT, respectively. The increases in SOC stock under NT declined with increases in soil depth when compared with other practices. Compared with ST, NT increased SOC stock by 7.1%, 6.6%, and 5.3% at 0.05–0.1, 0.1–0.2, and 0.2–0.4 m, respectively. However, an increasing trend in the effects of NT on SOC stock when compared with RT was observed. Compared with RT, increases by 4.3%, 7.0%, and 12.0% were observed under NT at 0.05–0.1, 0.1–0.2, and 0.2–0.4 m soil depth, respectively. SOC stock under PT was the smallest among tillage practices at each soil depth.

27.3.2.3 Effects of NT on Crop Production

Crop yield or production is the ultimate test when assessing the effects of the NT system. After 11 years of consecutive NT management in an oat field, a significant increase (12.4%) in oat cereal yield could be found under NT when compared with PT ($P < 0.05$, Table 27.1). However, there were no significant differences in cereal yield among other tillage practices (ST, RT, and PT). Similarly, no significant differences in biomass yield and harvest index were observed among the four tillage practices, although in absolute terms, NT produced the most biomass yield at 1.9%, 10.5%, and 9.1% higher than that under ST, RT, and PT, respectively.

Table 27.1 Cereal yield (kg ha^{-1}), biomass yield (kg ha^{-1}), and harvest index of oat under different tillage practices

Treatments	Cereal yield	Biomass yield	Harvest index
No-till	790.40a*	2916.46a	0.27a
Rotary tillage	735.29ab	2859.74a	0.26a
Subsoiling	708.59ab	2609.09a	0.27a
Plow tillage	692.06b	2651.98a	0.26a

*Different letters (i.e., a and b) indicate significant difference at $P < 0.05$

27.4 Challenges/Opportunities and the Research/Development Requirements

Based on NT technology, conservation tillage or conservation agriculture has gained popularity globally (Prestele et al. 2018) and in China (Zhang et al. 2014). In rain-fed areas of China, especially in northwest China, shortage in rainfall, sloping farmlands, serious soil and water erosion in the Loess Plateau Region, and the fragile ecological environment has badly restricted agricultural production. Soil and water erosion is very serious in this region and work needs to be done to control this. Research on NT practices in this region has been conducted for decades and the methods have been adopted locally; however, challenges still exist both in the site-specific NT studies and local practices.

27.4.1 Debates on Crop Yield Under NT Farming Systems

According to a global meta-analysis, a significant decrease in crop yield was reported under NT practices when compared to plow tillage (Pittelkow et al. 2015). Similar results have been observed throughout China, with Zhang et al. (2014) concluding that there was a decline in yield under NT, with the magnitude of decline varying depending on crop species and region. Specifically, declines in crop yield of 16.5%, 10.1%, and 8.9% were observed for wheat, rice, and maize, respectively (Zhang et al. 2014). In northwest China, the decline in crop yield could be up to 14.8%. However, contrasting results have been reported which indicated that crop yield may also increase under NT systems. For example, based on national field experiments, Zhao et al. (2017) conducted a meta-analysis and suggested that crop yield generally increased by 4.6% under NT practices with residue retention compared with plow tillage, while a decrease of 2.1% was observed under NT with residue removed compared with that under plow tillage. Thus, residue return played an important role in determining yield production of NT.

27.4.2 Small-Size Farm Holdings and Suitable Equipment

Different from the successful experiences in some countries (e.g., USA, Canada, and Australia), the farm scale in China is quite small in most regions (on average across China, the holdings are 0.3 ha per household). Moreover, even the "small scale" household farmlands are scattered further apart into distinct plots. Suitable equipment or agricultural machinery are very crucial for the implementation of NT practices in rain-fed areas of China. Specifically, small farming holders in this region urgently need suitable seeders. The soil surface of NT systems was mulched with crop residues to reduce evaporation and soil erosion in rain-fed areas. Other countries primarily use large and heavy machinery to ensure the quality of seeding under such conditions; however, it is hard to adopt such machinery in small and distantly scattered plots of farmland. Thus, the development and employment of small seeders are the key to local adoption of NT practices.

27.4.3 The Understanding and Willingness of Farmers to Adopt NT Practices

Farmlands in rain-fed areas of China are dominated by intensive farming practices (i.e. intensive labor, fertilizer, and irrigation). Historically, these practices can be dated back to the Xihan Dynasty (over 2000 years ago), and are thus deeply ingrained in generations of farmers. The attitudes of farmers toward CT and NT practices are very hard to change without incentive measures or policies. Compared with the perceived knowledge of intensive tillage, NT systems or conservation agricultural technologies are considered as a kind of "lazy technology," with farmers believing that these practices would lead to the reduction in crop yield and income. On the contrary, with the demonstrable economic, environmental, and social benefits, NT has been widely recognized as a modern technology and has attracted the attention of farmers and policy makers globally due to the potential climate change mitigation and sustainability. Thus, it is important to determine appropriate measures for how to educate farmers and popularize NT practices in this region via a site-specific strategy.

27.4.4 Sloping Farmland and Diverse Technologies

Although diverse cropping systems, such as single, double, and triple cropping, can be found in China, the cropping system in rain-fed areas of China (especially in northwest China) is relatively simple. Monocultures are the most common cropping system in sloping regions. However, farmland topography here is a challenge. Accordingly, level terrace and sloping land management should be considered when adopting NT practices. Different crop rotations, inter-cropping systems, and different crop species need their own strategies. Long-term, in-depth research is needed on how to best implement NT systems for this variety of crop species and improve adoption rates.

27.4.5 Competition for use of Crop Residue

Crop residue is an important agricultural output. The national production of crop residues was approximately 71.9 Mt in 2015 but only 11.5% of the total was produced in northwest China (Song et al. 2018). Residue retention or mulching is a great resource that can benefit the soil and improve water conservation in NT systems, which is vital to improving agriculture in rain-fed areas of China. However, in this region there is another use for crop residues, namely, crop residues are an indispensable source for fuel of cooking or heating as well as feed for animals. Therefore, enhancing residue carbon retention in soil (use efficiency) is key to improving soil organic matter and quality under limited residue amounts.

27.4.6 Climate Change Mitigation and Rural Development

Adapting to and mitigating climate change is a global issue. Since the "4 per 1,000" initiative after COP 21 in Paris, enhancing SOC sequestration to mitigate climate change has been widely understood by the public (Lal 2016). NT has been reported as an effective practice to enhance soil carbon sequestration, and thus NT potentially represents an opportunity to increase SOC storage in this region, although low biomass inputs may limit sequestration potential in some instances. In addition, a 12-year experiment states that NT not only improved spring maize yields, but can maintain yield stability compared with plow tillage in Northeast China (Wang et al. 2014), which may help maintain yield in face of increasing climate variability. However, a 12-year experiment on alkaline soils of Northeast China, NT did not show advantages in maintaining yield stability (Zhang et al. 2015). Thus, in-depth and longer duration studies are needed to assess yield stability under climate change in the future.

China's GDP has increased drastically since conducting reforms and opening policy. However, a farmer's income level is still of concern for the nation's economic development. The Rural Revitalization Strategy has been implemented to improve the rural economy. With the increasing cost of agricultural inputs (eg chemical fertilizer, irrigation, and machinery) and labor shortage, incomes from agricultural production are very low in rain-fed areas, especially in northwest China. As a practice with lower input costs and labor, NT can improve the economics of the region while also increasing crop output. Dixit et al. (2019) reported that the economic benefits were also maximum under continuous NT practice, higher than plow tillage by 13.1%.

27.5 Conclusions

NT is gaining global attention and has been widely adopted due to its ability to save time and labor, minimize soil disturbance, reduce soil erosion, increase SOC stock, and mitigate climate change; all while having the potential to improve grain yield and local incomes. Thus, it is a proper tillage practice for agriculture sustainability to improve soil water conservation and soil quality in rain-fed areas of China. A long-term case study showed that NT increased SOC concentrations by 4.0–17.9% compared to ST, RT, and PT, regardless of soil depths. In addition, NT significantly increased oat cereal yield by 12.4% compared with PT ($P < 0.05$). To realize the potential high yield under NT, the standard technology and suitable equipment are needed with the willingness of farmers to adopt it. However, various and complex crop rotations, inter-cropping systems, and diverse crop species are also significant influences on yield under NT. These barriers have constrained the rates of adoption of NT practices by farmers in the rain-fed area. Therefore, site-specific research and a corresponding strategy are needed to educate and popularize NT practices among farmers.

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Chapter 28
No-Till Farming Systems in Southern Africa

Christian Thierfelder

Abstract No-till (NT) farming, as part of a Conservation Agriculture (CA) system, has been practiced for more than 30 years in southern Africa. In contrast to other regions, and with the exception of South Africa, it has been mostly on smallholder farms, which are more diverse and complex. Tailoring CA systems to the needs and agro-ecologies of smallholder farmers in southern Africa has been a major effort by various research and development organizations with a lot of publicized biophysical benefits. However, despite these large promotional efforts and research to better understand the processes and merits of applying the basic principles of CA, its adoption has so far remained low given the large investments and attention received over the years. This book chapter summarizes historical developments around NT agriculture, current status and future directions needed to enhance adaptation and adoption.

Keywords Sustainable intensification · Conservation agriculture · Adoption · Climate smart agriculture

28.1 Introduction

No-till (NT) farming systems have been promoted in southern Africa for more than 30 years (Wall et al. 2014). Initially they were tried on commercial farms, based on the need to save fuel and improve efficiency. Rapidly declining soil fertility on predominantly communal land and the increasing impact of climate change also necessitated its promotion and application on smallholder farmers' fields. Since the late 1990s and early 2000s, efforts have been made to mainstream NT farming in southern Africa (Thierfelder et al. 2015c). This was mostly pursued through the concept

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of Conservation Agriculture (CA), which is strictly defined as a cropping systems based on the three principles of minimum soil disturbance (or zero tillage), maintenance of groundcover through living or dead plant material, and crop diversification through rotation, inter- or relay cropping. Since the beginning of the millennium, and tasked by a critical paper who questioned the suitability of CA for smallholder farmers (Giller et al. 2009), a large body of research has gone into providing the scientific background and evidence of NT agriculture in southern Africa (Thierfelder et al. 2015c; Wall et al. 2014). In particular, efforts have been made to test the biophysical benefits and challenges of this cropping system, its environmental effects, the socio-economic impacts on profitability and viability and its benefits on smallholder farmers' livelihoods. Increasingly, CA has also been promoted under the frameworks of sustainable or ecological intensification and climate-smart agriculture (Thierfelder et al. 2017).

In the following chapters, recent scientific advances in NT cropping systems in southern Africa will be outlined; the history of NT systems in southern Africa described; and different types of NT systems presented. In subsequent parts, the benefits and challenges of these systems will be explained. The book chapter will end with highlighting research and development needs and a conclusion.

28.2 Challenges in Southern African Farming Systems

28.2.1 The Need to Adapt to Climate Variability and Change

Southern Africa has seen an increase in climate variability and change in the last decades and it is evident that farmers will have to adapt to this new situation (Steward et al. 2018). For the region, it is predicted that rainfall will become more erratic but more intense (Cairns et al. 2013). Climate models also suggest that the onset of the cropping season will be delayed and the end of the season will tail off faster (Lobell et al. 2008). The most problematic climate effect will be the increase in temperature (Burke and Lobell 2010).

Since the early 2000s, great efforts went into breeding for drought-tolerant germplasm in different institutions (Bänziger et al. 2006). However, the yield gains from selecting for drought-tolerance were only between 10% and 30% as compared to commercial non-drought tolerant seed. A combination of different interventions was therefore needed to reap the benefit of several climate-adapted interventions. In parallel, the concept of 'climate smart agriculture' was formulated to continue agriculture research and development with a climate lens (Lipper et al. 2014). NT cropping systems such as CA fall under the 'climate smart agriculture' concept and developing climate-resilient farming systems has been a major effort (Thierfelder et al. 2017).

28.2.2 Declining Soil Fertility

The second major challenge to farming in southern Africa has been the continued decline in soil fertility and productivity due to population pressure and overuse of the otherwise fragile ecosystems (Thierfelder and Wall 2009). A large proportion of arable land in Zambia, Zimbabwe, Namibia, and South Africa is based on granitic sandy soils that are inherently low in soil fertility. Soil organic carbon (SOC) levels are commonly <1%, and sometimes even <0.5%, unless farmers use large proportions of animal manure, agroforestry, and/or sophisticated crop rotations in their farming systems (Nyamangara et al. 2014). However, the majority of smallholders still practice cereal monocropping, use mechanical tillage methods, and burn or graze their crop residues due to the lack of alternatives (Thierfelder et al. 2018).

In addition, farmers are using very low levels of mineral fertilizers which currently amount to approximately 17 kg ha^{-1} NPK in sub-Sahara Africa (Sommer et al. 2013). This means that smallholder farmers are continuously mining the soil. Soil fertility decline has been dramatic in Zimbabwe. In Mozambique, the extension advice has often been not to use mineral fertilizers as the soils are more fertile and mineral fertilizer “will kill the soil”. Although the productivity and fertility decline has been lower in Malawi and Zambia, tillage-based agriculture systems could only maintain their productivity through nation-wide fertilizer support programs (FISPs) which created new challenges and atrocities in the respective countries (Holden and Lunduka 2010, 2013). Besides this, a general decline of soil organic carbon is eminent even in Malawian farming systems, as has been summarized by researchers from Michigan University (Snapp 2015).

Smallholders in southern Africa increasingly face what is usually referred to as the “downward spiral of soil fertility”. This describes the lack of financial resources by farmers to buy expensive mineral fertilizers (Sommer et al. 2013). To achieve at least some crop yields, they till the land to mobilize some nutrients from breaking down organic matter. This slowly exhausts soil fertility, resulting in low productivity. This means that farming families can only maintain their basic food needs without being able to sell surplus, generate income, and buy additional agriculture inputs until the cycle continues again. Abject poverty and continued need for food aid and assistance are the inevitable consequences and there is little hope for change.

The NT cropping systems try to break this cycle by introducing alternatives and yield enhancing measures while farming closer to natural processes (e.g., NT, groundcover, and diversification are common in the natural ecosystems and are more sustainable than the extractive farming systems described above). Once farming becomes more sustainable and diversified crop rotations are producing additional income, there is a realistic chance to break the cycle of declining soil fertility.

28.3 History of No-Till Systems in Southern Africa

No-till systems have usually been promoted in tandem with CA. In many cases the terms NT and CA have been used interchangeably although they are not strictly the same (Derpsch et al. 2014). The first research was done by the Agriculture Research Council in 1976 and focussed on NT seeding systems on commercial farms in South Africa (Wall et al. 2014). In Zimbabwe, the first serious experiments and extension of NT seeding systems based on manual planting basins were started by a commercial farmer, Brian Oldrieve, at Hinton Estate in 1982/83. Soon afterwards the Agriculture Research Trust (ART) of Zimbabwe also initiated NT systems experiments on its farm (MacRobert et al. 1995). Ground-breaking seeding equipment, such as the star-wheel planter (also called the "supernova") was developed during this time by a resident machinery manufacturer, Rio Tinto.

In 1995, the National Farming Unit of Zambia formed a new Department called the "Conservation Farming Unit (CFU)" spearheaded by two visionary leaders Dutch Gibson and Peter Aagaard (Haggblade and Tembo 2003). In 1992, the German Gesellschaft für Technische Zusammenarbeit (GIZ) started research on NT systems in the so-called CONTILL project in Zimbabwe, which resulted in promotion of these systems to smallholder farming communities (Hagmann 1998). In 1996/1997, large numbers of CA demonstrations were established in South Africa, and, at about the same time Sassakawa Global 2000 also started promoting NT in their extension programs in Mozambique and Malawi (Ito et al. 2007).

Following these initial efforts, major research and development projects started from 2004 onwards with the Department for International Development (DFID) initiating the Protracted Relief Program, which led to a massive out-scaling of NT systems targeting vulnerable farmers in Zimbabwe with planting basin systems (Mazvimavi et al. 2007). At about the same time the International Maize and Wheat Research Centre (CIMMYT) and the International Centre for Research in the Semi Arid Tropics (ICRISAT) initiated on-station and on-farm research activities in Zimbabwe, Zambia, Malawi, Mozambique and Tanzania that provided the scientific foundation of NT agriculture for smallholder farmers in the region. Since then, NT systems have become mainstream in all agriculture research and extension departments of southern Africa and have been promoted in many small- and large-scale initiatives. NT-farming systems have also become a central narrative in recent policies targeting climate adaptation and mitigation in the region.

28.4 No-Till Systems and CA in Southern Africa

The combined efforts in southern Africa have produced a large body of research results in recent years (Thierfelder et al. 2015c). One of the key lessons learned is that NT systems have to be integrated with sound agronomy and require complimentary agriculture practices to function under the prevailing conditions of southern Africa. In a recent publication Thierfelder et al. (2018) put together the factors that influence successful application of CA, which includes NT farming systems, in southern Africa (Fig. 28.1).

It is evident from Fig. 28.1 that the three principles of CA (NT, crop residue retention and diversification) are both positively and negatively affected by the farming system. The core principle of NT requires appropriate machinery that can seed into mulched fields, can operate under the circumstances of untilled soil, and place the seed and fertilizer at the right depths. As most of the efforts in southern Africa have been on manual and animal traction systems, this has been less of a problem, whereas it has been a major research effort for machine planted systems. Other bottlenecks of successful application of NT systems have been: weed control, which required research on chemical weed control including herbicide types, and biological control strategies, spraying equipment, and green manures (Lee and Thierfelder 2017); shortage of crop residues due to intensive crop/livestock interactions, requiring research on grazing systems and alternative residue management strategies (Valbuena et al. 2012; Mupangwa et al. 2019); nutrient and water management (Mupangwa et al. 2017b); and socio-economic constraints requiring research on socio-economic aspects in the farming systems (Thierfelder et al. 2016b). The strong focus on cereal monocropping in the region, emanating from strong fears of food insecurity, have further complicated successful extension of NT cropping systems. Rotations with legumes have long been a challenge, also due to lack of appropriate markets for seed and grain, cash, and land constraints (Snapp et al. 2002, 2010). Recent efforts by various aid organisations are helping to increase the incorporation of legumes into farming systems, including the development of markets for produce.

28.5 Types of No-Till Systems in Southern Africa

No-till systems in southern Africa are traditionally distinguished by the labour and traction force needed for planting. Broadly, four different types of seeding systems can be distinguished: manual systems; animal traction systems; two-wheel and four-wheel tractor systems which operate very differently and involve a large degree of diversity in labour demands.

28.5.1 Manual Systems

Manual NT, usually done in form of either planting basins or planting with a dibble stick, have seen the greatest efforts of promotion as most of the traditional farming in Malawi, Zambia, Mozambique, and to a certain extent Zimbabwe, is still done manually.

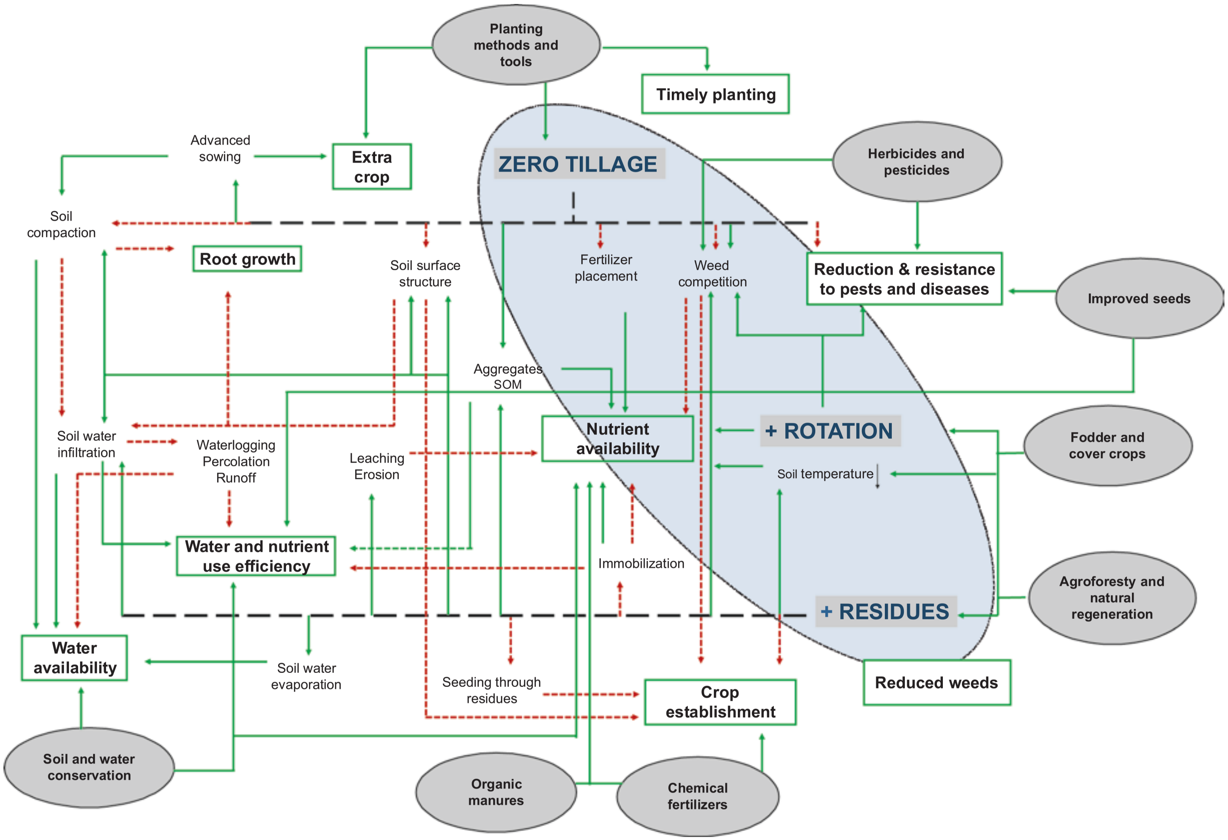

Fig. 28.1 Factors affecting the functionality of no-tillage systems under conservation agriculture in a positive and negative way. (Adapted from Thierfelder et al. (2018) with input from Brouder and Gomez-Macpherson (2014))

28.5.1.1 Basin Planting

The basin planting system is based on digging small planting holes 0.15 × 0.15 × 0.15 m in size (with larger basins also promoted in Zambia or smaller ones in Zimbabwe) and spaced at 0.90 × 0.6 m or 0.75 × 0.75 m row spacing (Sims et al. 2012). The basins are dug during the dry winter period and once the first rains fall, the seed is planted in the basins. Fertilizer, lime, and manure is usually accumulated in the basins making the system a precision agriculture intervention with accumulation of fertility on-site. The main benefits from basin planting are derived from early planting, water harvesting, and precision fertilizer placement, however, they involve a lot of manual labour, which can be a deterrent for its widespread adoption.

28.5.1.2 Dibble Stick Planting

Dibble stick planting has been more common in Malawi where traditionally farmers use planting sticks to place seed in the annually dug ridges. With a sharpened wooden stick, farmers make small planting holes (for seed and fertilizer) and then plant into those holes once moisture is adequate (Fig. 28.2). Different row spacings are practiced (e.g. 0.9 × 0.5 m, 0.9 × 0.25 m and 0.75 × 0.25 m) depending on agroecology and soil type. In northern Zambia, farmers have adapted the dibble stick into a two-pronged stick using a tree crotch. This further reduces the time needed for planting.

28.5.1.3 Jabplanter

The jabplanter, also called Matraca, has been fairly successful in Mozambique, but rejected in other countries due to problems associated with cost, tip clogging and the absence of reliable suppliers. The jabplanter operates by being pushed into the soil, opened to release seed and fertilizer of a defined quantity, then pulled out of the soil before moving to the next station (Fig. 28.2).

Fig. 28.2 Seeding into Planting basins in Southern Zambia (left), dibble stick planting in Northern Zambia (middle) and planting with jabplanters in Central Mozambique (right). (Photo credits: Thierfelder, CIMMYT)

28.5.2 Animal Traction Systems

Different types of animal traction systems have been promoted in southern Africa, which are based on rip-line seeding and direct seeding, mainly drawn by oxen. Anecdotal evidence also reports the use of harnessed donkeys as traction force, although this has not been common.

28.5.2.1 Rip-Line Seeding

Seeding with a ripper means that a traditional single row mouldboard plough is modified with a ripper attachment. Rip-lines are created based on the required row spacing (usually 0.75 m or 0.90 m) at a depth of 0.10–0.15 m. Seeding is done manually immediately after the rip-lines have been created. In Zambia, farmers rip twice; in April when the soil is still soft from the rainy season and in November, at seeding time. In other places, ripping once has been considered sufficient. The advantage of rip-line seeding is that farmers do not have to till the soil, which makes it more timely and efficient for planting. Also, the relatively weak animals at the onset of the cropping season have less difficulty pulling a ripper than tilling a whole field with a plough.

28.5.2.2 Direct Seeding

Several animal traction direct seeders have been tested since 2004 in southern Africa (Fig. 28.3). The direct seeder opens a furrow, places seed and fertilizer into the furrow, and closes it again. Approximately 1.5 ha can be easily seeded per day with a trained pair of oxen, Unlike ripper attachments, which provide a cheap replacement to an already existing mouldboard plough (approximately 25 USD), the direct seeder prices are still much higher (600–1000 USD per implement) mostly due to the lack of large quantities, competition, and available local production.

Fig. 28.3 Rip-lines created by a pair of oxen and a Magoye ripper ready to plant (left and middle), direct seeding with an animal traction direct seeder that rips, seeds, fertilizes, and closes the line afterwards in Zimbabwe (right). (Photo credits: Thierfelder, CIMMYT)

28.5.3 Two-Wheel Tractor Systems

Since 2012, two-wheel tractor systems of 12–15HP (Fig. 28.4) have become more popular, based on the assumptions that the most critical need in smallholder farming systems is the availability of farm power. Two-wheel tractors are versatile and can be used for planting a multitude of crops, provided the seeders are available. But more important they can be used for many other purposes (transport, shelling, threshing, and water pumping), which provides farmer or service providers alternative income sources in the farming communities. It is likely that these farming tools will see a massive increase in adoption in the next decade due to multiple use options.

28.5.4 Four-Wheel Tractor Systems

Finally, the first Four-wheel tractor mounted NT seeding systems have been tested in the commercial farming sector since the 1980s and were used there with great efficiency (Fig. 28.4). In Zambia, the CFU has promoted tractor hire services and have also implemented a credit scheme for smallholder farmers to access tractors. Mostly ripper-tine systems have been used with the tractor, due to the absence of suitable direct seeders of decent quality and price. However, with the general move towards NT farming systems in the region, it is likely that these equipment pieces will soon be available at an affordable price.

28.6 Benefits of No-Till Systems

NT farming systems have been extensively researched in southern Africa over the last 20 years and efforts have first and foremost concentrated on the immediate benefits of planting in untilled soils. Research later focused on other benefits to find

Fig. 28.4 Planting with 2-wheel and 4-wheel tractors with a single row direct seeder (left) a double row direct seeder (middle) and a seeder drawn by a 4-wheel tractor (right). (Photo credits: Baudron, CIMMYT)

successful entry points for farmers to adopt the cropping system. NT farming systems around the world have thrived in situations: where erosion or degradation was a major problem; where moisture was a limiting factor for crop production; where labour or farm power was a constraint; and where fuel and machinery costs made farming increasingly unprofitable (Baudron et al. 2015). Many of these benefits have also been observed in southern Africa.

28.6.1 Soil Moisture Retention

Research in southern Africa found greater infiltration rates if soils were untilled and covered with crop residues. In long-term CA trials of Zambia and Zimbabwe run by CIMMYT, there was a marked increase in infiltration at all sites, although the positive effect of increase in soil moisture during dry years could turn negative if there was too much moisture in a wet year (Thierfelder and Wall 2009). It was found that NT systems had 3–5 times higher infiltration rates than conventionally tilled systems in dry years, which led to 25–50% greater available soil moisture. Similar results were found by ICRISAT in Zimbabwe, who researched basin and ripline seeding systems and their moisture retention. Researchers established a strong relationship between NT, crop residue retention, and increased soil moisture. (Mupangwa et al. 2008).

28.6.2 Erosion Control

Erosion control was initially a strong driver for research in NT farming systems in southern Africa. Erosion research was conducted during the CONTILL project in Zimbabwe from 1990 onwards and at Henderson Research station, Zimbabwe since 2004. Results showed that erosion loads could be drastically reduced by more than 50% when fields were not mechanically tilled and physically covered with mulch (Munyati 1997; Thierfelder et al. 2012).

28.6.3 Diversification

Conventional farming in southern Africa in the last century has become more and more cereal-based without systematic diversification. The introduction of legumes in NT systems helped in breaking pest and disease cycles, improved the nutritional status of the soil and humans, and gradually increased carbon sequestration and water holding capacity, depending on context (Thierfelder and Wall 2010). Soil carbon sequestration under NT is also only believed to happen under the prevailing climatic conditions of southern Africa if there is a strong diversification element – be it through legumes in rotation or tree-based components (Powlson et al. 2016).

28.6.4 *Climate Resilience*

Increased water retention and reduced evaporation in NT systems has opened up research on the adaptive capacity of such systems in southern Africa (Steward et al. 2018). The main research questions were how “climate-smart” these systems are and to what extent can NT farming systems adapt to the adversities of climate (drought, heat, and delayed onset of the cropping season) (Thierfelder et al. 2017). Research results show that indeed there is a greater adaptive capacity of NT cropping systems to heat and drought stress if they also have mulch as surface cover to buffer against those effects. The adaptive capacity becomes more favourable in sandy and loamy soils, whereas under heavier soils, conventional systems can equally respond (Steward et al. 2018).

28.6.5 *Productivity*

Recently, major research efforts have gone into assessing the productivity of NT cropping systems under the conditions of southern Africa. This work has found generally positive effects of NT systems as compared with conventional tillage systems (Mupangwa et al. 2017a; Thierfelder et al. 2015a, 2016c). However, NT systems do not show immediate yield benefits and need approximately 2–5 cropping season until these benefits become significant (Thierfelder et al. 2015b).

28.6.6 *Labour-Use Efficiency*

No-tillage cropping systems can be more labour effective than conventional tillage practices, depending on which systems are compared. When rip-line seeding is compared with mouldboard ploughing, for example, the labour needed for planting can be more than 50% lower. However, smallholder farmers in southern Africa rarely use herbicides for weed control due to cash constraints and might lose this benefit if weeding is delayed, especially in the first years of conversion from tillage to NT. If herbicides are used then labour savings can be significant amounting to 25–35 labour days on planting and 15 labour days on weeding in Malawi (Mupangwa et al. 2016; Thierfelder et al. 2016a, b).

The predominant NT system that has been promoted in southern Africa has been the manual basins. Basin planting can be very laborious, and if farmers own a pair of oxen and a mouldboard plough, they cannot be convinced to revert back to basin planting. For such farmers an adequate planting solution has to be provided, which should be either based on animal traction or tractors (Thierfelder et al. 2016b).

28.7 Major Challenges in Research and Promotion

NT in itself does not lead to yield benefits and requires the other components of a functional CA system to lead to such benefits. The adoption of CA in southern Africa has remained much lower than in other parts of the world due to a range of challenges.

28.7.1 Bio-physical Challenges

The implementation of successful NT systems requires that soils are protected with groundcover, that weeds are efficiently controlled and crops are diversified.

Residue retention and maintaining a permanent groundcover has been a major bottleneck in southern Africa as most farmers rearing livestock depend on crop residues for animal feed. Free grazing systems also mean that farmers who want to practice surface crop residue retention cannot maintain groundcover as roaming cattle feed on those residues (Valbuena et al. 2012). Efforts to introduce controlled grazing systems, or to grow alternative feed (e.g., forage grass or green manure cover crops), are still in their infancy but will have to become the norm if NT agriculture should become the predominant farming system. Efforts have been made to restrict grazing by growing non-palatable intercrops in farmers' fields, temporarily removing residues, importing alternative biomass material for groundcover, repelling cattle, and fencing. Although, many of those practices are effective, they require additional labour or resources and are therefore unattractive for farmers. For an effective implementation of NT systems, community agreements are required and can be successful (Wall 2007; Erenstein et al. 2012).

In line with maintaining groundcover, controlling weeds in NT systems has been a major challenge to its successful implementation. Where NT farming has been successful, this has usually been achieved through the use of herbicides. Sufficient groundcover and/or rotations with green manure cover crops further supressed weeds. In southern Africa, farmers lack land and capital to extensively grow green manures and efforts to change this have so far not been successful. In addition, the predominant maize-based subsistence farming systems have low gross margins that prevent farmers from gaining a lot of surplus to sell and raise cash to buy additional farm inputs. Successful examples of credit schemes for herbicide have increased the adoption of NT farming dramatically, for example in Malawi (Ngwira et al. 2014). The herbicides addressed a critical bottleneck (e.g., the labour shortage for weeding) and once this was addressed, farmers were very happy to adopt CA. Continued use of NT practices with control of weeds through herbicides may reduce the weed seedbank over time, as has been found on trials in Domboshawa, Zimbabwe (Muoni et al. 2014). However, this requires that weeds are prevented from setting new seed to reduce the weed pressure.

Pest and diseases have also been a challenge in maize-based NT farming systems, specifically foliar diseases and insect pests, such as the white grub (*Heteronychus arator* Fabricius). However, these can easily be remedied through diversified crop rotations and intercropping (Thierfelder et al. 2015c). In recent studies on the control of Fall Armyworm (*Spodoptera frugiperda* Smith), CA systems showed increased control of insect pests due to proliferation of natural enemies (ants, spiders and beetles) (Baudron et al. 2019; Harrison et al. 2019).

28.7.2 Socio-economic Challenges

Low adoption of NT systems amongst smallholder farmers in southern Africa has often been associated with the complex nature of NT farming systems, which requires additional knowledge and skills. To break the perception that crop production is not possible without tillage has been challenging and the slow improvements and maybe decline in yields in the initial years of conversion have not helped in encouraging spontaneous adoption (Wall 2007). Many initiatives have provided funding for CA, however, once project activities cease, farmers fall back to their traditional practices because a transformational change has not happened. For NT farming to be widely adopted there is need for site-specific adaptation and modifications to fit farmers' local needs.

Smallholder, resource constrained farmers need immediate returns to their investments and lack the ability to absorb risks. Trying a relatively new way of farming that reduces labour for tillage but increase labour for weeding with no guaranteed immediate yield increase may not be attractive to some types of farmer. New efforts have therefore focussed on the complimentary practices of NT systems to provide farmers with a faster and more sustained economic return to their investments (Thierfelder et al. 2018).

Creating an enabling policy environment for more sustainable, climate-smart NT farming systems have been a major task of the last decade. This has included reversing the government promotion of tillage-based agriculture schemes and changing the curricula of agriculture schools and universities. Some contradictory policies still need to be removed or aligned with new thinking on how cropping systems can be made more climate resilient. However, since 2010, NT farming has become a mainstream topic regarding adaptation to climate change in southern Africa. It is very likely that farmers will accelerate adoption of NT systems as the traditional ways of farming become more and more unproductive with temperatures increasing and rainfalls becoming more erratic and unpredictable.

28.8 Future Requirements for Research and Development

The research conducted on NT cropping systems in the last decades in southern Africa has focussed on the merits and demerits of adopting such a new system. Major efforts went into quantifying the benefits on productivity, profitability and the environment. Baudron et al. (2015) clearly highlight where NT farming systems may be most suited e.g. in labour constrained environments, where moisture is limiting, and erosion or degradation is a major challenge. However, the effect of NT cropping on social and human indicators has been poorly researched. While it is proven that NT cropping systems will have greater bio-physical benefits to farmers, there is need to spend more time on researching why these systems, despite their benefits, have not been adopted widely. Future research will have to place more emphasis on how to overcome the barriers of adoption and what is needed to achieve transformational change. Current research frontiers are around:

- targeting of NT cropping systems to certain farm types and agro-ecological recommendation domains;
- quantifying tangible and intangible social and human benefits of NT at different scales;
- creating behaviour change within farmers to reduce the fear of the unknown;
- reducing labour burdens on smallholder farmers and identifying what mechanization is needed for planting, weeding, harvesting and postharvest;
- researching how NT farming systems can decrease their dependency on mineral fertilizer, chemicals and herbicides;
- identifying how diversification within NT cropping systems can be strengthened to increase carbon sequestration;
- exploring how the suppliers of goods and services can be encouraged to invest in and foster NT cropping systems.
- determining what scaling strategy is best suited to enhance the uptake of NT farming; and
- enacting legislation to foster the uptake of NT farming systems to increase benefits for farmers and the society.

28.9 Conclusion

NT farming systems have been researched and promoted extensively in southern Africa since the beginning of the millennium. Research results show that NT, especially when combined with crop residue retention and crop diversification, can increase water infiltration, enhance soil moisture content, reduce water run-off and erosion, while gradually increasing soil carbon. This will usually lead to yield benefits after 2–5 cropping seasons and more climate resilient cropping systems. However, while biophysical benefits are evident and have been researched extensively in the last decade, data on social and human benefits have been slim and new research should focus on these missing aspects to achieve greater adoption. A major challenge remains and will be the focus of future research in southern Africa: why, if NT farming is so beneficial, has it not been adopted on a large scale as it has been before in Brazil, Argentina, and Australia. This will require research on farmers' behaviour, risk perception, economics, markets, gender, and other aspects to overcome the barriers to adoption and achieve transformational change.

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Chapter 29
No-Till Farming Systems in Australia

Peter S. Cornish, Jeff N. Tullberg, Deirdre Lemerle, and Ken Flower

Abstract Australia has witnessed a remarkable transformation in land management over 50 years, as the technologies enabling no-till (NT) evolved and they were adapted by farmers to their own situations. The history of NT innovation reveals enduring principles regarding the value of collaboration between farmers and researchers and the need to develop NT as part of a farming system, to adapt to different climates and soils, and to be flexible enough to allow strategic tillage or residue burning for sound agronomic reasons. Soil structure improves under NT and there is often more water available, but individual crop yields overall are no better (except through more timely planting). Inefficient or incomplete water-use point to unrealised yield potential to be captured through improved management, particularly of subsoil constraints that often require tillage to ameliorate. The climate is not conducive to accumulating soil organic carbon, so increases with long-term NT have been small in Australia, especially under continuous cropping, which is becoming more common as sheep numbers fall and ley-farming declines. Diminishing contributions by pastures to the N economy of crops strengthens the demand for economically more competitive pulse varieties and weed management options, and for ongoing research to manage N-fertiliser more efficiently. Intensified cropping increases the major challenge of herbicide resistance. Herbicides are central to NT, raising questions about herbicide dependency and safety, and particularly about alternatives to glyphosate, which remains unrivalled for safety and cost-effectiveness. Maintaining registration is a key challenge. Current weed research emphasizes

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weed-seed management to reduce herbicide dependency. Accurate GPS and allied technology create opportunities for controlled traffic farming and 'precision' agriculture, offering prospects for further improving NT systems, including minimizing herbicide inputs.

Keywords Australia · No-till · Stubble management · Herbicide resistance · Yield gap · Soil water

29.1 Introduction

Arable land management has been transformed in Australia since the 1970s when crop residues were burnt and fields were typically cultivated 5–10 times before planting. Today, around 80% of farms and more than 70% of the rainfed grain crop area is under no-till (NT) (Llewellyn et al. 2012). Most of the remaining area receives only strategic cultivation or burning for sound agronomic reasons (Kirkegaard et al. 2014). Concerns about soil erosion sparked this transformation, but it was enabled by new technologies and sustained by improved profitability. The benefits have been far-reaching for soils and the off-farm environment, but there have also been risks, including dependence on herbicides and herbicide resistance.

Regional differences in soils and climates led to differences in the early steps taken by farmers to reduce soil erosion. In the northern (N) grain-growing region (Fig. 29.1) the focus was on crop residue retention, and in the southern (S) and western (W) regions it was on reduced cultivation. However, all farmers depended on cultivation for pre-planting weed control until Imperial Chemical Industries (ICI) released the non-selective, non-residual bipyridyl herbicides in 1962. ICI and Australian researchers began to evaluate crop establishment without cultivation in 1967, sparking the evolution of tillage practices that, over 50 years, has converged on the NT systems practiced today. The long timeframe required for development and adoption reflects the complex nature of farming systems, the corresponding complexity of technological development, and the time required to develop appropriate technology. Farmers have needed time to meet the high capital costs of new machinery, to learn new and constantly evolving techniques and skills, and to learn how to economically and sustainably exploit the advantages of NT systems.

This chapter draws lessons from the history of NT development in Australia and summarizes contemporary NT practices and farming systems in contrasting regions. We review the key enabling technologies in weed management and machinery, and set out some future challenges and opportunities for research and development. Further details are provided in Pratley and Kirkegaard (2019).

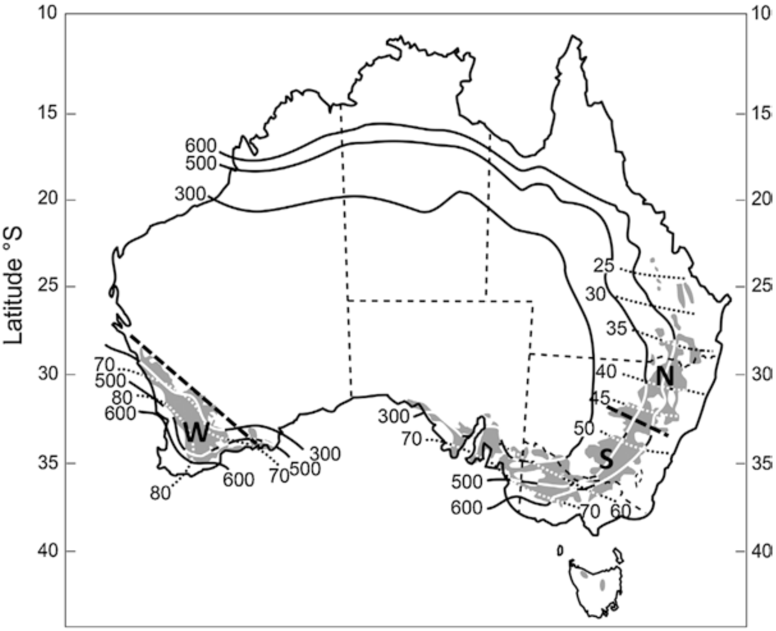

Fig. 29.1 Distribution of broadacre rainfed crop production in Australia showing rainfall isohyets (solid lines) and the percentage of annual rain falling during winter months (dotted lines). After Kirkegaard et al. (2014). Dashed lines demarcate the Northern (N), Southern (S) and Western (W) grain regions

29.2 The Grain-Producing Regions of Australia

Differences in soils and in rainfall amount and seasonal distribution define the three grain-growing regions in Australia (Fig. 29.1). The N region is characterized by intense, potentially erosive summer rainfall, inherently fertile clay soils with high water-holding capacity, fallows of varying duration for water conservation, the potential for both warm- and cool-season crops, and low use of pastures in rotations. The W region and western part of the S region are characterized by winter-dominant rainfall and cool-season crops, infertile mostly light-textured soils, and little fallowing except in the drier regions and during the short period between the onset of winter rains and planting. The rest of the S region is characterized by equiseasonal rainfall, diverse cool-season crops, light to medium-textured soils, and little fallowing except in low rainfall areas and incidentally in autumn.

Pastures have been integral to crop production in the W and S regions, using annually-regenerating legumes and/or lucerne (*Medicago sativa*) in a 'ley farming' system in which an exploitative crop phase of several years is followed by a restorative pasture phase of several years. However, sheep numbers and the area under pasture have declined since the 1990s, crop area has increased, and the enterprises have become less integrated.

These regional differences influenced the course of NT development and adoption through their effects on fallowing, the relative risks of water or wind erosion and the techniques developed for their management, rates of crop residue breakdown between crops, and the relative importance of livestock and crops. However, farming systems in all regions are designed for efficient use of rainfall.

29.3 Historical Development of No-Till

The history of NT in Australia is characterized by phases of innovation, mass adoption and consolidation.

29.3.1 Innovation (1970–1990)

During this period, researchers and leading farmers developed the basic principles and practices underpinning NT and demonstrated unequivocal improvement in soil physical properties, reduced erosion risk, and productivity gains for the farming system. However, yields were generally no better than with multi-pass tillage (Kirkegaard 1995), and the disappointing possibility emerged that soil organic carbon (SOC) may increase only slowly or not at all under continuous NT, despite improvements in soil physical properties. Much of the following account of these developments is drawn from Cornish and Pratley (1987).

29.3.1.1 Southern and Western Regions

In the S and W regions, the initial focus was on minimizing cultivation, using bipyridyl herbicides to control weeds before planting. Research commenced during the 1970s near Wagga Wagga, NSW, Rutherglen, Victoria, and north-east of Perth, Western Australia. Early-adopting farmers were involved in this pioneering research, a role ICI formalized in the National Direct Drill Project Team. From 1976–1982 they developed the "Spray Seed" approach involving direct combine-drilling of cereals after killing fallow weeds and regenerating pasture with bipyridyl herbicides. "Direct-drilling" was popular with farmers as it minimized the loss of grazing during seedbed preparation at a time when stock feed was in short supply. This research, plus on-farm experience and subsequent longer-term experiments (listed in Kirkegaard 1995), revealed improved soil structure, often more available soil water (but no greater yield), savings in time and fuel, benefits for animal production, more timely planting and the potential to crop larger areas. At this time, it was not widely appreciated that grazing comes at the cost of soil water storage during the 'incidental' fallow between the onset of winter rain and sowing.

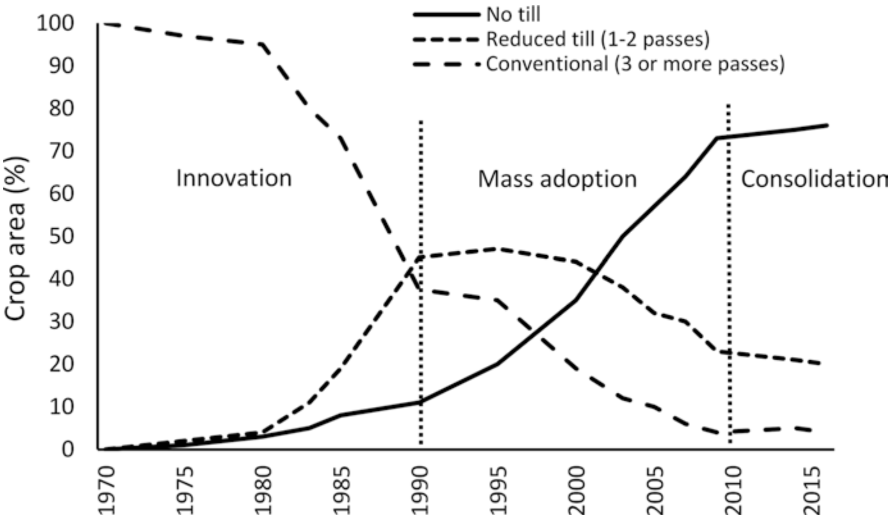

Fig. 29.2 Changes in methods of land preparation for crops in Australia (multiple sources)

With direct drilling, crop residues were burnt (in autumn) because they broke down slowly over the dry summer and blocked planting machinery. The risk of erosion is low before the onset of winter rains, so minimizing cultivation for soil conservation was prioritized over retaining residues. Direct drilling was promoted as a *crop establishment* 'package', but farmers ensured the *farming system* benefits were identified and exploited (Pratley and Cornish 1985), and that pragmatism influenced implementation (Kirkegaard et al. 2014). Adoption commenced in the west in the early 1970s, but weed control with bipyridyls was often incomplete, and annual grass weeds emerging in-crop could not be controlled, so adoption faltered until the release of glyphosate and selective herbicides for in-crop weed control, notably diclofop-methyl in 1977. The development of planters with good stubble clearance and seed placement during the 1980s, and the discovery that the pre-emergent herbicide trifluralin could be incorporated during seeding, set the stage for NT adoption (Fig. 29.2).

29.3.1.2 Northern Region

In the N region, the seminal development was a visit by a farmer and an agronomist to North America in 1969 to investigate stubble mulching (shallow, non-inverting cultivation that retains crop residues). This led to machinery demonstrations and loan schemes for farmers to test machinery. Stubble mulching to control fallow weeds was widely adopted as the machinery became available. Although the initial emphasis was on cultivation for weed control, research had begun in 1969 on fallow weed control with chemicals including bipyridyls, 2,4-D, 2,2-DPA and later, glyphosate. Soil erosion studies in the mid-1970s confirmed the benefit of retaining residues on the surface and an additional benefit from also not cultivating. Long-term tillage experiments commenced in Queensland at Warwick in 1968, Biloela in 1983, and Warra in 1986; and in northern NSW in 1981, all confirming the benefits of NT for soil structure and available soil water. Improved water was reflected in the yields of sorghum, but not of wheat. By the mid-1980s farmers knew that repeated applications of glyphosate would control fallow weeds, but this was costly. When a range of residual herbicides became available in the late 1980s, the stage was set for NT in the north.

29.3.1.3 Key Enabling Technologies

The key enabling technologies in all regions were advances in chemical weed control supported by improved spray equipment and the development of suitable planting machinery. All farmers had embraced chemical weed control early in the 1980s, although few had adopted NT before 1990. When fuel prices jumped in 1980, farmers were equipped to partially replace cultivation with herbicides, resulting in fewer cultivations and a rise in the area of 'reduced tillage' (Fig. 29.2). Increased herbicide use was followed by the appearance of herbicide resistance in the early 1980s, leading to the concept of integrated weed management (Sect. 29.5).

Enabling technology also included improved knowledge of stubble and soil-borne diseases that lay the foundation for better disease management in NT systems, and new varieties of oilseeds and pulses that provided rotation crops to help manage weeds, pests, diseases, and soil fertility.

In a defining feature of the era, farmers prioritized objectives and made pragmatic decisions to cultivate or burn stubble, in order to meet higher-order objectives (Kirkegaard et al. 2014).

29.3.1.4 A Recurring Theme of More Water But No Greater Yield – Where Does the Water Go?

Research during the "innovation" era showed that soils improved over time under NT, and runoff (R) and/or soil evaporation (E_s) were reduced. More water should have increased wheat yields, but over many experiments they were actually *reduced*, by 0.02 Mg ha^{-1} (Kirkegaard 1995). The notable exception was on farms where NT enabled more timely planting. Sorghum and pulse crops appeared to make better use of any extra fallow water (Scott et al. 2010). Direct drilling and stubble retention also reduced the early growth of wheat, for varied and often unclear reasons (Kirkegaard et al. 1994); although soil strength, temperature, N and sometimes P effects, and stubble-borne diseases, were all suspected. Many tillage experiments included N-fertiliser treatments, anticipating reduced mineralization of organic N and increased N tie-up. However, even with added N, wheat failed to realize the potential of increased water availability. The absence of a yield *increase* suggested some water was unused and/or it was used less efficiently under direct drilling and

NT. The distinction between effects on water-use and water-use efficiency (WUE) was not always made, and nor were system-effects always considered, for example the benefit of extra autumn grazing with direct drilling must have come at the expense of water for the subsequent crop.

During the 1980s (before NT), yields on farms were much less than their rainfall-limited potential, with the gap widening with increasing water supply (French and Schultz 1984; Cornish and Murray 1989). So, it is not surprising that NT crops failed to use, or efficiently use, any additional available water. Low WUE was seen to reflect crop management, raising questions about nutrition and disease management in both cultivated crops and the emerging NT systems. This led to research on ‘break crops’ to improve the control of soil-borne diseases, which then enabled crops to respond to higher soil (or applied) N and use more water (Kirkegaard et al. 1994).

The common farmer measure of WUE is yield/growing-season rainfall, which makes no distinction between inefficient water-use and incomplete water-use. In studies of WUE it is rarely possible to say confidently where the inefficiencies lie, but they include (i) non-transpiration losses (R, E_s, and drainage, D), (ii) low transpiration efficiency (mainly phenology effects), and (iii) weed transpiration (T_w). Where management increases the apparent WUE, it is because the managed variable increases crop T (T_c) at the expense of R, $E_{s,}$ T_w, or D. NT potentially improves rainfall-use efficiency by reducing R and $E_{s,}$ both before and after planting, and increasing T_c. When NT doesn’t increase T_c (or T_w), the extra water must go to E_s or D, raising questions about increased D and its implications for dryland salinity, not just questions about unrealized yield potential.

The hypothesis underlying efforts to raise WUE is that, for given crop-available water, yields may be increased towards the water-limited potential by managing key variables including sowing time, nutrition, and crop sanitation. This formed the basis of crop benchmarking, that has contributed greatly to productivity gains in Australia since the 1980s. The possibility that crops could be managed well but *not* use all of the available water was given less consideration, but questions did arise regarding factors that may restrict the use of the available water, including subsoil constraints (SSC). Several studies in the period from 1970–1990 (http://www.regional.org.au/au/roc/1984/index.htm#TopOfPage) used deep tillage to increase access to subsoil water, but the complex causes of SSC demanded further research.

The innovation era ended with questions that continued to recur over the next 30 years, about drainage, unrealized yield potential, and research to bridge the yield gap.

29.3.2 Mass Adoption (1990–2010)

By the 1990s the conservation benefits of NT were clear, the technical foundations had been laid, and there was ample evidence of profitable integration into farming systems, even if individual crop yields were not always better. The economics favored NT over cultivation, especially after glyphosate patents expired in 2000. Economics also favored crop over sheep production, and NT made it possible to increase crop area and cropping intensity without significantly increasing the risk of soil erosion. Thus, the stage was set for mass uptake of NT and the steady decline of ley-farming. However, burning residues before the onset of winter rains remained common in south-eastern grain growing areas, where a small increase in erosion risk was the price paid for being able to direct-seed without concern for heavy stubble loads.

Grower-groups emerged to support farmers adopting NT, amongst the earliest being the Western Australian No-Till Farmers Association (WANTFA) formed in 1992. These groups have been integral to on-farm research enabling farmers to adapt NT to emerging challenges. The most serious challenge to mass adoption was herbicide resistance that developed during the 1990s (Powles et al. 1996), and was made worse in southern Australia by the decline of crop-pasture rotations that reduced the options and flexibility for weed management. During the 1990s, a nationally coordinated research, development, and extension program developed strategies to slow the spread of resistance, ultimately leading to improved management of both herbicides and weeds.

Advances in GPS, GIS, and yield monitors, plus significant innovation by leading farmers, pointed towards ‘precision farming’. This technology is not central to NT, but it nevertheless enhanced the benefits, for example by facilitating controlled traffic farming (CTF). It also reduced costs. Pioneering research revealed the benefits of controlled traffic for both soils and farm profitability (Tullberg et al. 2007).

Long-term studies in all regions confirmed that the climate is generally not conducive to increasing SOC under continuous cropping with NT (Chan et al. 1992; Dalal et al. 1995). To the disappointment of many, it became clear that C sequestration will occur only by reintroducing pastures into rotations or by incorporating large amounts of organic material (Chan et al. 2003; Sanderman et al. 2010; Scott et al. 2010).

Research identifying the extent, causes, and possible correction of subsoil constraints (SSC) in Australia, published in a Special Issue of the Australian Journal of Soil Research (2010), revealed the most extensive area of sodic soils in the world - more than 60% of cropping soils have the potential for sodicity to reduce yields by up to 50%. Other constraints are subsoil acidity and salinity, boron toxicity, tillage-induced soil compaction, naturally dense subsoils, and waterlogging. The most common effect of this complex and variable combination of constraints is to reduce effective plant-available water capacity (Dang et al. 2010), providing a likely reason for many crops falling well short of their rainfall-limited potential despite progress through crop benchmarking (Hochman and Horan 2017).

In an analysis of yield gaps, Anderson (2010) stressed the importance of capitalizing on the potential of good years. He then evaluated the relative benefits of *strategic investments* (made infrequently with long-term impacts) and *tactical decisions* (made each growing season). He concluded these were independent and additive, i.e. it is necessary to combine tactical management (choice of crop/cultivar, fertilizer amount/timing, and weed, insect and disease control), with strategic management (of compaction, sodicity, acidity, and water-logging).

29.3.3 Consolidation (Post 2010)

During this period, the motivation to adopt NT has changed. The soil erosion that once motivated early adopters no longer differentiates adopters from non-adopters (Llewellyn et al. 2012). The present tilled or burnt crop area appears to result from pragmatic decisions by farmers with multiple objectives to achieve, rather than rejection of NT *per se*. Research is addressing how to integrate these actions into NT systems without losing the benefits. No-till farmer groups remain active in supporting farmers to adapt to emerging threats (e.g. herbicide resistance) and opportunities (e.g. CTF). On-farm research continues to improve NT in areas where implementation has been difficult, notably some low rainfall areas in the S region.

The gap between farm yields and the modelled rainfall-limited potential has narrowed by 0.7% year^{-1} since 1990 (Hochman and Horan 2017), i.e. since the mass adoption of NT began. This is impressive, yet by the end of the study, when 96% of crops in Australia were NT or reduced till (Fig. 29.2), actual average yields were still <60% of potential. The gap varies between farms, with leading farmers approaching the economically realizable limit of 80% of potential.

New work commenced to find and implement practical solutions to subsoil constraints. The scope for management actions that may be required to address subsoil constraints is illustrated in the W region (https://grdc.com.au/news-and-media/newsletters/paddock-practices/tips-and-tools-for-planning-management-of-soil-constraints-in-2019) and N region (Page et al. 2018). Almost all proposed methods involve surface or subsoil tillage, demanding accommodation in NT systems. Nationally, 'strategic tillage' will be needed for as much as half of the Australian wheat belt to allow NT crops to fully utilize subsoil water. The multiple reasons for strategic tillage in NT systems are set out by Kirkegaard et al. (2014). Fortunately, Dang et al. (2018) concluded that occasional tillage may have no lasting negative impacts.

Concerns about increased drainage and possible effects on dryland salinity were confirmed (Silburn et al. 2011), but after a series of dry years, these concerns have subsided – for now.

29.4 Contemporary No-Till Farming Systems

This section provides an overview of practices based on case studies provided by farmers.

29.4.1 Western Region

The number of farms with no livestock is increasing as NT cropping intensifies and fewer farmers practice ‘ley farming’. Even on farms with sheep, the land most suited to cropping may be continuously cropped, with sheep grazing permanent pasture in winter and crop residues over summer, taking care to retain sufficient residues for soil conservation. For cropping, farmers typically follow rotations of wheat-canola (or legume)-wheat (or barley)-canola; or, in drier areas, less canola and more cereals. Some farmers include pulses to provide a disease break and improve soil fertility, but many do not because of low profitability and limited weed control options. Tillage may be required occasionally to address common problems of soil acidification, soil compaction, non-wetting surface soils, and herbicide-resistant weeds.

Since the introduction of direct-drilling in the 1980s, the most striking change to the cropping system has been the introduction of residue retention and NT, reportedly leading to improved water capture, earlier seeding, higher water use efficiency, the ability to crop larger areas, and better yields/profit. Farmers stress this is a system based on integrating many aspects from seeding through to post-harvest residue management.

Priority is given to early planting, enabled by NT. Crops may be sown into dry soil, most commonly using a ‘knifepoint’ planter. High accuracy auto-steering on tractors is seen increasingly as a key component of the stubble management system to ensure accurate seed placement next to last year’s crop rows with minimal stubble interference. There is a trend towards wider row spacing (up to 0.3 m) to assist with stubble management, reduce fuel consumption and speed up seeding, often using a ‘splitter seed boot’ to seed two crop rows 3–4 cm apart, effectively reducing row spacing and increasing competition with weeds. Farmers rotate the class of pre-emergent herbicide to help manage herbicide resistance.

Some farmers are adopting controlled traffic farming (CTF) to manage soil compaction and enable harvest weed-seed control by placing chaff from the harvester (with any weed seeds) onto the wheel tracks, rather than spreading it over the field or burning stubble.

29.4.2 Northern Region

Summer-dominant rainfall and soils with high water-holding capacity provide a wide range of cropping options, with some restrictions imposed on pulses by widespread subsoil sodicity. Winter crops are typically grown after a short summer fallow and summer crops after longer fallows. Livestock play a minor role. Farming systems and technology are designed to efficiently use rainfall. Most farmers optimize cropping intensity to achieve efficient rainfall use with manageable risk – higher cropping intensity increases both rainfall-use efficiency and risk. An important principle is that crops are sown when soil water, together with expected rainfall, provide the opportunity to grow a good crop. Sowing is not to a timetable.

Wheat and sorghum are the primary crops, with pulses in the rotation on suitable soils. Stubble management is an important consideration in most decisions. Wheat with a high plant population and narrow row spacing (<0.2 m) provides good stubble cover to protect soil from erosion and capture fallow rainfall, whilst a sorghum break crop reduces stubble-borne diseases. Sorghum tends to be planted on wet soil profiles to provide yield security. Paddocks with low ground cover may be planted to wheat with sub-optimal water to improve stubble cover, accepting the lower yield potential of these crops. Both tine- and more commonly disc-planters are used. Over the last 10 years, GPS-guided CTF has been widely implemented.

The major weed species are small-seeded, surface germinators, with populations of glyphosate resistance on many farms. A range of herbicide modes-of-action is used in the crop rotation to reduce the risk of herbicide resistance. Combinations of knock-down and residual herbicides keep weed seedbanks low, reducing the risk of large weed populations requiring modifications to planned crop rotations.

Farmers are alert to current research on deep placed phosphorus and on whether to ameliorate subsoil constraints or reduce inputs to match the lower yield potential of unamended soils.

29.4.3 Southern Region

‘Ley farming’ has been replaced widely by longer cropping sequences and even continuous cropping. There are exceptions, however, with some farmers reverting to mixed farming as a consequence of recurring drought, herbicide resistance, and the need to manage increasing costs. Diverse crops and pastures enable a range of options to manage risk, increase soil N, and control weeds and diseases. However, the area of the main pulses, lupin, and field peas, has declined over 20 years due to low prices and poor competitive ability with weeds. Soil acidification and sodicity are problems in some areas.

Over much of this region, relatively high rainfall and high yields result in heavy crop residue loads that decompose slowly over the dry summer. In the 1980s, many farmers started to direct-drill crops following a late (autumn) burn, moving to NT in the 1990s but with strategic burning. During the 2000s, precision auto-steer has allowed wider row spacing and better trash handling with only occasional burning. The expanding range of herbicides enabled these NT systems to evolve, but led to a major problem with herbicide resistance.

Farmers have adopted many strategies to manage herbicide resistance based on managing the seedbank and integrating non-chemical with chemical control tactics. These include grazing during the summer fallow to stimulate weed seed germination and increase seedbank decline, desiccating and windrowing canola to kill weed seeds, narrow windrow burning, diverse rotations, pre-emergent herbicides, and other non-chemical options such as cutting for silage or hay, crop competition, and a triple-knock in spring in the companion crops using glyphosate, paraquat, and grazing. Successful management of herbicides and weeds requires a systems-based approach, good managerial skills, sometimes extra costs, acknowledgement that control options do not always work, and a willingness to adapt and evolve practices.

29.4.4 Synthesis of Regional Studies

Despite differences in climate and soils and early approaches to managing soil erosion, there has been a convergence of technology towards minimal soil disturbance with retained residues, often enabled by strategic burning or tillage. The quest for efficient and profitable use of rainfall is paramount. Farmers stress that they manage systems with many aspects including water, crop residues, weeds and herbicide resistance, diseases, and soil fertility. Many also manage some form of subsoil constraint.

There is a nation-wide decline in animal numbers, greater separation of animal and crop enterprises on the same farm, and a trend towards continuous cropping, although farmers change their enterprise mix in response to market signals or to manage herbicide resistance. Continuous cropping has implications for the use of N-fertiliser and long-term changes in SOC, and sustainability. Continuous cropping also has implications for pulse development. Pulses currently play a relatively minor role, but farmers say they want improved pulses with good weed control options.

All farmers have drawn, and continue to draw, on innovation across a range of technologies for their NT systems, but the key enabling technologies lie in herbicides for weed control with the attendant need to manage herbicide resistance, and in machinery, including the current move to CTF and more precise farming with yield mapping and variable rate fertiliser-use.

29.5 Key Enabling Technology

29.5.1 Integrated Weed Management (IWM)

Herbicides are *the* major enabling technology for NT systems, but along with them came the need to manage herbicide resistance and to develop integrated weed management (IWM) systems. Weeds remain the major constraint to adoption and management. A succession of herbicidal innovations underpinned the development of effective weed control (Sect. 29.3), followed by the development of herbicide-resistant crops that broadened herbicidal options across crop and pasture rotations. The resultant dependence of NT systems on herbicides led to rapid development of herbicide resistance (Powles et al. 1996; Thill and Lemerle 2001).

29.5.1.1 Emergence of Herbicide Resistance

The status of herbicide resistance world-wide is summarized by Heap (2019). The first cases of herbicide resistance in Australia were in the early 1980s in *Lolium rigidum*, within several years of introducing the post-emergence herbicides in Group A (e.g. diclofop-methyl, sethoxydim). This was followed by resistance to Group B (e.g. chlorsulfuron), which also developed in some broadleaf species including *Raphanus raphanistrum* and *Sisymbrium* spp. *L. rigidum* resistance was slower to develop to Group C1 (e.g. simazine, atrazine) and Group K1 (e.g. trifluralin), while resistance was much slower to develop to Group G (e.g. glyphosate). In Australia, 92 weed species are resistant to the following herbicide groups: 26 to Group B, 17 to Group G, 12 to Group A, 11 to Group D (e.g. paraquat), and 8 to Group C1. Multiple resistance to different modes of action is a major problem in *L. rigidum*, *R. raphanistrum*, *S. orientale*, *P. paradoxa* and *A. fatua*.

The rates of evolution of resistance depend on patterns of herbicide usage, which are related to the farming system. Agronomic practices that change weed flora include crop rotation, tillage, herbicide use, soil amendments, and mechanization of harvesting (Murphy and Lemerle 2006). Resistance develops rapidly when (i) simple rotations are used favoring a few dominant species; (ii) weeds are present at high densities, widely distributed and genetically variable with prolific seed production; and (iii) multiple applications of single or similar mode-of-action herbicides occur (Powles et al. 1996). In WA, high rates and rapid development of resistance in *L. rigidum* were attributed to the continual use of a wheat-lupin rotation combining a weakly competitive legume, limited herbicidal options, and lack of stubble burning and tillage for weed control. In contrast, resistance was slower to develop in the more complex crop-pasture rotations typical of south-eastern Australia.

Biological characteristics are also important. *L. rigidum* has the highest incidence of resistance because of outcrossing, genetic diversity, prolific seed production and low seed dormancy (Powles et al. 1996). Other factors influencing rates of spread include the availability of cheap, easy-to-use herbicides and reliance on only a few modes of herbicidal action. Resistance may occur rapidly but go unrecognized in small patches. In the early years following detection, some farmers were slow to accept and respond to resistance because of the stigma attached to it. This was overcome by a ‘community’ approach to managing resistance through grower-groups.

Several problems for weed management arise when growers adopt NT systems. These include shifts in the dominant weed species and population densities, sometimes poor herbicide efficacy, and often reduced crop competitive ability. The distribution, biology and longevity of weed seeds in the soil change depending on the species and levels and frequency of disturbance. Generally, annual wind-dispersed species with low seed dormancy that favor conditions on or close to the soil surface thrive in NT systems, and this influences patterns of seed germination and seedling emergence and evolution to changed systems (Chauhan et al. 2006).

29.5.1.2 Development and Application of Integrated Weed Management (IWM)

When the incidence of resistance was limited, farmers switched to alternative herbicidal modes of action believing new herbicides would always be available. By the 1990s, declining numbers of new modes of action highlighted the need for broader approaches to weed management.

Rotating modes of action was the first recognised tactic to reduce the spread of herbicide resistance in Australia (Norsworthy et al. 2012). This included increased use of low-risk, pre-emergent alternatives such as trifluralin and pendimethalin, combined with innovative new chemicals and cultural tactics including delayed sowing combined with a non-selective pre-plant herbicide or shallow cultivation. The herbicide-based 'double knock' approach is the sequential application of two different modes of action, the first herbicide is translocated (e.g. glyphosate) and the second is a contact herbicide (e.g. paraquat) intended to control survivors of the first application. In pulse crops, 'spray-topping' uses low rates of paraquat applied late to manage grass weed seed production. The introduction of herbicide-resistant crops enabled in-crop application of different herbicidal modes of action. Farmers can apply non-selective herbicides (e.g. glyphosate) multiple times within a crop without concern for crop injury, but the approach imposes a greater selection pressure on resistance toward such herbicides.

Many growers have reverted to 'strategic' tillage and burning of crop residues for weed, disease and pest control. Burning can target patches of weeds or windrows to kill weed seeds. Windrows are the concentrated harvest residues that remain behind the harvester. Strategic tillage as a weed management practice may alter the density and composition of weed seedbanks (Chauhan et al. 2006).

Crop competition is an important component of IWM (Lemerle et al. 2001). Weed suppression can be increased by narrow row spacing, row orientation, increased crop density and seeding rate, choice of vigorous crops and varieties, optimal crop sowing time and depth, and nutrition. The responses vary considerably across environments and with crop and weed species. Factors that enhance wheat competitive ability are extensive leaf display, height, rapid early growth (Lemerle et al. 1996), and allelopathy (Wu et al. 1999).

Utilizing a pasture phase in the rotation is well recognized as an important way to manage seed input; by grazing, use of non-selective herbicides for spray-topping, or cutting for hay or silage. Cutting a heavily infested crop for fodder, and green or brown manuring prior to weed seed production, are used to control high densities of herbicide-resistant weeds like *L. rigidum*. Where weed populations are out of control, farmers may bale the crop and weeds.

Harvest weed-seed control refers to the collection and destruction of weed seeds present at crop harvest time (Walsh et al. 2013). Tactics include chaff carts, narrow windrow burning, direct baling, and the Harrington Seed Destructor. The effectiveness of this approach depends on weeds retaining a high portion of their seeds at the time of crop harvest. The practice can select for weeds that shed seed prior to harvest or grow below harvest height (Walsh et al. 2013). Adoption of non-chemical control is generally low until growers have high levels of resistance and few effective chemical options. Non-chemical options are often more expensive, require greater management skills, and are less convenient and less effective than herbicides.

Effective IWM of herbicide-resistant weeds requires a long-term approach to weed population management, working with farmer-communities. Farmers have kept in-crop weed populations and crop yield losses due to weeds relatively low, despite the challenges of herbicide resistance, and while also increasing cropping intensity (Llewellyn et al. 2009). NT systems are enabled by a range of herbicides and non-herbicidal strategies. Continued reliance on herbicides brings increasing emphasis on weed-seed management. Farmers demonstrate flexibility in applying NT and residue retention, using cultivation and innovative residue management techniques as weed control options. Dealing with the constantly evolving challenge to maintain weed control in intensive cropping systems requires ongoing flexibility and the capacity to adapt.

29.5.2 Machinery and Related Technology

Discussions of equipment for NT often focus on the role of seeders, but machinery and equipment developments go well beyond this.

29.5.2.1 Herbicide Application

With the advent of NT, the sprayer became the most heavily used machine on the farm. It has developed from a roughly calibrated, tractor-mounted, tank-pump-regulator rigid boom, to the present sprayers that are often self-propelled and fitted with minimum-drift nozzles, sophisticated pressure and GPS-activated section controls, with suspended, height-controlled booms up to 50 m wide. Such units are commonly used when rapid broadacre herbicide/fungicide application is required. To manage scattered weeds, weed-detecting sprayers, pioneered in Australia by Felton et al. (1987), have evolved using infrared plant detection. These technologies reduce the herbicide applied, with both economic and environmental benefits. They are likely to become more important in dealing with herbicide-resistance. Detection technology is already incorporated in robotic sprayers. Future technologies include individual weed recognition, which is in the early stage of development.

Encouraging results have also been reported with selective mechanical, electrical and thermal weed control systems, but commercial application appears unlikely in the near future.

29.5.2.2 Seeding

Murray et al. (2006) provide detailed discussion of NT seeders. They require ground tools (openers) to displace or cut through surface residues, create a trench and, after seed placement, return soil to the trench and firm it around the seed. Various devices have been used to displace residues ahead of openers, but for practical purposes broadacre seeders in Australia are classified by opener type – tine or disc.

Narrow tine openers displace soil from the seed trench abruptly. The consequent soil throw can assist pre-emergent herbicide distribution and incorporation, but speeds >10 km hr^{-1} results in excessive soil throw, interference with neighboring rows and creating unnecessary moisture loss. Tines operate in a range of soils and are simple and robust, but the wide transverse and longitudinal spacing required for residue clearance increases machine complexity. Better depth control can be achieved by mounting the opener in a parallelogram frame supporting the row-firming press/depth control wheel. Tine seeders are the most common, outside the N region.

Disc seeders attempt to cut through residue and move surface soil more gently, producing less soil disturbance and moisture loss, and allowing operation at greater forward speeds. Discs can have difficulty with soil adhesion and residue ‘hair pinning’ in moist conditions and with penetration in dry conditions. They are more expensive and require greater weight to achieve penetration. Around 60% of N region farmers use disc seeders.

29.5.2.3 Precision Agriculture (PA)

Satellite-based GPS positioning and guidance technology has made an important contribution to improved herbicide, fungicide and nutrient application. At the base level, “2 cm” Real-Time Kinematic (RTK) autosteer has reduced overlap to negligible levels resulting in substantial savings in input costs. It also facilitates ‘shield spraying’ when non-selective herbicides are used for interrow weed control, and can be used for on-row nutrient and fungicide application.

Precision guidance allows seeder openers to operate within the interrow area and avoid most residue. The improved handling of heavy residues played an important role in NT adoption.

Accurate positioning and guidance greatly improve the quality of harvester-based yield mapping and is fundamental to ‘site-specific management,’ using remote sensing from the ground, an unmanned aerial vehicle, or satellite platform. This has allowed rapid delineation and treatment of problems such as local weed or disease infestations and nutrient deficiencies, using indices such as NDVI (Normalized Difference Vegetation Index) and canopy temperature. Further developments can be expected with continuing research and commercial interest in these topics.

Yield mapping is practiced on >30% of the grain cropping area, but further PA applications such as variable rate technology cover <10% of the crop area.

Comprehensive use of PA is restricted to early adopters, but this might reflect the slow development of effective service providers and limited evidence of short-term benefit. PA technology appears to be more commonly applied where benefits are clear and methodology is commercially available, e.g. zone application of lime.

29.5.2.4 Controlled Traffic Farming (CTF)

Unless traffic is controlled, heavy machinery wheels impact at least 40% and commonly >50% of field area in each crop cycle (Tullberg et al. 2007). Axle loads in the range 8–25 Mg are commonly applied by modern farm equipment, often when subsoil or topsoil is relatively moist, so soil compaction is endemic in Australian grain production, regardless of tillage methods.

Much effort has been expended worldwide in the study of compaction mechanisms in a variety of soil types in the field and in soil tanks. It appears to be generally true that:

- Most soil compaction occurs on the first application of any given load;
- Surface compaction intensity is proportional to contact pressure (tyre pressure);
- The depth to which compaction effects penetrate is proportional to axle load.

Significant soil deformation has been found at depths to 1 m in soil bin experiments with 30 Mg axle loads. Field measurements often demonstrate compaction effects to about 0.5 m.

The direct impact of traffic compaction is greater soil strength and reduced porosity, which reduces root exploration, infiltration, aeration and available water capacity. This often reduces crop yields, particularly in more difficult years (both wet and dry). Compaction also increases run-off, denitrification, and soil emissions (Tullberg et al. 2018).

CTF addresses these problems by restricting heavy field traffic to permanent traffic lanes, where greater soil strength improves trafficability. Because permanent traffic lanes are slightly depressed, a well-designed CTF system can also provide surface drainage. This is common in the N region, where traffic lanes are often left bare, and shrink-swell clay soils in CTF beds will self-repair to depth with wetting/drying cycles and biological activity.

Permanent lanes in the W and parts of the S regions are often sown to protect against wind erosion. Compaction to depth is often evident, but in some soils, particularly the deep sands, self-repair capacity is negligible. In these soils substantial yield benefits have been achieved with deep (0.35–0.5 m) ripping (https://www.agric.wa.gov.au/soil-compaction/deep-ripping-soil-compaction), an energy-intensive, slow and expensive operation. Ripping costs are reduced by not ripping traffic lanes, and benefits preserved by maintaining CTF after ripping.

Growers refer to the ‘system benefits’ of controlled traffic, such as traffic lanes increasing the window of operation for time-critical operations, and reducing fuel costs for spraying where most power is dissipated in overcoming motion resistance. Crop performance and crop management is enhanced by greater crop uniformity.

Soil/crop conditions can be different in traffic lanes, but these have a consistent dimensional relationship with machines, and are dealt with by adjustments. These characteristics make CTF an excellent fit with NT farming, improving the capacity to absorb and store moisture and facilitate greater cropping intensity. CTF does not increase machinery or agricultural chemical sales, so it has received little commercial encouragement. The Australian Controlled Traffic Farming Association provides information via farmer-focused CTF conferences, its magazine and website (www.actfa.net).

29.5.2.5 Machinery Costs and Scale

Increasing size and weight of equipment is driven by demand for greater capacity, driven in turn by the requirements of timely operation and the cost or availability of labor. Timely operation is important when yield or cost penalties apply when spraying, seeding or harvesting operations occur outside relatively brief optimum periods, and labor availability is inevitably difficult for short-term peak workloads. Speed of operation is limited, so with current technology the demands for greater capacity can be satisfied only with larger, more powerful and inevitably heavier operator-controlled machines. Limited machinery work hours per year ensures that ownership costs of farm equipment far exceed operating costs. This issue may be addressed by contractors moving equipment between different environments.

29.6 Conclusions and Future Challenges, Opportunities and Directions for R & D

NT has been adopted widely for good biophysical and economic reasons, including the capacity to intensify cropping whilst minimizing the risk of soil erosion. As cropping has intensified for economic reasons, the traditional 'ley farming' system has widely declined and with that, the role of pastures in maintaining soil fertility. Consequently, improved (profitable) pulse crops with good weed control options would provide major benefits to NT systems, as would more efficient use of N-fertiliser.

The climate of much of Australia is not conducive to accumulating SOC under continuous cropping, even with NT (Sects. 29.3.1 and 29.3.2). In lower rainfall areas, SOC actually declines under continuous NT (although more slowly than when tilled), highlighting the need for research on structural stability when total C is stable or declining. The potential for C sequestration in crop land is limited without a return to ley pasture phases, although research is exploring the possibility of adding supplementary N, P, and S to the soil before cultivation to minimize the loss of existing C and increase the capture of added C (Kirkby et al. 2016).

In 2015, following widespread adoption of NT, farm yields were still <60% of the water-limited potential (Hochman and Horan 2017). Efforts to bridge this gap are using combinations of strategic and tactical agronomic management (Anderson (2010), but there is clearly a need for further research. It has been suggested that breeding wheat better adapted to NT would narrow this gap, citing disease resistance, longer coleoptiles, and enhanced allelopathic characteristics (Scott et al. 2010). This may be so, but five decades of wheat breeding in Australia has not influenced the adaptation of wheat to NT although it has improved yield (Kitonyo et al. 2017). Perhaps this simply reflects too little selection pressure for NT.

Of the 'strategic' approaches to bridging the yield gap, controlled traffic and amelioration of subsoil constraints (SSC) hold most promise, although more research is needed. Addressing SSC will generally require some tillage. A slowly developing but promising approach to improved 'tactical' management is variable-rate input application for different zones in the same field, based on crop growth and yield potential.

Many NT practitioners live with herbicide resistance. IWM makes this possible. Glyphosate resistance, weeds with long seedbank survival, and loss of herbicide registration are major risks or constraints. There are also opportunities to develop weed management systems that draw on multiple technologies to reduce costs, herbicide dependence, and risks of resistance.

Machinery is evolving, and autonomous operation is a tentative commercial reality for spray application, but probably some years away for fully autonomous seeding and harvesting.

Adoption of new farming systems is influenced by many factors. Change is more likely if systems are flexible, profitable, and resilient to the challenges of climate change, rising costs, herbicide resistance, and subsoil constraints. Strategic tillage or burning crop residues to meet higher-order objectives exemplifies this flexibility.

An effective extension system is essential, including farmer groups, consultants and agronomists. The development of NT in Australia proves the benefit of collaboration between farmer groups, researchers and advisors.

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Chapter 30
No-Till Farming Systems for Sustainable Agriculture in South America

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Abstract A high demand for food production has placed tremendous pressure on the finite land area and natural resources for agricultural production in different South America (SA) countries. Traditional agriculture in almost all SA countries places an emphasis on intensive tillage and monoculture, which has led to a severe environmental degradation and loss of soil productive capacity. This has led to declining crop performance and yield, which has created a risk to food security for future generations. The no-till (NT) farming system can bring a real opportunity to create a legacy of healthy farms and healthy, living soils that will form the base for future food security. The evaluation and history of soil and water management in different SA countries and the strategies developed by researchers, farmers, and organizations in order to test, validate, and promote the diffusion of the sustainable

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technologies that make up the NT system (NT, suitable machinery, cover crops, crop rotation, enhancing biological, physical and chemical soil attributes) are detailed in order to highlight the lessons and learning for other regions and countries.

Keywords Conservation agriculture · Direct seeding · Sustainable agriculture · Crop rotation · Soil health

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30.1 Introduction

South America is a region where profound changes in intensive farming systems for grain crop production have occurred in recent decades due to the introduction of no-till (NT) farming systems. The adoption of NT systems has brought significant benefits to farmers from an economic, environmental, and social viewpoint. However, although its evolution has been remarkable, the adoption of NT systems farming among the countries of the region, and in different cropping systems, has been uneven. While it was first adopted mainly in the so-called southern cone (Argentina, Brazil, and Paraguay) in the 1990s and 2000s, it has only recently reached other countries (Fig. 30.1). This may be the reason for the lack of systematized information about the advances of NT farming in the subcontinent.

NT systems have been widely successful in many South America countries. The role of Brazil and Argentina in the development of NT systems and technology has encouraged the spread of NT systems throughout other regions. This has occurred via an effective and innovative network of researchers, farmers (and their associations), and private and public partnerships. However, in other regions, such as Central America and the Andean region, NT systems adoption has proven more difficult (Speratti et al. 2015).

This chapter aims to contribute to knowledge systematization around the technologies for NT systems, their adoption in South-American countries, and expand

Fig. 30.1 Latin American countries covered in this chapter. (Source Google Maps)

access to information and experiences on the main technical specifications of NT systems across the continent. It focuses on the history of the departure from traditional soil management towards conservation agriculture principles, mainly based on NT systems. More specifically, it will address the expansion of the NT system in some South America countries (Fig. 30.1), and its general effects on soil; water; increasing soil biodiversity; improving crop water balance; diminishing risks with pest, diseases/nematodes, weeds infestation; inputs reduction; minimizing pollutant outputs (in particular, water losses, pesticides and nutrients); and crop yield, including contributing to decrease greenhouse gas emissions.

30.2 No-Till in Brazil

30.2.1 The Early Years and State of the Art

The history of the Brazilian NT evolution was well described by Bolliger et al. (2006), Casão Junior et al. (2012), Fuentes Llanillo et al. (2013), Calegari et al. (2013). No-till in Brazil came first as a farmer demand and went forward with support of research. Brazilian farmers' early experiences with NT took place in the 1970s. One important pioneer farmer was Mr. Herbert Bartz, who introduced NT to help deal with erosion events on his farm. While his initial attempts at machinery modification for NT were less than successful, he made contact with Rolf Derpsch, a researcher at the Meridional Agriculture Research Institute (IPEAME), and travelled overseas to research NT systems internationally. Over time, and with much trial and error, he adapted tractors, seeders and sprayers to successfully implement a NT system of management (Fig. 30.2).

The most remarkable benefit resulting from the adoption of NT in Mr. Bartz's farm was the improvement of soil quality, mainly due to the increase of its biodiversity. Soil fertility was highly enhanced and improved over the years, to the point that in some cropping seasons it was not necessary to use chemical fertilization. Crop yield was also improved, with soybean and corn yield doubling in 20–25 years, and wheat production increasing by almost four times in 13 years (from <1 Mg ha^{-1} in 1972 to >3.8 Mg ha^{-1} in 1985).

Fig. 30.2 Examples of NTS seeders in annual cropping production in South Brazil. (Photos: D. Gassen)

He was also a pioneer in crop-livestock integration starting in the middle of 1980s. Due to the large amount of straw in the fields and the inability of the seeders and planters to operate over it, he decided to use the straw excess to feed buffalos and to produce animal protein. Under this management, a 10-year pasture area was recovered due to the rotation with annual and cover crops.

Challenges regarding pests and diseases were faced by means of integrated management based on biologic tools (for example, *Baculovirus anticarsia* and *Bacillus thuringiensis*) and crop rotation (specific cover crop species reduced the populations of some fungi), leading to a remarkable reduction in pesticide use. The equilibrium achieved among all soil attributes (biological, physical, and chemical) enhanced soil biota and allowed him to eliminate the use of insecticides in corn fields from the middle 1980s until 2007. Therefore, Mr. Bartz showed how to achieve sustainable soil management that regenerated soil health and productive capacity, and increased crop grain yield and profitability.

Following the example of Mr. Bartz, the first large scale production of NT planters began in Brazil 1974, with Bartz's advice. The new idea spread among farmers and a group from Mauá da Serra visited his Rhenânia farm and soon started to adopt NT in their region. In 1976, the farmers Manoel Henrique Pereira ("Nonô") and Frank Dijkstra from the Campos Gerais region (center south of Parana State), took NT to their region and start a group that would result in the foundation of the "Clube da Minhoca" (Earthworm Club). The aim was to discuss NT challenges among farmers and researchers and look for technical solutions.

During this period, the main NT challenges were weed control, due to the limited availability of herbicides, and the lack of appropriate machinery (Derpsch et al. 1986). In the beginning of the 1980s, the NT technique – planting on the straw of the previous crop – evolved to the NT system, which was based in three principles: minimum soil disturbance, permanent soil cover, and crop rotation with cover crops. The 1980s were also the period of the spread of the NT system in southern Brazil. By 2019 the area under no-till in Brazil was around 32 Mha (Kassam et al. 2019), having increased from 200 ha in 1972. Although, at its beginning, the main objective was soil erosion control, other important benefits related to:

- enhanced soil organic carbon, regeneration of soil attributes (biological, chemical, and physical) and carbon sequestration;
- less use of machines and fossil fuel, consequently less labor and lower costs;
- enhanced conservation of soil biodiversity, improvement of macro and meso soil fauna and flora, and improving ecosystem services;
- restoration of soil structure and increasing soil microbiota, reducing the pressure of pest, root diseases and nematodes;
- improved soil productive capacity through harmonized soil attributes, equilibrium and better soil-water-plant relations, and consequently higher crop yield.

After more than 47 years of NT in Brazil, the main challenge is to keep the quality of the system, obeying the three worldwide principles of (1) minimal soil disturbance; (2) permanent soil cover; and (3) crop rotation including cover crops. The partial or limited adoption of these three principles has led to several problems, including soil compaction, erosion, greater pest, root disease (especially nematodes) and weed pressure leading to a higher pesticide use. Indeed, diverse legumes cover crop species, such as, Leguminosae/Fabaceae, as well Crucifers and grasses, are a particularly important part of the NT system in Brazil. Grasses are also an important component of the Integrated Crop/Livestock/Forest System, which has been validated in different Brazilian agroecological zones, for protecting the soil, enhancing soil attributes, and increasing the farm net income in a sustainable way (Moraes et al. 2013; Silva et al. 2014).

Over the years, the NT system has been adapted for almost all agricultural crops in Brazil, and technologies validated for large, medium, and smallholders' scales. Scientific research has been driven almost entirely by investing public resources in state and federal research institutions, and by federal and state universities throughout the country. In addition, farmers' organizations also played a role in disseminating information and technologies, participating in and guiding research, providing training for farmers, and shaping public policies. The Brazilian Federation of NT (FEBRAPDP, www.febrapdp.org.br) is the main organization representing NT at a farmer level. Its board is also composed of professors and researchers working in several areas, including cover crops, machinery, soil quality, carbon sequestration, and microbiology. In addition, FEBRAPDP supports farmers' activities, like training and meetings, in collaboration with research institutes, universities, and NGOs. It also plays a relevant role in shaping public policies in order to develop a high quality NT system at all levels (technical, ecological, and economical) for different regions of the country.

The latest official information about NT was provided by Brazilian Agricultural Census (IBGE 2018). The NT system is adopted in 59.5% of the total area with annual crops in the country corresponding to 32,878,660 ha, but only 17.6% of the 3,169,868 farms with annual crops adopted NTS, indicating that there is a great number of small farms still not using NT. The southern region is the pioneer in NT adoption, but the largest area under NT is the central-west region (the Brazilian Savannah, known as Cerrado). In these two regions NT comprises 78.6% (southern) and 76.6% (central-west) of the annual crop cultivated area. However, only 14.1% of annual crop farmers adopted NT in the southeast region, largely due to the large areas of sugar cane production here, which is a system that has been slow to adopt NT. Sugar cane is one of the crops that needs incentives for NT adoption and development of innovations.

The GMO technologies adopted after 2000s created an environment of permissiveness in the use of glyphosate and natural weed resistances are increasing. World commodities markets also encourage soybean monocultures, putting in risk the accomplishment of NT systems principles. Besides that, NT systems also have several old and new challenges to overcome:

- there is a lack of crop rotation and low permanent soil cover;
- increase in water and soil losses because of removal of terraces and soil compaction led to excessive reliance on NT and increase of machinery sizes (Merten et al. 2015);

- poor GMO's management, resistant weeds, and waste of transgenic events;
- strong nematodes population and high chemical use for pest and diseases as a result of low biodiversity;
- NT system improvement is required for sugar cane, cassava and irrigated rice among other crops.

30.2.2 Growing Cover Crops in Brazil

The estimated area grown in Brazil with cover crops is between 11–12 Mha, including many different fall/winter species in the Southern region, mainly, black oat (*Avena strigosa*), radish (*Raphanus sativus*), hairy vetch (*Vicia villosa*), common vetch (*Vicia sativa*), field pea (*Pisum sativum* subsp. arvense), Lupin (*Lupinus albus*), rye (*Secale cereale*), rye grass (*Lollium multiflorum*) etc. and other adapted species for tropical regions, such as, millet (*Pennisetum americanum*), *Crotalaria* sp. (spectabilis, ochroleuca, juncea, breviflora), buckwheat (*Fagopirum esculentum*), cowpea (*Vigna unguiculata*), *Cajanus cajan* (normal, dwarf), *Mucuna aterrima* (grey, black, dwarf), Lablab (*Dolichos lablab*), *Clitoria ternatea*, sudangrass, *Stylosanthes* sp., *Arachis pintoi*, sunflower, *Neonotonia wightii*, *Urochloa* spp., *Paspalum* sp., *Panicum maximum*. Important data about the main cover crop species grown in Brazil is shown in Table 30.1.

The benefits of cover crops under NT systems is an important research topic in Brazil (Tables 30.1, 30.2 and Fig. 30.3). A long-term experiment (19 years) in Southwestern of Parana State on an Oxisol with high clay content (72% clay), comparing conventional tillage (CT) and NT associated with several winter cover crop treatments found (Calegari et al. 2008): (a) in the 0–0.2 m soil layer, NT sequestered 1.24 Mg C ha^{-1} $year^{-1}$ while CT sequestered 0.96 Mg C ha^{-1} $year^{-1}$; (b) the fallow treatment resulted in the lowest SOC (soil organic carbon) stocks compared to other winter treatments for both tillage systems; (c) NT associated with winter cover crops attained soil properties that most closely resembled the undisturbed nearby forested area; and (d) maize grain and soybean yields were 6% and 5% higher, respectively, under NT than CT. This increase in soil organic carbon and enhancing soil attributes agree with many other results obtained by farmers and also achieved by researchers in long term experiment in different regions of Brazil (Sá et al. 2009, 2010; Scopel et al. 2012).

In Tables 30.2 and 30.3 it can be observed that NT including cover crops and crop rotation over 25 years produced higher amounts of biomass and stronger effects on different soil attributes (biological, physical and chemical) and also increased the crop grain yield and profitability in a sustainable way.

Beyond the use of individual species, mixing cover crops (a cocktail/mix of 2 or more species) has also been studied and recommended in the last two decades (Calegari 2000, 2018) (Figs. 30.3 and 30.4). Mixed cover crops include two, three, four or more species, such as: oat + vetch, radish + black oat + vetch; buckwheat + radish + pear millet, Crotalaria + pearl millet or cajanus + Pear millet + Crotalaria,

Table 30.1 Main cover crops grown in Brazil

Species	Soil and climatic requirements	Days to flowering	DM (Mg ha^{-1} year^{-1})	Advantages and limitations
Winter nonlegumes				
Avena strigosa (Schreb.)	S-C; LF-MF	120–160	2–11	AF; WC; decrease soil root diseases (Fusarium spp., and so on); FASM
Lollium multiflorum (L.)	S-C	120–150	2–6	AF;WC
Raphanus sativus ssp. (L.)	S-L;A-	90–110	3–9	High-nutrient recycling capacity; BP; WC; FASM
Secale cerea le (L.)	S-C; LF; A+; Wlog-; DT	100–120	4–8	BP; WC; controls some soil diseases
Winter legumes				
Lathyrus sativus (L.)	S-C;MF	100–120	2.5–4	AF; HF; mech. harvesting difficult; sensitive to aphids and diseases
Lupinus albus (L.)	S-C; MF; Wlog-	120–140	3.5–5	AF; HF; BNF; BP; sensitive to diseases (Fusarium spp.)
Lupinus angustifolius (L.)	S-C; A+; Wlog-	120–140	3–6	AF; HF; BNF; BP; sensitive to diseases (Fusarium spp.); FASM
Lupinus luteus (L.)	S-C;LF;A+;Wlog-	130–150	3–4	Recommended for restoring depleted soils (sandy and clay)
Pisum arvense (L.)	S-C; A-	100–130	2.5–7	AF; FEG; BNF; sensitive to aphids and some diseases
Vicia sativa (L.)	S-C;HF;A-;Wlog-	120–150	3–5	AF;BNF
Vicia villosa Roth.	S-C;LF;A+;WL-	140–180	3–5	AF; BNF; WC
Summer nonlegumes				
Brachiaria spp.	S-C;A+	n.a.	>4	AF; BP; high biomass; SOM
Helianthus annuus (L.)	S-C; A+; LF; DT	70–120	4–8	FEG, high nutrient recycling; WC
Fagop yrum esculentum (L.)	S-C; A+; DT	35–50	3–6	L/M; DT; AF; HF; FEG; GC; WC; high biomass, efficient in nutrient cycling,
Panicum maximum (L.)	S-C; WD; DT; A+; Wlog-	n.a.	>20	FEG; AF; BP; SOM
Paspalum notatum Flugge	S; DT; CT	n.a.	3–8	AF; SOM

(continued)

Table 30.1 (continued)

Species	Soil and climatic requirements	Days to flowering	DM (Mg ha^{-1} $year^{-1}$)	Advantages and limitations
Pennisetum glaucum	S; A+; LF; DT	90–120	3.5–1	AF; BP; SOM; WC; FASM
Setaria italica (L.)	S-C; WD; MF; DT	45–60	2.5–8.5	AF; FEG; FASM; high-seed production
Sorghum bicolor (L.) Moench	S-C; WD; MF; DT	60–110	3.5–18.5	AF; BP; SOM
Summer legumes				
Cajanus cajan (L.) (dwarf variety)	S–L;LF;Wlog-	70–85	2–6.5	AF; NC; high-seed production
Cajanus cajan (L.) Millsp.	S-C; LF; Wlog-	140–180	3–7.5	AF; BP; BNF + nutrient recycling, NC
Calopogonium mucunoides Desv.	L-C	n.a.	4–10	WC;GC
Canavalia ensiformis (L.) DC.	S-C; LF; DT	100–120	5–6	WC (allelopathic effects against Cyperus spp. and Cynodon dactylon)
Crotalaria sp. (juncea, spectabilis, ochroleuca, breviflora) (L.)	S-C; MF	70–120	3–10,0	BNF; WC; NC; efficient in nutrient cycling, nematode control
Dolichos lablab (L.)	S-C; LF; A+; DT; WD	75–150	4–13	AF; HF
Macroptilium atropurpureum (DC.) Urb.	S-C; WD; A+; MF; DT	n.a.	3–6.5	AF; SOM; WC
Mucuna pruriens (L.) DC.	S-C; LF	130–150	2–5	FEG; GC, BNF; NC
M. pruriens (L.) DC. (dwarf varieties)	S-C; LF	80–100	2–4	NC; FASM; rain during harvesting period can damage the seeds
Pueraria phaseloides (L.)	L; WD; Wlog-; DT	n.a.	3.5–8	AF; GC
Stylosanthes spp.	S-C; A+, LF; DT	n.a.	n.a	AF; BP; SOM
Vigna radiata (L.)	S-C; DT; WL-	60–80	3.5–6.5	AF; HF; high seed production
Vigna unguiculata (L.)	S-C; L/MF; A+; WL-	70–110	2.5–5.7	AF; HF

DM dry matter, *n.a.* Data not available, *S* light-textured (sandy) soil, *L* medium-textured (loamy) soil, *C* heavy-textured (clayey) soil, *L/M/H* low/medium/high fertility, *WD* well-drained soil, *Wlog−/+* intolerant/tolerant of water logging, *A−/+* intolerant/tolerant of soil acidity, *DT* drought tolerant, *AF* animal forage, *HF* human food, *FEG* fast early grow, *BNF* high-N fixation, *GC* produces good cover, *WC* weed suppression, *BP* biological plowing, *SOM* good SOM builder, *NC* nematode control Adapted from Calegari et al. (1993), Bolliger et al. (2006) and Wütke et al. (2014)

Table 30.2 Average above-ground dry matter yield from 1986–2011 under no-till (NT) and conventional tillage (CT) in a long-term experiment in an Oxisol from Paraná State, southern Brazil

Winter crop	Winter cover crop (Mg ha^{-1})		Summer crop residues[a] (Mg ha^{-1})		Total (Mg ha^{-1})		Annual average (Mg ha^{-1})	
	NT	CT	NT	CT	NT	CT	NT	CT
Black oat	116.0	99.5	110.5	108.1	226.5	207.6	9.1	8.3
Rye	104.6	90.1	109.8	105.3	214.4	195.4	8.6	7.8
Common vetch	104.6	91.4	115.1	106.3	219.7	197.8	8.8	7.9
Hairy vetch	102.7	86.2	108.5	102.8	211.2	189.0	8.5	7.6
Radish	100.1	82.0	114.4	111.6	214.4	193.6	8.6	7.7
Blue lupin	104.2	88.1	113.4	106.0	217.6	194.1	8.7	7.8
Wheat	92.4	82.7	104.1	99.1	196.5	181.8	7.9	7.3
Fallow[b]	42.5	31.0	108.6	106.0	151.1	137.0	6.0	5.5

Adapted from Rheinheimer et al. (2019)

[a] Maize (1986, 1987, 1988, 1992, 1994, 1996, 1999, 2003, 2008, 2009, 2011) and soybean (1989, 1990, 1991, 1993, 1995, 1997, 1998, 2000, 2001, 2002, 2004, 2005, 2007 and 2010)

[b] Dry matter of weed aerial parts in winter season

Fig. 30.3 Mixed cover crop species in Brazil. (**a**) pearl millet, finger millet, buckwheat, crotalaria spectabilis, crot. ochroleuca, radish; (**b**): black oat, rye, radish, field pea, hairy vetch, white lupin (partial slash for regrowing). (Photos from Ademir Calegari)

pear millet + crotalaria sp. + buckwheat, and can be used in annual and perennial cropping systems.

Some species can be also oversown on soybean, maize or bean around 20–30 days before harvesting. Many cover crop species can increase the abundance of predators or antagonist organisms that promote nematode species decrease and increase the abundance of some biological products such as *Bacillus* sp., *Trichoderma* sp., that promote better environmental equilibrium and enhanced soil health. Therefore, in many Brazilian production systems where there are challenges such as soil compaction, root diseases, and nematode population increase, the use of cover crops and integrated soil management that includes nutrient balancing plus cover crop species

Table 30.3 Soybean grain yield (Mg ha^{-1}) after winter cover crops, in São Jorge do Oeste, Paraná State, South Brazil

Cover crops	Soybean yield (Mg ha^{-1})		
	2016	2017	Mean
Bo	3.669 ± 0.213Ab	4.239 ± 0.346Aa	3.954 ± 0.279A
Bo + Rad + Rye + Wl	3.668 ± 0.321Ab	4.287 ± 0.452Aa	3.977 ± 0.386A
Bo + Rad	3.619 ± 0.145Aa	3.919 ± 0.521Aa	3.769 ± 0.333B
Bo + Rad + Rye + Cv + Wl + Buc	3.768 ± 0.278Ab	4.487 ± 0.374Aa	4.127 ± 0.326A
Buc	3.410 ± 0.543Bb	4.101 ± 0.451Aa	3.755 ± 0.497B

Tessaro et al. (2019)

Means followed by the same uppercase letter in the row and lowercase letter in the column do not differ significantly by the Tukey test (5%). *Bo* black oat cv. Iapar-61, *Rad* Radish cv. Iapar-116, *Wl* white lupin, *Buc* buckwheat, *Cv* common vetch

±: standard deviation of the mean

Fig. 30.4 Cover crop managed by knife-roller and soybean growing after. (Photos from Ademir Calegari)

adequately recommended for each specific condition, plus biological products, plus bioactivation of the system (compost, manure, organic residues) can lead to better integrated soil and water management, and enhanced sustainability of production.

Indeed, NT combined with winter cover crops is seen as the soil management system of choice to achieve sustainable crop production on Oxisols in subtropical and tropical regions. Similar results have also been achieved in different Brazilian agricultural regions with single or mixing cover crop species (Calegari 2014, 2016; Calegari et al. 2013; Wütke et al. 2014; Tessaro et al. 2019). This system produces higher amount of biomass, improves soil biological, physical, and chemical attributes and increases crop grain yield and profitability in a sustainable way. An example of the increase in grain yield can be achieved with this approach and it can be seen in Table 30.3. This shows that the highest soybean grain yields in the years of 2016 and 2017 were obtained in the area with an adequate mix with black oat, radish, rye, common vetche, white lupin and buckwheat (Bo + Rad + Rye + Cv + Wl + Buc), yielding 3.768 ± 0.278 and 4.487 ± 0.374 Mg ha^{-1}. These yields differ at the level of 5% significance and show that an increase of about 19.1% in soybean grain yield.

30.2.3 Case Study: Barbosa Family Farm

The farm is located at Não-me-Toque, southern Brazil, and has a long tradition of using NT, crop rotation, and cover crops in clay soils. Wheat is the main crop in winter, but the area is also partially covered with some cover crop species. In the summer, soybean predominates, and a small part of the area is rotated with maize. The maize yields obtained for different combinations of cover crops are presented in the Fig. 30.5. A strong effect of cover crops on maize yield was achieved. After a fallow, maize yielded 9 Mg ha^{-1} but reached 12.771 Mg ha^{-1} when a five-species-mix was used (radish + rye + oat + vetch + white lupin) plus soil & plant bioactivation (Pen®). So, beyond a better soil protection and higher biodiversity, cover crops also promoted higher crop grain yield.

The positive results obtained throughout the years in Paraná and other parts of Brazil prove that cover crops and cropping rotation in a NT system are economically feasible as well as ecologically sustainable; proving not only greater crop productivity, but also conservation, maintenance, and/or recovery of soil fertility, beyond higher soil biodiversity, greater biologic balance in the soil, and decreased pests and/or disease. In other words, they represent a very promising way to manage soils with greater sustainability.

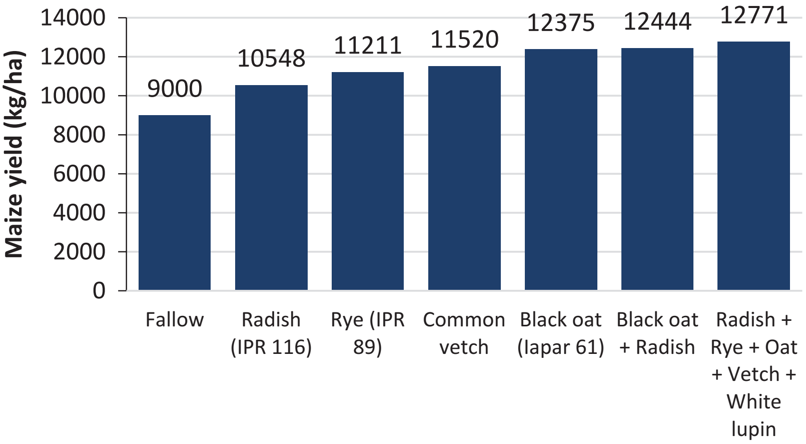

Fig. 30.5 Effect of different winter cover crops on corn grain yield (kg ha^{-1}) at Mr. Barboza Farm. (Personal communication – Report of Living Soil Project, Renovagro, Uberaba, MG, Brazil, 2017)

30.2.4 No-Till Mechanization in Brazil

Brazil has a large and consolidated agricultural machinery sector focused on NT. In the late 1970s, the sector began adapting conventional planters and seeders for use in NT, with favorable results. This process was described in detail by Casão Junior et al. (2012). There are currently more than twenty NT planter and seeder companies in Brazil, with models ranging from small (e.g. two rows of corn) to large (>40 rows) areas. Most of them are nationally owned industries.

No-till seeders with 7 and up to 13 rows for corn and soybeans are more common in southern Brazil where small and medium-sized farms predominate. In the Central-west region (Cerrado), where farms with extensive areas are common, machines with 13–24, or even more rows, predominate for corn and soybeans (Araújo et al. 2019).

Two configurations of soil-tool interaction components of NT planters are most typical. The first is used in medium to heavy soils (clayey) and has a smooth cutting disc, 15 or 17 inches in diameter, for cutting the vegetative cover; a tine, whose function is to open the slot and deliver fertilizer rearwards; an offset double discs for seeds delivered into the gap between them; a pair of side wheels for seeding depth control; and two narrow V-shaped press wheels for coverage and compaction of the soil slot. The second configuration is used in medium to lighter soils where penetration of the planter components occurs more easily. In this case, the tine is replaced by offset double discs. It is common for all components to have adjustments for ground contact pressure (discs and wheels), working position (wheels and tine), and relative position (longitudinal and transversal distances) between components.

Once properly fixed, the available Brazilian NT seeders are able to operate satisfactorily on NT soils and over common plant residues or cover crops and have been essential to enable the advance of NT systems. However, the configurations of the NT seeders restrict the full compliance of two of the three principles of NT systems, that is, the maintenance of permanent soil cover and the reduction of soil disturbance. This occurs because of the principle of action of the soil-tool interaction components, especially the tine.

The tine acts on the soil slot by compressing it forward and laterally and causes the disruption and displacement of part of the mobilized soil mass out of the seeding slot. The displaced soil thus remains over the vegetative cover and exposed along the surface. The area of disturbed soil in the slot is not restricted to the width and depth of the tine, although it is proportional to the first, since there is an additional effect of lateral compression. Consequently, using the tine exposes the soil surface and disturbs excessively the soil slot. This phenomenon is exacerbated by increasing the operation speed, a common practice adopted by farmers when the seeding time span is narrow. Innovations on soil-tool components of NT planters and seeders are required to minimize soil disturbance and increase soil cover during seeding operations.

30.3 No-Till in Argentina

In Argentina, NT started in the mid-1970s and early 1980s in the central Pampas area, and gradually spread to other regions. The new system soon proved its ability to stop, and even revert, the soil erosion and degradation that had been accelerated by farming mechanization, intensification, and the shift from cultivated perennial pasture lands into grain production. The land degradation and yield loss experienced under this conventional system were clearly perceived by farmers, which pushed them to start looking for alternative solutions. No-till was brought into the farming scenario to be evaluated. However, its large-scale adoption had to wait for another decade when the confluence of soil erosion problems, increasing costs, and lower prices for herbicides made the system economically viable.

By the end of the 1980s the area under NT was 100,000 ha, while in 1996 it reached around 3,000,000 ha. Since then, adoption has grown exponentially reaching around 95% of the total cultivated area (33 of 35 Mha) with major crops (grain and oilseeds). The central players in NT development were commercial farmers from both small (50 ha), medium (several 100 ha) and large (several 1000 ha) operations. Crops grown with NT include wheat, barley, oats, and canola in the winter, and corn, sorghum, millets, soybean, and sunflower in the summer. Moreover, forage crops such as alfalfa or pasture for grazing were also cultivated under NT.

The shift from CT to NT represented a drastic reduction in the number of machines required for crop production and machinery was completely redesigned to allow operation on NT soils with large amounts of crop residues. Since the beginning, several pioneer industries devoted resources to develop totally new planters and drillers for NT. The use of cover crops was also a relevant tool to further improve the benefits of NT, especially regarding weed control and fixing a considerable amount of N and C when legumes were included. The adoption of an appropriate crop rotation, including cover crops, was fundamental for biomass production, both to be harvested and supplied to the system. The supplied C and organic matter constitute the energy source to increase the soil micro and meso-biology and nutrient cycling. Also, organic matter encourages fungi growth, which generates useful byproducts, such as glomalin (a stable protein), which contributes to improved soil aggregation and soil structure (Balota et al. 2014).

30.3.1 Strategies to Promote NT

An efficient way to promote NT is to support local leader farmers to enlarge their capacity and to explore alternatives. Support may include providing specific knowledge, new inputs or infrastructure to run field trials, and offering funds to attend field days and travel to interchange with other regions or countries. In general, farmers trust in each other better than another actor, so this kind of communication speeds up the adoption of innovations. In Argentina, a group of leader farmers from the central Pampas started to interchange practical experiences based on the NT principles. At the end of the 1980s they founded the AAPRESID (The Argentinean No-Till Farmer Association).

AAPRESID enhanced farmer to farmer communication as well interaction with academics and research organizations. Politicians, suppliers, commercial companies and civil organizations were also called on board, facilitating connection with farmers. AAPRESID has 30 regional groups with 15–30 associated farmers in each group, and a professional agronomist as coordinator. The groups hold a monthly meeting and at least one open gate field and conference day in the region of influence. Private commercial companies frequently sponsor these field days, creating an opportunity to show their inputs, machineries, and services.

30.3.2 Benefits of NT

Several relevant benefits are evident after 50 years of NT in Argentina. Erosion and soil deterioration have decreased, leading to increased sustainability. In addition, based on indicators of soil health, functionality, and productivity, NT is achieving not only sustainability, but leading to soil improvement.

When NT principles are correctly adopted, water contamination is drastically reduced, and soils become more resilient allowing a higher level of farming efficiency. The agroecosystem becomes more reactive and gradually gets more outputs for a given amount of input supplied. This positively impacts gross income while reducing total cost.

When the productivity of agricultural land in Argentina is examined over time, splitting data into two periods – 1969/1970 to 1995/1996, and 1995/1996 to 2018/2019 – it can be seen that a relative higher rate of total production growth was detected for the second period (Fig. 30.6). In both cases, it can be seen that total production grew at a higher pace than the area farmed. However, in the second period, NT adoption along within other technologies, such as balanced fertilization and biotechnology, resulted an even higher pace of production growth and a relative higher impact on the yield increase.

30.4 No-Till in Paraguay

30.4.1 The Beginning of NT in Paraguay

Paraguayan extensive agriculture started in the 1970s based on soil management systems adopted from temperate countries with plowing and harrowing. As a subtropical country, Paraguay is characterized by high temperatures and rainfall, which associated with low soil covering and a predominant wavy topography, quickly

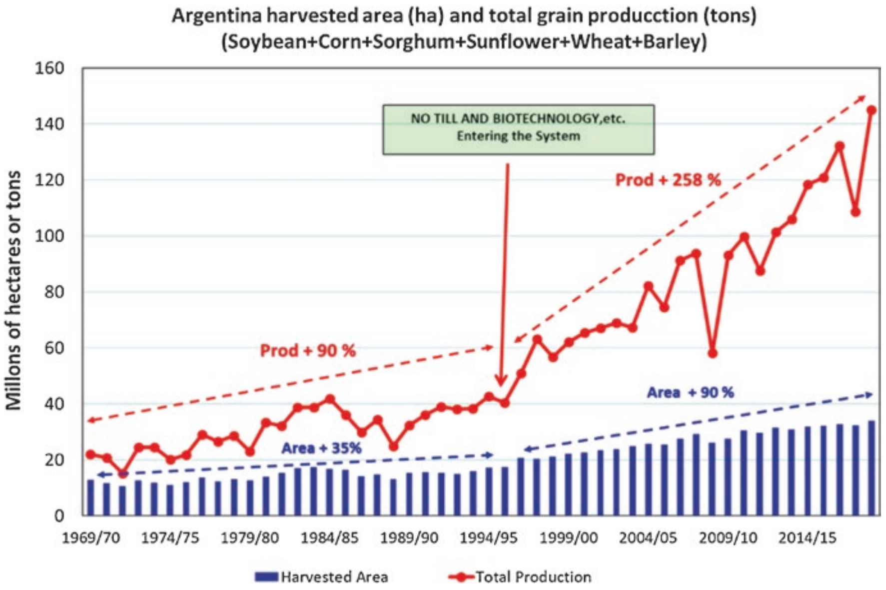

Fig. 30.6 Analysis of the harvested area of grain crops and total production, in Argentina, in two periods: 1969/1970 to 1995/1996 and 1995/1996 to 2018/2019. (R. Peiretti)

made evident the negative effects of plowing, including soil and nutrients runoff, water course clogging, decreased soil organic matter, and low crop yield.

NT adoption started in 1982/1983 season as an initiative of a farmer's cooperative located near the Brazilian border. At this early stage there was little or no influence from outside, and 10 years later, about 20,000 ha of NT was being trialed, but with several problems due to the lack of technical support. In the 1990s, the Paraguayan Ministry of Agriculture and the German Development Agency (GTZ), developed a project to control erosion and extend NT to farmers. At the beginning, one problem was the mindset of soil preparation which was "you do one or two ploughings followed by two disk harrowing". This attitude was institutionalized across extension services, universities, and agricultural schools and aroused a strong resistance for the new method of seeding. To overcome this paradigm an important strategy was to create a public-private-partnership alliance between the Paraguayan Grains and Oilseed Trader Association (CAPECO), the Ministry of Agriculture, and GTZ. Under CAPECO's influence, it was possible to break the resistance against NT and farmer associations were created, which had an important role in spreading NT in Paraguay. Their union resulted in the foundation of a federation – FEPASIDIAS (Paraguayan No-till farmer Association for Sustainable Agriculture).

30.4.2 Challenges to Spread NT in Paraguay

The “farmer to farmer extension” method is an effective way of getting farmers interested in new technologies and was adopted in Paraguay. Initially, three pioneers in NT systems from Brazil (Nonô Pereira, Franke Dijkstra and Herbert Bartz), together with local pioneer farmers, were invited to discuss their experience with Paraguayan farmers. After 3 weeks, 1500 farmers had learned from experienced pioneers and discussed with them the novel way of farming. Over time, the process of peer to peer extension successfully continued. Different types of meetings and farm tours to other regions and neighboring Brazil, such as IAPAR (Agricultural Research Institute), researcher support, and the provision of cover crop species seed to Cooperative Farmers during the process of technological validation, consolidation, and dissemination, were also fundamental to educate farmers, extensionists, technicians, and researchers in all the aspects of the NT system. To get more farmers involved, messaging with a multimedia extension approach was adopted including newspapers, radio, television, posters, and documents as well as field days in different regions of the country. In the 1990s, NT had become the predominant system in Paraguay and by 2019 was practiced on over 3 Mha or > 90% of the total cropping area. According to Derpsch and Moryia (1999), this rapid uptake occurred due to: (i) the efficient and economic soil erosion control provided by NT; (ii) availability of knowledge on how to practice NT within the region; (iii) the widespread use of cover crops (Fig. 30.7); (iv) consistent and positive messaging provided by private and public sectors with no other forms of ‘conservation tillage’ like minimum tillage, reduced tillage ever recommended; (v) effective farmer-to-farmer extension; (vi) strong economic returns of NT compared to CT; and (vii) a global market requiring highly competitive farmers without subsidies, which meant that production costs were managed accordingly. In addition, one of key factors for fast growth in Paraguay was the technical support provided by the German Cooperation (GTZ), and by agronomists Rolf Derpsch and his Paraguayan counterpart, Ken Moriya, who coordinated in the Ministry of Agriculture with other partnerships the

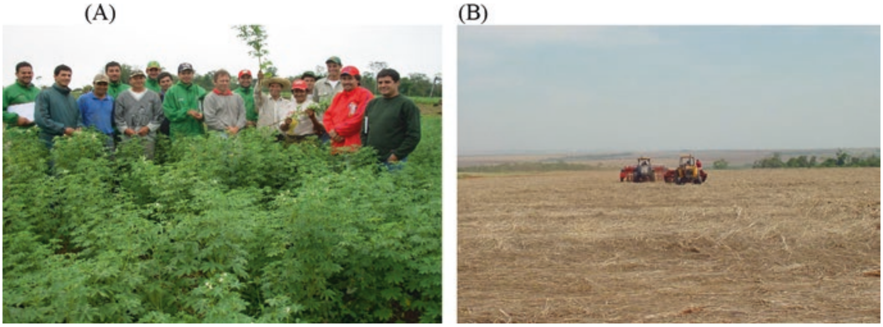

Fig. 30.7 (**a**) Technicians and Paraguayan Farmers in a white lupin field. (Photo: Ademir Calegari); (**b**) Soybean no-till planting over the black oat mulch. (Photo: Erni Schlindwein)

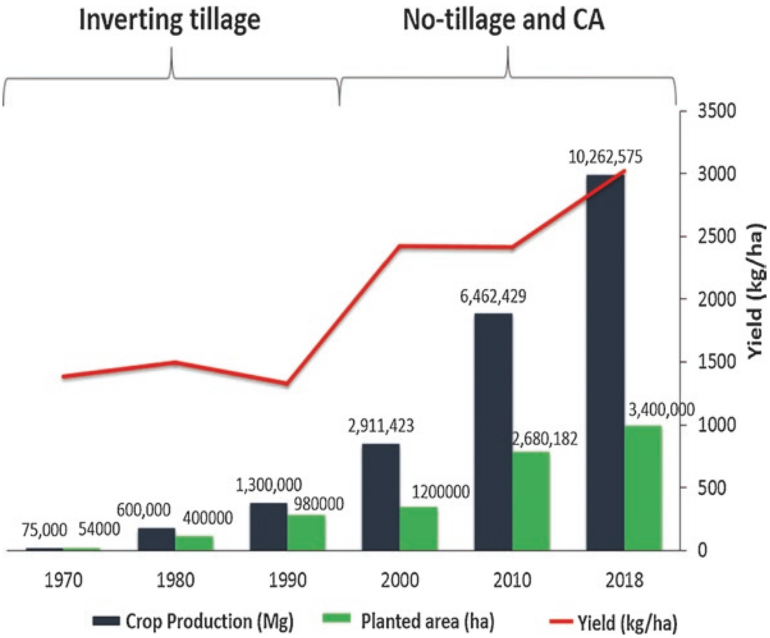

Fig. 30.8 Evolution of soybean area and yields in Paraguay from 1970–2018. (CAPECO y FEPASIDIAS 2019)

extension activities and were responsible for creating the National Soils Department, which accounts for policies and actions for agricultural production sustainability.

A continuous growth of soybean production and yield was also observed as a consequence of establishing NT in Paraguay in the 1990s (Fig. 30.8). This improvement was also achieved for all income crops, leading directly to the transformation of the social, demographic and economic system of the country by economic and technological forces.

However, a number of challenges in NT adoption throughout Paraguay still exist. Although the goal was always to get the adoption of NT as a system that included NT, soil covering, and crop rotation, this has only been achieved by top farmers. The majority still practice a soybean monoculture with 2.5–3 crops or cover crops in a year to try to maintain soil cover, and greater research to economically incorporate diversified crop rotations is required. Another important drawback is the lack of adoption by small farmers. While more than 90% of mechanized farmers have adopted NT, only a small proportion of small farmers practice it currently. Small farmers, in general, need a longer time of technical support (up to 10 years) until they can operate independently.

In addition, the promotion of NT has often not occurred uniformly across agencies. For example, when municipalities support small farmers they usually donate or supply access to a tractor with a plough and disc harrow, as the intensive tillage paradigm is still the mindset of influential people. However, this is changing and, for example, in 2018/2019 the hydroelectric power companies Itaipu and Yacyretá started to support NT, realizing the co-benefits of reducing soil erosion and the siltation of dams. Indeed, the tillage paradigm has largely changed at all levels in the government and in private sector ensuring the project strategy will persist in a self-supporting sustainable way without need of international financial support. Paraguayan Agriculture is always looking for more regenerative agriculture towards sustainability.

30.5 No-Till in Uruguay

30.5.1 The Beginning of NT in Uruguay

Grain crop production in Uruguay has a high rate of NT adoption, exceeding 90% of the total cultivated area. This has been achieved via technological adaptation appropriate to the current and future production reality. NT has allowed intensification of production to meet the demands of a world population, with less machinery investment and less environmental impact.

Uruguay experienced periods of agricultural expansion followed closely by severe soil degradation, leaving large areas unused for production. Soil tillage with plows and harrows were the main cause of this degradation, including severe soil erosion. In the 1970s along the agricultural coast region, the “crop-pasture rotation” was a common practice. Two years of pasture (e.g. bird’s trefoil (*Lotus corniculatus*) or red clover (*Trifolium pratense*)), was followed by one wheat crop and another associated wheat crop (plus pasture), then pasture again re-incorporated. Soil tillage was used for sowing wheat, but fields were not tilled for pasture. However, in the 1980s, legal protection for wheat production were lost, decreasing farmer profitability and changes were demanded. Sunflower was included in rotation and, after harvesting, wheat was sowed again with a bi-annual legume, which left the pasture for cattle. Vertical tillage with chisels and vibrocultivators replaced heavy plows and harrows. Farmers also started to adopt conservation practices to reduce erosion, such as contour sowing. In the early years of the 1990s, NT started to be adopted by a small group of coastal farmers (Fig. 30.9).

Fig. 30.9 Maize and soybean growing over the mulch of a rye cover crop. (Luciano Dabalá)

Later, NT associated with glyphosate became popular due to its low associated economic risks. Simple and affordable practices to achieve adequate soil coverage and reduce raindrop impact, reduce the length of the slope and runoff, and to increase soil organic matter content had a fast and widespread adoption. In 15 years, NT had almost completely replaced CT. Uruguay has improved NT systems over the years, and during 2015/16 it was practiced on around 1,260,000 ha (Kassam et al. 2019).

30.5.2 Advantages and Challenges of NT in Uruguay

No-till has been successful in Uruguay as it (1) minimizes soil deterioration and makes sustainable agriculture viable; (2) is accepted and adopted by the vast majority of the farmers; and (3) provides economic advantages due to reductions in machinery, fuel, and labor costs.

In the first years of the 1990s, a group of farmers founded AUSID (Uruguayan Association for No-till), which was key to the spread of NT of throughout the country. The work of AUSID is based on methodical observations of field crop development, analysis of problems, and dissemination of results. Research institutions are always invited to collaborate, including via farm monitoring, which is a very efficient tool to identify problems and challenges and study new techniques for effectively implementing the NT system. AUSID also carries out numerous extension activities, with support from research organizations. The aim is to bring the advances in science and technology; to gather knowledge and experience; integrate research, technical assistance, and farmers; and to professionalize the activity. However, despite its recognized advantages and wide adoption, there are areas in Uruguay where NT has not been fully adopted. AUSID is gathering efforts in those places as well in consolidated areas. AUSID is a founding member of CAAPAS (Confederation of American Associations for Sustainable Agriculture) which was established in 1992 together with Brazil, Argentina, Chile, and Mexico. This integration of countries with different soils, climates, methodologies, and production capacities, has enabled a strong relationship and exchange between members.

In addition, the sustainable integration of agriculture/livestock is a subject that arouses much interest in many areas in Uruguay, mainly regarding the introduction of some forage/cover crops species to improve soil attributes and system sustainability. The term "sustainable" no longer refers only to soil care, but includes the management of weed resistance, crop fertilization, CO_2 fixation, crop rotation, and other aspects of the modern agriculture. Thus, the principles NT have never been more relevant than today.

30.6 No-Till in Bolivia

30.6.1 State of the Art of NT in Bolivia

NT systems farming in Bolivia is conducted nearly exclusively in the tropical eastern plains in the department of Santa Cruz, and more particularly by farmers subscribed to the Association of Oil Crop Producers (ANAPO), which provides technical assistance for NT and conservation agriculture. Farm sizes using NT are mainly medium (50–300 ha) to large (>300 ha) due to the lack of available equipment for small-scale NT.

The department of Santa Cruz comprises three agroecological rainfall zones: dry (<800 mm rainfall), intermediate (800–1200 mm) and humid (>1200 mm). About 70% of precipitation falls in the summer and 30% in the winter. The climate in the humid region allows for two crops per year, whereas in the dry zone only 30% of the area is planted with crops during the dry winter period. In the intermediate zone, 50% of the areas is covered with winter crops. Most agriculture is rain fed.

The crops grown in the area are soya, maize, sorghum, wheat, and sunflower with 87% of the total cropland (2,137,600 ha) under NT, most of which can be considered as a NT system. In other parts of Bolivia NT might be used as technique for some crops alternated with CT. Other crops grown in the area are rice, sugar cane, beans, chia, sesame, and more recently cotton. Livestock production is also common, with pasture sometimes included in crop rotations (ANAPO 2019). Crop rotations in the dry and intermediate zones include soya as a summer crop, rotated with sorghum, sunflower, or wheat as winter crops. Very little maize is produced. In the humid zone, soya is also used as a winter crop, leading to soya mono cropping.

30.6.2 Description of NT in Bolivia

No-till was the traditional way of farming in Bolivia before colonial times. Today this traditional way of planting with a stick without disturbing the soil may still be applied with some smaller subsistence farmers in the Amazonian forest. However, for most of the country, CT with mouldboard or disc ploughs and big disc harrows or “rome plows” is standard.

Foreign aid projects initially introduced NT in the 1980s, however, these attempts did not lead to a lasting change in cultivation practices. In the 1990s, a NT project started in the tropical eastern lowlands of Santa Cruz department, involving the institute for tropical agriculture, CIAT, and the International Wheat and Maize research institute CIMMYT, in collaboration with ANAPO. In the early 2000s, with farmers and machinery companies coming to Santa Cruz from neighboring Brazil and Argentina, the NT technologies came into that part of the country and were adopted. ANAPO has collaborated with organizations such as AAPRESID from

Argentina and can be considered today the authority on NT and conservation agriculture in Bolivia.

The main farming systems adopting NT are soybean based. Soybean has become an important export crop and rotation crops often suffer from price controls, which makes them economically unattractive, particularly for smaller farmers. The result can be soybean monocropping, with negative impact on yield, which in Bolivia are far below 3 Mg ha^{-1}. However, among the membership of ANAPO, good crop rotations are often observed and provide sufficient inputs of carbon-rich residues into the soybean system. Preferred crops are sorghum, which is used for grain and forage, and maize with an under sown grass, preferably *brachiaria*. Research has determined the positive effects of surface residues for water infiltration and moisture retention and found minimum levels required in dry years of 2 Mg ha^{-1} dry matter, while in moist years 1 Mg ha^{-1} dry matter was sufficient (Campero and Wall 1999). The Bolivian government is becoming increasingly interested in NT and conservation agriculture to recover soil productivity, national food production, and economic security, particularly in the face of the challenges of climate change (ANAPO 2019).

30.6.3 Quality of NT at the Field Level

The arable cropland in Bolivia is about 4.5 Mha, of which 70% (3 Mha) are in the tropical eastern plains, including the dryer Chaco region in the south east. No-till systems farming, comprising the three principle of permanent minimum soil disturbance, soil cover, and crop diversity, is only applied on some 1.8 Mha, of which "good quality" NT systems comprises probably 70–80%. No-till systems increase yield in all crops compared to tillage with chisel ploughs or disc implements. However, this only applies if all three principles are observed. No-till on its own without crop rotation can, in some cases, lead to yields inferior to vertical tillage, but always superior to conventional tillage (Paz 1999).

There is a clear effect of good quality NT on crop drought resilience. For example, in 2018/2019, the soybean yields with good quality NT, and in particular a good soil cover, reached 3 Mg ha^{-1}, despite drought, while adjacent CT fields or NT fields with no ground cover saw total crop failures. In addition, average yields under NT systems increase in the long-term and become more stable (ANAPO/CIMMYT/CIAT 2001). This is supported by early experiments that showed better moisture management and water infiltration with NT and good soil cover, as compared to CT (González 2004 ; Wall 1999).

30.6.4 Main Technological Constraints

The growth of NT in Bolivia attracted the agricultural machinery sector and there is good accessibility of direct seeders, sprayers, and harvesters in the department of Santa Cruz. Other equipment, such as knife rollers, are also locally produced. However, most of these equipment is directed to medium and large-scale operations, with no suitable machinery available for small scale farmers. In addition, outside the department of Santa Cruz, the commercial availability of machinery suitable for specific regions, for example in the Andean valleys or highlands, is absent. Additionally, there are no controls or regulations for agricultural inputs. For example, the pesticide sprayers used often do not comply with any international technical or safety norms.

Bolivia in general is facing a crisis in agricultural production, aggravated by an ever-increasing pressure from climate change. The country is nearly every year alternating between drought and flood crises. The majority of agroecological zones suffer from severe land degradation (erosion, soil fertility decline), leading to low crops yield across all cropping systems. As a result, the country is becoming more dependent on food imports, while income from agricultural exports is decreasing. Alerted by this situation the government is showing increasing interest in fundamentally changing the way agriculture is practiced. The NT systems model is an example of the way forward, and it is expected that this farming concept will now also be promoted in other cropland areas and different cropping systems across the country.

30.7 No-Till in Peru

30.7.1 The Beginning of No-Till in Peru

Since the Pre-Inca era, many Andean communities used agriculture based on the principles of NT systems: direct sowing with a manual “chaquitaclla” seeder without removing the soil and maintaining a protective plant cover on the ground (Fig. 30.10) (Benites and Bot 2014). However, since 1530 the agriculture introduced by the Spanish has been practiced, based on burning, fallow, monoculture, and intensive plowing. These techniques are still used today in almost the total cultivated area of the country (2,216,000 ha). The use of tractors for tillage with plows and heavy harrows has resulted in significant losses of soil and water due to runoff and erosion, as well as the contamination of the rivers with sediments, fertilizers, and pesticides. The continuous use of plows and harrows at the same depth during periods of high soil moisture have also created underlying compact layers known as a ‘plow floor’ or ‘harrow and erosion floor’.

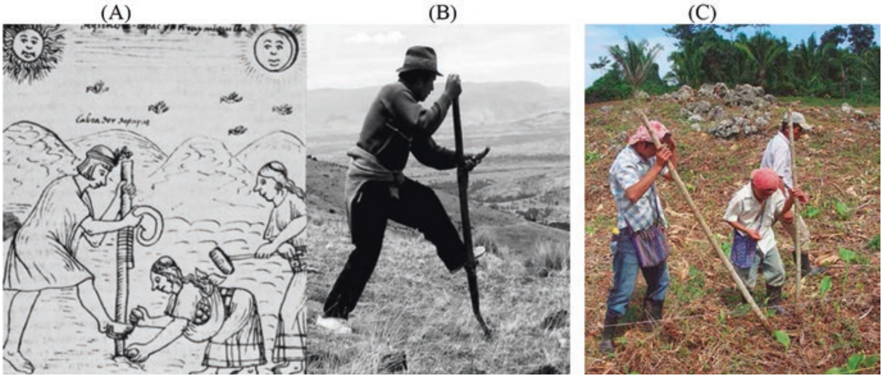

Fig. 30.10 Chaquitaclla before (**a**) and nowadays (**b**) (Photo from Fabiola Galvez), and direct seeding with "tacarpo" (**c**) (Benites 2017)

30.7.2 Need for a Paradigm Change

In recent decades, farmers have expressed concern about the soil erosion, labor power, and input costs of CT agriculture. Some have tried to reduce the intensity of soil disturbance, but have often faced problems such as low germination, low yield, and high weed infestation. High investment in soil conservation programs based on physical structures were made. These further emphasized isolated erosion control, with expensive and inefficient soil physical interventions, leading to decreasing crop yield.

Agricultural production requires a lot of labor and considerable efforts. In Peru, to produce one hectare of corn in a non-mechanized way 80–120 people are required, without considering time for harvesting. Soil tillage and sowing with hand tools consumes more than 80% of the total working time. The low productivity of the workforce results in high costs that reaches up to 65% of the total cost of corn production (Huamanchumo de la Cuba 2013).

The first research on the benefits of NT systems in Peru was carried out at the experimental station "San Ramón" Yurimaguas, Loreto, between 1982–1987 and aimed to study alternatives for transition technologies based on NT systems principles to change shifting cultivation into permanent agriculture (Sánchez and Benites 1987).

30.7.3 Advances of the NT System

The territory of Peru is traditionally divided into three differentiated natural regions: the Coast or coastal desert, the Sierra or Andean region, and the Jungle or Amazon region. The agriculture of the Coast is irrigated and mechanized, dedicated to annual

Fig. 30.11 Farming systems on the Coast with conservation agriculture (**a**) Corn; (**b**) Manzano; (**c**) Vine; (**d**) Wheat. (Photo: Benites)

crop production (corn, soy, sorghum, etc.), fruit, and vegetables. The sierra is mostly dry land (pastures), with small areas of green vegetables and annual crops with supplementary irrigation. The Amazon region is dedicated to agroforestry systems of coffee, cocoa, and oil palm.

30.7.3.1 Coastal Region

The San Fernando Group in the Coast region started using conservation agriculture in 2003 through pilot projects with corn apple, cotton, mandarin, and grape wine (Solier and Chávez 2005). From an initial area of 45 ha, the project expanded to >140 ha and included other crops such as tangerine, olive, and wheat. In grain crop production (soybean, corn, and wheat) the group started to test new varieties and hybrids, which has improved yields and reduced costs (Solier and Chávez 2005) (Fig. 30.11). It is also undertaking projects to increase the use efficiency of water, soil, and climate resources, combining NT systems and precision agriculture (Ikeda 2017 personal communication).

The principles of NT systems in fruit plantations under irrigation are also being applied. In Huaral, north of Lima, plant cover is used to control weeds instead of plowing. Similarly, in Mala and Cañete, the leading producers of apple, grape wine,

Fig. 30.12 Farming systems in the Sierra with conservation agriculture (**a**) Reforestation; (**b**) High Andean pastures; (**c**) Artichokes; (**d**) Lettuce. (Photo: Benites)

and citrus are using cover crops to protect the soil, improve weed control, promote biological control of pests, and improve irrigation water retention. However, currently only 1% of the plantations (3500 ha) are using NT system practices.

30.7.3.2 Sierra Region

The Sierra region is the leading supplier of agricultural and livestock products for the country. Farming is based mainly on traditional practices, and problems of soil erosion due to improper management are large. Currently, there is about 400 ha in the Sierra region under NT, especially wheat, corn, quinoa (250 ha), fruit trees (100 ha), and vegetables (50 ha) planted with hand and mechanized equipment (Fig. 30.12). Many other initiatives and other Projects are promoting CA, including cover crops use, crop rotation, and also trying to improve the use of biological products (Solier, 2020, Personnel comunication).

30.7.3.3 Amazon Region

Agriculture in Amazon region is mainly migratory. The main crops are rice, hard yellow corn, and soybeans, which are managed based on both a traditional and mechanized direct seeding. Traditional direct seeding using a stake known locally

Fig. 30.13 Production systems with conservation agriculture in the humid tropics (Amazon Region) (**a**) Oil palm with Kudzu spp.; (**b**) Shade-grown coffee with Inga edulis; (**c**) Shade-grown cocoa; (**d**) Dryland rice in alluvial lands. (Photo: Benites)

as a ‘tacarpo’ occurs following ‘slash and burn’ of vegetation. Fertilizer application and phytosanitary control are absent and weeding and harvesting are manual. Yields are well below national averages.

The introduction of mechanized NT in Peru is recent with only ~1000 ha currently using mechanization for the production of hard yellow corn, rice, and soybeans. Yield is ~6.5 Mg ha^{-1}, depending on the variety or hybrid used. However, greater use of this system is limited by lack of appropriate machinery and low stubble loads (Agroenfoque 2008), although some new no-till machinery are been introduced and tested on different farm conditions (Solier, 2020, Personnel Comunication).

In Tocache, Yurimaguas, and Pucallpa the principles of the NT systems are being used successfully on ~10,000 ha of oil palm fields. They use kudzu (*Pueraria phaseoloides)* to protect fragile soils from heavy rains. Also, the production of coffee under shade occupies about 20,000 ha and cocoa with a transient and permanent shade of approximately 60,000 ha. Leguminous trees albisia (*Albisia falcatarea),* guava (*Inga edulis*), and erythrina (*Erythrina* sp) are used (Fig. 30.13). The use of hedges in tropical plantations is also a superb soil cover that reduces or prevents soil erosion, maintains productivity, combats weeds, and promotes the biological control of pests.

30.7.4 Potential of NT Systems in Peru

Given the importance of NT systems in the humid tropics, they must be supported and promoted by the government's agriculture sector. Low crop yields and high farm production costs currently marginalize many farmers and affect the profitability of rural sector and the country. NT systems are one way to reverse this situation. NT systems protect the soil, ration the use of water, save costs, time, fuel and labor, improve income and are friendly to the environment (Benites and Bot 2014). The total area under NT systems in Peru is currently ~200,540 ha which represents only 10% of total cultivation. However, this area could be expanded to incorporate about 200,000 ha of irrigated area on the coast and nearly 2 Mha of alluvial land in the Amazon, and also improve in small/medium farm areas on the Sierra region. The adoption of NT systems in these areas could mean a real productive revolution and with very low cost. However, farmers face a great challenge in making the change to NT systems farming. This requires a mindset change, increases in the availability of appropriate tools and equipment, and an understanding of how to appropriately manage soil, weeds, cover crops, and water under this modified system of agriculture. These changes will require capital investment and preferential credits.

30.8 No-Till in Ecuador

In Ecuador, while large areas of higher-elevation land have been cultivated under indigenous systems since pre-Columbian times, many areas are farmed under smallholder systems, which evolved following land reforms beginning in the 1950s. Prior to these reforms, extensive cultivation systems were wide-spread, and poor laborers were connected to the hacienda through institutional mechanisms such as indentured servitude. The reforms promoted the division of large areas into smallholder production systems, but most were not accompanied by agricultural services such as extension or applied research support (Alwang et al. 2013). Plowing the soil using animals and/or tractors is the traditional method of cultivation and occurs on slopes of up to 50 degrees (Fig. 30.14). This practice is contributing to loss of soil organic matter and erosion at rates as high as 150 Mg ha^{-1} (FAO 2014; Chela 2008; Dourojeanni and Jouravlev 2001). A large number of people live in extreme poverty driven by agricultural systems that have low productivity. Farmers have minimal access to agricultural extension services and technologies that could help maximize production, and banking systems and loans to invest in their farming operations (Barrera et al. 2010, 2012).

NT systems have been identified as a potential and sustainable way to develop an agricultural system that protects the environment from degradation and the associated poverty and food insecurity in the region (Nguema et al. 2013). Studies conducted in Ecuador have shown that NT systems have the potential to improve the livelihoods of the many rural poor communities (Nguema et al. 2013). For example,

Fig. 30.14 Typical example of low soil covering and high erosion rate – Sicalpa River watershed in Chimborazo, Ecuador. (Photo Jorge A. Delgado)

preliminary research conducted by Instituto Nacional de Investigaciones Agropecuarias (INIAP) found that there is potential to use NT systems to develop more intensive and sustainable agriculture in the Chimbo sub-watershed to the potential benefit of ~200,000 farmers (Barrera et al. 2012; Escudero et al. 2014). It is imperative to develop and implement viable NT systems that promote less soil degradation and improve crop yield and farm net income.

30.8.1 Research Results in Soil Management and Crop Grain Yield

In general, there is a lack of research regarding the potential to use NT systems in Ecuador. The general information reported has been that minimum tillage (MT) reduces yields for some crops and could increase the potential for weeds (Knowler and Bradshaw 2007; Yanggen et al. 2003). Crop residues management is also a point of conflict, with farmers having to choose between allowing animal grazing or retaining residues to increase the long-term sustainability of the cropping systems (Delgado 2010). However, NT and MT systems do provide advantages for small farmers, especially if labor is not available (Martínez et al. 2001).

A long-term (5 year) study conducted by Delgado et al. (2019) assessed the effects of tillage, crop residue management, and N fertilization on the yield and economic returns achieved on three farms using a grain forage rotation (corn–cover crop mixture of oat–vetch) in the high-altitude Ecuadorian provinces of Bolívar and Chimborazo. For these systems, MT is the use of a hoe to till the plots to plant the

Table 30.4 Average gross and net income and average cost for the corn, oat–vetch, and bean crops grown from April 2012 to December 2014 under different tillage, crop, and N management systems[†]

	Gross income	Total cost	Net income
Treatments	(US$ ha^{-1})		
Minimum tillage (MT)	5900	3600 a	2300
No-tillage (NT)	5800	3200 b	2600
Crop residue harvested (CRH)[‡]	6500 a	3600 a	2900 a
No crop residue harvested (No-CRH)[§]	5100 b	3200 b	2000 b
Nitrogen fertilizer (NF)	6200 a	3500 a	2700 a
Zero nitrogen (ZN)	5500 b	3300 b	2200 b

[†] Within a column (crop residue harvesting vs. no crop residue harvesting; MT vs. NT; N fertilizer vs. no N fertilizer) numbers with different letters are significantly different (LSD) at $P \leq 0.05$;

‡ CRH, crop residue was harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and removed from the field;

[§] No-CRH, no residue harvested for corn and all aboveground biomass for the oat–vetch and bean crops was cut and left on the surface. (Delgado et al. 2019)

The crop residue harvested provided a net income of 2900 ha^{-1} which was higher than the 2000 in net income resulting from not harvesting crop residue or leaving all of the oat–vetch crop to cover the surface soil ($P < 0.001$). Although there were no significant differences in yields due to NT and MT, the data suggest an advantage for the NT over the MT. The cost of 3200 ha^{-1} for NT was significantly lower than the cost for MT of 3600 ha^{-1} ($P < 0.001$). The net income between NT and MT was very similar, with a difference of about 300 ha^{-1} in favor of NT, but not a Significant difference. Since there was a lower cost for the NT when compared with the MT 2600 ha^{-1} was higher than the net income of MT of $2300 ha^{-1}, but not significantly higher ($P < 0.11$) (Delgado et al. 2019)

crop in a furrow and control weeds, and NT is the use of a pointed wood bar to make holes where the crop seeds were planted (Delgado et al. 2019).

Although there were no significant differences in yields due to NT and MT, the data suggest an advantage for NT over MT due to reduced production costs. Overall it was concluded that NT providing a net income of $2900, which is higher than the $2200 obtained with MT ($P < 0.001$) (Table 30.4).

The results obtained also show that N addition led to a significant increase of $500 in the net economic returns for farmers despite the cost of fertilizer application (Table 30.4). The authors of the study also note that while the harvesting of crop residues was more economic than residue retention, they suggest that it may be possible to harvest only 50% of the crop residue, which would generate some additional income, but would also contribute to environmental conservation and reduce erosion. Additional follow-up studies on crop residue management are required (Delgado et al. 2019).

If the NT system trialed by Delgado et al. (2019) were implemented across the region there is potential to impact close to 200,000 farmers. These studies show that conservation agriculture is an attractive management alternative even in systems where, due to small farm sizes and highly sloped fields, mechanization is not viable. Simple techniques such as jab-planting, combined with chemical weed control, can be easily adapted to a NT system and contribute to higher net income for farmers in Ecuador.

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Chapter 31
No-Till Farming Systems in Europe

Jacqueline L. Stroud

Abstract No-tillage (NT)systems in Europe share three main characteristics: they are driven by pioneering farmers, dependent on peer-to-peer extension activities, and are becoming more popular. There is a growing body of natural and social science research highlighting the importance of science-farmer social learning networks to achieve sustainable agriculture transformations. However, there is little effective policy support for this throughout Europe. Marginalization of no-tillers occurs in Germany and France, where the replacement of mechanical tillage by herbicides is rejected as a 'good farming' practice by the community. The UK has one of the fastest growing and highest rates of no-tillage adoption, but this has been built on self-experimentation and peer-to-peer learning, resulting in uncertainties in best management practices. Indeed, policy in the UK actively inhibits farmers and scientists from working together, due to privatisation of the agricultural information network and the defunding of agricultural science. Finland has one of the highest levels of NT adoption in Europe, led by pioneer farmers, and supported by research, subsidies and NT drill manufacturers to become an accepted 'good farming' practice. Spain has uniquely high rates of conservation agriculture in Europe linked to policy support. However, mal-adaption has occurred in some regions due to NT drill technologies and inadequate extension activities. The sustainable trajectory of NT across Europe is uncertain.

Keywords Social learning · Co-participation · Co-design · France · England · Finland · Spain · Conservation agriculture

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31.1 Introduction to No-Tillage Systems in Europe

European farming ranges from cool temperate Northern regions to semi-arid Mediterranean regions, with diverse infrastructure, traditions, languages, practices, soils, topography, and policies at local, regional, and national scales. No-tillage (NT) farming systems in Europe share three main characteristics: they are driven by pioneering farmers, dependent on peer-to-peer extension activities, and are uncommon at national scales. This situation is similar to the early development of NT systems in Brazil where NT was initially driven by farmers, and subsequently supported by research, policy, and agribusinesses, leading to its widespread adoption across the country (Lahmar 2010).

There is a lack of scientific evidence across both the socio-economic and ecological impacts of NT systems across Europe (Lahmar 2010). This is caused by the paucity of research and diversity of NT management practices (Lahmar 2010). Agriculture and soil science research has been largely defunded by policy makers (Baveye et al. 2018), and there are few updates to report since the review of NT in Europe for crop production and the environment (Soane et al. 2012). In summary, it is thought that NT is not suited to all European agroecosystems (Soane et al. 2012), and has mixed impacts on soil physical properties critical for crop production (e.g. bulk density and hydraulic behavior of the soil) (Basch et al. 2015). There are consistently positive effects for controlling soil erosion, improving earthworm activities, and aggregate stability (Lahmar 2010). However, extrapolating carbon sequestration and impacts on greenhouse gas emissions remains controversial.

There have been substantial advances in the understanding of NT adoption by farmers. This is an exciting development, with implications for the fundamental structure of agricultural policy and the role of science to support the agroecological transition of farming. Traditional research approaches are problematic because of the inherent diversity of NT systems. There is no single recipe for 'NT' and farmers do not copy each other's NT practices. It has been overlooked that NT is a quiet revolution in farming and requires new research approaches. NT is a co-designed system, a network product rather than an individual creation (Coughenour 2003). Through interactions with their social learning networks, farmers reconstruct NT practices to fit into their farming system and reconstruct their identity in the process (Coughenour 2003). This is why NT systems are fundamentally different from conventional agriculture; farmers form new beliefs about soils, crops, and the environment during the process of adoption (Coughenour 2003).

In the broader context of societal demands for improvements in the environmental impact of farming, a key hurdle is how to empower farmers to make pro-environmental choices. Specifically, the adoption of environmental management practices is limited by knowledge valuations (Coquil et al. 2018). These evaluations are based on personal beliefs about what it means to be a 'good farmer', described as productivist and stewardship values (Huttunen and Peltomaa 2016). Whilst productivist values are well defined, quantitative and universal (e.g. yield, gross margin), stewardship values are ambiguous, qualitative, and contextual (e.g. soil health, sustainable). At an individual level, creating contextual stewardship 'values' is achieved through actions and ideally through the co-production of knowledge (Mills et al. 2017), resulting in new beliefs about soils, crops, and the environment. At a community level, the agroecological transition is not a specific management practice, but the creation of a knowledge network (Coquil et al. 2018). This causes the erosion of 'universal goodness' farming ideals and the transition from conventional agriculture. Traditional productivity beliefs are not replaced, a diversity of practices become socially acceptable 'good farming' practices (Hiironen and Niukkanen 2014). For example, in Finland NT is now an accepted 'good farming' management practice (Hiironen and Niukkanen 2014).

Current conventional farming practices are the result of state sponsored productivist ideologies, with pioneers that deviate from conventional agriculture stigmatized as social deviants and ostracized from the farming community (Landesmaki et al. 2019). However, these marginalized individuals, through effective stigma management, lead the institutional change in agriculture. This process includes the individual rejection of negative evaluations, e.g. 'oddity', by stigma communicators (mostly conventional farmers); reconstruction of their identity as an innovative, entrepreneurial, and resourceful farmers around their stewardship beliefs; and the formation of connections with other like-minded people, e.g. farmer groups, to share information and skills to develop their farming practices (Landesmaki et al. 2019). These groups both undermine the legitimacy of conventional agriculture whilst building trust with conventional farmers by using traditional productivist terms to describe their farming activities, ultimately leading to social acceptance (Landesmaki et al. 2019).

The transformation to a more sustainable system not only requires appropriate innovations, but also the societal acceptance of a diversity of practices (Landesmaki et al. 2019). Traditional NT research was focused on esoteric debates about the advantages and disadvantages of NT adoption, overlooking that it is the adoption process itself that determines the durability and sustainability of this management practice. Hence, there are substantial opportunities for farmer-science partnerships to shape the sustainable trajectory of NT, with appropriate policy support. Indeed, the KASSA project (adoption of Conservation Agriculture in Europe) recommended that research and policy should anticipate NT adoption by farmers in order to target improvements in the sustainability of this agricultural management practice (Lahmar 2010).

This chapter focusses on the availability and quality of feedback for NT systems in Europe to highlight the challenges, opportunities, and strategic research and development needs. Four themes are explored (1) the marginalization of no-tillers; (2) the impact of privatizing agricultural information networks; (3) acceptance of NT as a 'good farming practice' in the rural community; and (4) the environmental and economic impacts resulting from the mal-adaption of NT practices.

31.2 Characteristics of Contemporary NT Systems in Europe

Conventional tillage (CT) dominates European farming systems, with NT accounting for <10% of crop establishment practices in countries (Soane et al. 2012). The European average is 1.92% of the arable land area (Basch et al. 2015). NT is one part of the defined Conservation Agriculture system; but Conservation Agriculture is not well established in Europe (Basch et al. 2015). NT systems include situations where NT is used for crop establishment in part of a rotation (but tactical tillage or rotational ploughing is still used), and where NT is used on part of the farm and deployed using seed drills or planters marketed as 'NT' machines with varying degrees of soil disturbance. Rotational tillage is not considered to be NT in many regions in the world. In Europe it is included because Conservation Agriculture is misunderstood, and there are no official statistics for crop establishment or soil management practices (Basch et al. 2015). NT is supported and promoted by NT farmers associations in each country, who join together to form the European Conservation Agriculture Federation (ECAF), which advocates for Conservation Agriculture at the European Parliament and European Commission levels (Kassam et al. 2019). In terms of the use of NT within conventional and organic farming, NT is rare in European organic farming systems (Peigné et al. 2016), but some organic farmers in Northern Europe are trialing NT techniques (Casagrande et al. 2016).

31.2.1 Adoption Characteristics of NT at National Scales

31.2.1.1 Germany

Adoption rates of NT systems vary within Europe. For example, NT is negligible in Germany, accounting for <0.5% of the arable area (Soane et al. 2012). NT is subsidized and supported in erosion prone hotspots in Germany (Lahmar 2010). Voluntary NT adoption is associated with lower costs of crop establishment, but farm sizes are small in Germany, typically <60 ha (Zikeli and Gruber 2017). NT is used by large farms (>150 ha) in the Eastern states growing cereals, oil seeds, and protein crops (Zikeli and Gruber 2017). Low adoption rates are linked to the role of ecologists who discourage the use of NT due to concerns about the use of herbicides (Basch et al. 2015).

31.2.1.2 France

France has below the European average adoption rate of NT at 1% (Basch et al. 2015). Unlike most European countries, there has been no privatization of the Agricultural Knowledge and Information System in France (Labarthe 2009). French agronomic and extension research is directed towards Integrated Crop Management to reduce pesticide use (Compagnone and Hellec 2015). The Chamber of Agriculture advisors support periodic NT, but not complete NT as it is not considered to be suitable for all soil types or compatible with reducing pesticide use (Compagnone and Hellec 2015).

31.2.1.3 UK

The UK has above-average European adoption levels of NT, accounting for 4% of arable land in 2010 and 7–8% of arable land in England in 2016 (Alskaf et al. 2019). The UK was one of the first countries to dismantle its agricultural knowledge system, which fragmented advisory services and led to the loss of trust in the Department of Environment, Farming, and Rural Affairs (DEFRA) by the farming community (Sutherland et al. 2013). No-till is principally used by farmers growing combinable crops (cereals, oil seeds) during part of the rotation or on a part of the farm, with 0.5% of farmers adopting NT on all of their farm (Alskaf et al. 2019). There is considerable uncertainty in best management practices, with farmers learning about the techniques of NT through self-experimentation and from other farmers (Alskaf et al. 2019).

31.2.1.4 Finland

Some of the highest rates of arable NT in Europe are found in Finland (humid snow climate), with estimates ranging between 9–13% of the arable area (Soane et al. 2012). There was a boom in NT directly linked to agro-environmental policies tackling water quality (Huttunen and Peltomaa 2016). This was linked to pioneering NT farmers disseminating their management practices through their social learning networks, and subsequently supported by research, policy and agribusiness (Derpsch et al. 2010; Basch et al. 2015). The adoption is also linked to intensive research programs, knowledge transfer, and the identification of environmental benefits of NT (Soane et al. 2012).

31.2.1.5 Spain

Spain (semi-arid climate) has the highest levels of Conservation Agriculture adoption in Europe. Here Conservation Agriculture is defined as permanent NT plus crop rotation and permanent soil cover. Regional governments provided € 200 million support for Conservation Agriculture, and this practice is used on 25.5% perennial and 7.5% arable crop area (Gonzalez-Sanchez et al. 2015). However, mal-adoption has occurred in some areas - farmers consider they practice Conservation Agriculture but regularly use tillage and sell crop residues leaving the soil surface bare (Carmona et al. 2015).

31.3 Challenges and Opportunities with the Use of NT in Europe

In Europe, NT is farmer driven and the decision to adopt NT is initially associated with reducing the cost of crop establishment, and subsequently sustained by perceived improvements in soil organic matter, earthworms, erosion control, water infiltration, and productivity in dry areas (Lahmar 2010). The principal challenge with the use of NT is that it is a farmer-led initiative, hence there is limited support to ensure that the trajectory of NT systems is sustainable.

31.3.1 Marginalization of No-Tillers, France

Contrasting to most of Europe, there has been no privatization of the Agricultural Knowledge and Information System in France (Labarthe 2009). Agricultural policy aspires to achieve agroecological transitions aligned with Europe (Chantre and Cardona 2014). These policies were pursued by using 'target' systems, overlooking the process of behavior changes needed in the farming community (Chantre and Cardona 2014). Specifically, a sudden shift in extension services to encourage farmers to abandon productivity and adopt low input systems for ambiguous environmental goals led to a perception of irrelevance by farmers and resulted in a disconnection between farmers and advisory services, and difficulty in bringing about change (Chantre and Cardona 2014). This led to a demand for private provision whose role in sustainability is mixed, including companies that "fiercely reject scientific knowledge" and investment aimed towards increasing their market share over environmental transition support (Coquil et al. 2018).

There is a continued government policy aspiration to achieve an agroecological transition (Coquil et al. 2018). NT is not considered to be a sustainable agricultural management practice when used alone because it is implemented for cost-saving purposes, and with no change in rotation, a common trajectory is weed problems, increase in herbicide use leading to resistance-to-herbicide weed problems (Chantre and Cardona 2014). However, NT within a system-redesign to reduce pesticide use is supported by the Chamber of Agriculture advisors (Compagnone and Hellec 2015). Confusingly, complete NT is not supported by these advisors (Compagnone and Hellec 2015), but Conservation Agriculture is considered to be an agroecological practice (Cristofari et al. 2017).

Agricultural research and extension activities influence who occupies the role of early adopter and innovator positions within the local network, often leading to re-enforcing local hierarchies and marginalizing innovations such as Conservation Agriculture (Compagnone and Hellec 2015). For example, within local farmer networks in Burgundy, East France, advisory services do not support complete NT, and early adopter and innovator positions are only occupied by people who use tillage and are highly critical of the amount of glyphosate used in NT systems (Compagnone and Hellec 2015). This causes two distinct technical pathways to co-exist within the same network; those that are supported by advisory services, and the no-tillers that are not. Each pathway has distinctive relational, cognitive, and symbolic resources (Compagnone and Hellec 2015). The network product is rival-associates reconstructing techniques to suit their farm within local social settings (Compagnone and Hellec 2015).

In terms of farmers moving towards Conservation Agriculture in South-West France, research indicates their social learning network includes peers, extension workers, and researchers (Cristofari et al. 2017). The learning process is based on developing pragmatic judgements on a course of action (Cristofari et al. 2018). Implementation is characterized by experimentation (planned and unplanned), and adoption is typically progressive, for example, experimenting on part of a field, before adoption to field scales (Cristofari et al. 2017). Scientific information is used as a source of ideas, an indicator to assess management practices, a way to explain observed phenomena, and scientific methodology is used for field experiment designs, for example replicated control and treatment plots (Cristofari et al. 2017).

Hence, Conservation Agriculture is adopted by farmers in France regardless of seemingly hostile agroecological policy interpretations that impact advisory services and social learning networks. The agroecology aspiration by policy makers is a top-down mandate that causes many challenges in its implementation by the Agricultural Knowledge and Information System (Coquil et al. 2018). Whilst those adopting Conservation Agriculture are motivated to change their skills, develop new ways of thinking and living as farmers; advisory services attempting to implement these environmental policies may need to facilitate this fundamental change in mindset for each farmer, noting this has mental health impacts (Coquil et al. 2018). Further, this is not simply the traditional application of generic knowledge and interventions, the agroecological transition is a learning process requiring initiative and motivation to reconstruct environmental management techniques to suit their farm and achieve ambiguous environmental policy goals (Coquil et al. 2018). This indicates missed opportunities through these policies to gain a better understanding of NT adoption that would provide key insights into how to empower conventional farmers to achieve agroecological transitions.

31.3.1.1 Case Study: Peer to Peer Learning Between BASE-France and BASE-UK Farmer Groups

Farmers have formed their own groups and networks interested in Conservation Agriculture, with Biodiversity, Agriculture, Soil and the Environment (BASE) group started in France by Frederic Thomas (@FthomasTcs, >4k followers). BASE-UK runs in parallel with BASE-France, and has >1000 members (BASE 2019). Subscriptions by members fund speakers for meetings, field trials, and farm tours to share experiences and collective learnings, principally disseminated online.

BASE-UK farmer David White (@RTKfarmer, >5k followers), organized and shared the learnings from the BASE-UK farmers tour to Northern France in November 2018 (Fig. 31.1, (White 2018)). He noted that CT dominated and high yields are easy to achieve providing little incentive to change. There was a sense that

Fig. 31.1 Study tour by BASE-UK farmers looking at the effects of NT practices by BASE-France farmers on the soil (White 2018)

French farmers are 'greening' because they have to, rather than appreciate the wider benefits. They visited a Conservation Agriculture farmer (@VictorHolistic, >2k followers) who has root crops in his arable rotation, deploying a mixture of strip-tillage and tillage for sugar beet, potatoes and beetroot, providing novel insights into the use of cover crops to build organic matter and soil biology (Fig. 31.1). The group also visited a NT farmer (@Senez8, >2k followers) who over the past 8 years has used 60 trials to improve his soil and reliable yields, highlighting to the group the importance of research and building up a personal knowledge base (White 2018).

31.3.2 Fragmentation of Agricultural Information Systems, England

In contrast to France, there was a deconstruction of Agricultural Knowledge Information Systems across Europe during the 1980's and 1990's. This privatization of information is criticized for failing to meet the multifunctional (e.g. productivity and environmental) needs of sustainable agriculture (Labarthe 2009). Trusted environmental advisors have gone into financial administration under the fee-for-service model, indicating the trajectory of advisory services is biased towards conventional agriculture productivity goals (Sutherland et al. 2013).

The UK government privatized knowledge production and transfer by (1) privatizing the public extension service ADAS in 1997; (2) shutting down 83% of Research Institutes, which provided the information base for extension services; and (3) disbanding of the agricultural training board (Curry et al. 2012). This political-economy approach resulted in the loss of social networks between farmers and advisors (Curry et al. 2012), and loss in trust between farmers and the government (specifically, DEFRA, caused by its actions) (Sutherland et al. 2013). This fragmentation at best provided choice, at its worst, has led to gaps, overlaps, confusion, contradictions, and misinformation (Sutherland et al. 2013).

It has recently been suggested that researcher–farmer networks are needed to consolidate on-farm information to support effective NT adoption (Alskaf et al. 2019). However, privatizing information changed the role of researchers. Extension activities are now inimical to the scientific career pathway, which is dependent on publications in journals marketed as high impact (Moher et al. 2018). There is a presumption that career scientists can communicate effectively with end-users of research, but this is an overlooked problem tackling sustainability issues (Porter and Dessai 2017). Even if these challenges can be overcome, it is unclear as to what evidence-base researchers would use to inform best NT farming practices in the UK. The 2015 DEFRA soils evidence review recorded “research into NT practices within the UK is extremely limited” (Smith et al. 2015). There was a concomitant defunding by DEFRA within the remaining institutes during the deconstruction of the agricultural information system, eroding the national scientific capacity in weed ecology and control, alternatives to agrochemicals for pest and disease control of major crops, the environmental fate and behavior of pesticides, crop agronomy and nutrition, soil processes, and environmental protection (Parliament 2007).

The focus of UK agricultural policy is to integrate nature into the economy (Baveye et al. 2016). For example, there is a DEFRA policy aspiration to achieve sustainable soils by 2030 by using a suite of quantitative soil health targets to determine Payments for Ecosystem Services (DEFRA 2019). Beyond the technical problems of quantifying soil health and ethical considerations of assigning monetary values to sustainable soil functions (Baveye et al. 2016), the simple homo economics model of human behavior overlooks the process of change at both individual and community levels. Financial mechanisms erode green self-identity and sustainable pro-environmental behaviors of the individual (Evans et al. 2013). The resistance to change within the agricultural community is linked to the loss of self-identity associated with what is means to be a ‘good farmer’, that is, the community rituals and symbols associated with productivity (Burton 2004).

To support the process of change towards environmental policy goals, identity theory suggests that new symbols and rituals can be developed to indicate ‘good farming’, and the prestige of early adoption leads to rapid dissemination through social learning networks in the community (Moran et al. 2013). This would explain the farmer led NT phenomenon in the UK, for example, and the belief within the NT farming community that they are leading sustainable soil management practices (Krzywoszynska 2019).

Sociological research in engaging farmers in environmental management highlights that short-termism and year-on-year funding decline causes problems in sustaining trusting relationships and durable environmental management outcomes in these networks (Mills et al. 2017). The authors conclude that co-production of knowledge is needed to empower farmers, facilitate changes in their underlying beliefs and values to achieve sustained and durable transformations in their environmental management (Mills et al. 2017).

The sustainable soils farming community (no-tillers) are on the change pathway, and support strengthening links with researchers to co-produce knowledge on-farm, and test hypotheses and the sustainability of different management practices for dissemination in their social learning networks (Krzywoszynska 2019). Modern dissemination channels are used, for example, the use of social media such as Twitter, to share sustainable soil management content (Mills et al. 2019). Farmers have set up events to facilitate NT knowledge exchange, for example, 'Groundswell – The No-Till Show' is a highly popular 'by farmers for farmers' event (Kassam et al. 2019) led by farmers in the sustainable soil management community.

However, the peer-to-peer dissemination of observations can lead to the spread of misinformation and create tensions with the scientific community. The insensitivity of natural scientists to the meanings behind these environmental symbols and indicators used on-farms is often overlooked. For example, NT leads to the perceived improvements in soil organic matter and earthworms (Lahmar 2010), which is extrapolated to mean climate change mitigation and healthier soils by NT farmer associations (ECAF 2019). From a social sciences perspective, these visual indicators are strengthening green self-identity and transformations towards environmental management practices. From a natural sciences perspective, the role of NT in climate change mitigation is uncertain, for example, dependent on variable soil properties such as soil wetness and susceptibility to compaction (Soane et al. 2012). Similarly, whilst research agrees that there is an impact of tillage on the earthworm community structure (Briones and Schmidt 2017), whether this is positive, negative or inconsequential to soil health, is unknown (Briones 2014).

These problems are confounded by the disconnection between soil health research, and application by farmers, which has only recently been recognized (Bünemann et al. 2018). To effect change in soil security and agricultural sustainability it has been argued that there needs to be a fundamental change in mindset towards creating connections between soils and people (Ball et al. 2018). For example, indicators that foster direct connections to the physical, biological, and chemical soil such as the Visual Evaluation of Soil Structure (VESS), earthworms, and soil pH (Ball et al. 2018). Research from the Rothamsted Institute piloted the co-production of knowledge model coordinated using social media leading to >1000 hectares of farmland surveyed for earthworms by farmers in England (Stroud 2019), indicating the popularity of this type of approach.

The UK has some of the fastest and highest adoption rates of NT in Europe, 4% land area in 2010 to 7–8% land area in 2015 (Alskaf et al. 2019). This is led by farmers experimenting on their own farms and learning from other farmers, with great uncertainty over best NT management practices (Alskaf et al. 2019). There is a body of natural and social science research highlighting the importance of science-farmer learning networks for sustainable agriculture. Hence, the UK is at a tipping point dependent on DEFRA policy that will determine the sustainability of the NT trajectory.

31.3.2.1 Case Study: No-Tillage Farmer Bridging the Links Between Science and Policy Makers

Tim Ashton (@Tim_Ashton, 1k followers), of Soulton Hall, Shropshire England is a soil regenerative farmer using NT over the past 5 years to establish crops and help save the soil. For example, Tim says "More than half global CO_2 emissions could be locked into the ground if we stopped tilling them". His primary information sources include NT books e.g. Growing a Revolution: Bringing our soil back to life (Montgomery 2017) and other farmers e.g. Nuffield farm scholars and Groundswell (NT show). Tim bridges the gap with science through his own research (Masters degree at Harper Adams University, collaborating with scientists at Oxford University). He has found that ploughing reduces springtail populations by 80% and causes water run-off problems on his farm. He also joined the participatory research by a Rothamsted scientist (@wormscience, 3k followers) project to assess earthworm populations on his farm. Tim bridges the gap with policy, for example, hosting the Secretary of State for Environment, Food and Rural Affairs (Rt. Hon Michael Gove MP, 2017–2019) to raise awareness of NT in UK farming and showcased his NT farm practices on the popular TV show BBC Countryfile (six million viewers per week).

31.3.3 Acceptance of NT as a 'Good Farming' Practice in the Rural Community, Finland

Finland is the most sparsely populated country in Europe and has a fragmented farm structure (fields scattered), and a small average farm size of 37 ha (Hiironen and Niukkanen 2014). Finland joined the EU in 1995 and agri-environment schemes were introduced as part of the agricultural income subsidy, with 88–96% of the agricultural land area participating (Huttunen and Peltomaa 2016). The focus of the agri-environment schemes was water protection, which led to the NT adoption boom (Huttunen and Peltomaa 2016). This was triggered by one of the first agri-environmental schemes that introduced compulsory winter plant cover in Southern Finland, which become voluntary in the rest of the country over time. NT methods were well suited to achieve this target, resulting in its rapid adoption (Huttunen and Peltomaa 2016). This adoption is linked to pioneer farmer dissemination activities and local NT drill manufacturers (Derpsch et al. 2010) and research driven knowledge transfer (Soane et al. 2012). NT is a voluntary practice, which is characterized by strong internalization (meeting 'good farming' ideals), but results in lower levels of adoption than forced practices e.g. compulsory fertiliser restrictions to improve water quality (Huttunen and Peltomaa 2016).

The ideals of ‘good farming’ in Finland are linked to both flexible productivist and stewardship values (Huttunen and Peltomaa 2016). Whilst NT was initially stimulated by agri-environmental schemes, the authors determined that the use of NT is principally associated with productivist values in terms of cost and labor savings. Equally, its rejection is linked to these productivist values, being yield stability between years (e.g. weather) and within fields (e.g. seven soil types within one field). Their research showed that personal beliefs about NT influenced whether someone used it or not, but various tillage practices have become part of farming culture and are perceived as ‘good farming’ practices in the community. It was found that only pioneer no-tillers remember the time when other farmers disapproved of their farming practices. This indicates that farming ideals have widened and diversified over time, and there has been an erosion of ‘universal goodness’ farming ideals, resulting in a socially acceptable diversity of practice and social cohesion in rural communities (Huttunen and Peltomaa 2016).

31.3.3.1 Case Study: Improving UK Arable Efficiency by Learning About Finnish NT Systems

The Agriculture and Horticulture Development Board (AHDB) is the levy funded (>£50 million per annum) organization by UK farmers to improve business efficiency. Recognizing the popularity of NT in the UK, the AHDB organized a study trip to Finland in 2018 to bring back learnings for UK farmers, disseminated online. This is because Finland has the biggest NT arable adoption in Europe (AHDB 2018; Henderson 2018).

Harry Henderson (@AHDB_Arabletech, >1 k followers) highlighted that the success of NT is linked to the quality of decision making by farmers. Specifically, an attitude to tailor crop establishment to the conditions, including the occasional use of tillage if the weather has caused drilling to be postponed. No-till is simply part of the farming system, rather than a temporary fix or a separate system with its own rules (Henderson 2018).

The trip reports shares insights, such as arable cropping in Finland is low yielding (compared to the UK, with wheat at 5.5 Mg ha^{-1}) and is barely profitable, with many farmers having a second job to subsidize income. NT is the cheapest way to establish arable crops and is subsidized by the Finnish government (€30–40 ha^{-1} year^{-1}). Caraway seed is one of the most profitable crops in the rotation (which includes winter wheat, faba beans, spring barley, and oilseed rape) and the season is too short for cover crops, so crop residues are retained on the soil surface (Henderson 2018).

Decisions are based on cost-benefit analyses in a low-margin system, with ‘good farming’ practices (e.g. avoiding soil compaction) being central and innovations such as precision farming avoided. Locally made e.g. Valtra, light tractors (<200 horsepower), with high power to weight ratios are used to avoid compaction (Fig. 31.2). Locally designed, small (<4 m) disc-based drills e.g. Tume or Multiva, are capable of operating in NT or ploughed systems, to provide flexibility (Fig. 31.2).

Fig. 31.2 Small machines and disc-based drills in Finland (Henderson 2018)

The capacity problem caused by an infrastructure of small machinery is overcome by the 'keeping the drill running' mentality, with neighbors working together, including 24-h drilling in peak times (Henderson 2018).

Inefficiencies in the UK NT system compared to Finland include: larger drills e.g. 6 m size for capacity building, necessitating the use of powerful, heavy tractors, resulting in compaction management rather than avoidance, and fixed mindset of NT farming practices, rather than farming to conditions on the ground (Henderson 2018).

31.3.4 Mal-Adaption of Conservation Agriculture Principles, Spain

Spain has had a consistent increase in Conservation Agriculture adoption over the past decade, supported by government policy (Gonzalez-Sanchez et al. 2015). Where Conservation Agriculture was introduced well it spread rapidly, but in areas where it was introduced poorly, it is not accepted and adoption rates are very low (Lahmar 2010).

Adoption quality is rarely reported, but an interesting case of mal-adaption of Conservation Agriculture was reported in the Andalusia region. Here, farmers think that they have adopted Conservation Agriculture, but this is incorrect. The mal-adaption includes partial application, regular tillage, and removal of crop residues, leading to an absence of quantitative environmental and economic benefits from adopting 'Conservation Agriculture'(Carmona et al. 2015). There is a lack of suitable NT drills for sowing sunflowers in wet Vertisols (Carmona et al. 2015), which resulted in the local adaption of conservation agriculture principles.

Adoption quality from socioeconomic aspects was also recorded by the researchers indicating a number of barriers to uptake. For example, conservation agriculture farms were large (average size 472 ha compared to 18 ha conventional farms), 67% conservation agriculture farmers have a university degree (compared to the average 2%), and 100% conservation agriculture farmers were males (compared to 22% farmers being female in the region) (Carmona et al. 2015).

31.4 Research and Development

To till, or not to till, that is the traditional research question. It overlooked that NT is farmer-driven, and the process of adoption leads to a reconstruction of the meaning of 'good farming' to the farmer across soils, crops, and the environment (Coughenour 2003). This is important for two reasons, firstly, a better understanding of NT adoption provides key insights into how to empower conventional farmers to achieve agroecological transitions. Secondly, the sustainable trajectory of NT is dependent on the quality of feedback (e.g. co-participation, co-design) during this adoption process, and science can shape this process to support the farming community achieve their agroecological goals.

However, Europe has many disconnections between policy-science-farming. For example, whilst the UK may have some of the fastest and highest NT adoption rates in Europe, policies have led to almost no research on NT practices (Smith et al. 2015). Farmers are developing their NT practices alone or with other farmers (Alskaf et al. 2019). Policy actively inhibits farmers and scientific communities from working together e.g. the UK government privatized the agricultural information network (Curry et al. 2012). The quality of policy support will ultimately determine the agroecological transition of farming in Europe.

The transformation to a more sustainable system requires appropriate innovations and the societal acceptance of a diversity of practices (Landesmaki et al. 2019). Hence, NT research and development is a partnership between natural and social scientists creating an effective social learning network to support the farming community. Research topics include effective networks, social learning, weed ecology and control, alternatives to agrochemicals, the environmental fate and behavior of pesticides, crop agronomy, soil processes and environmental protection. For example, limited knowledge and technical advice to solve problems of NT in Spain include compaction, residue management, weeds, slugs, and mice (Lahmar 2010). Similarly in the UK, barriers to NT adoption include weed control, suitable NT machinery, slugs, and yield reductions (Alskaf et al. 2019).

Virtual social learning networks are an area of considerable development potential, although currently they are not used to inform on NT management (Alskaf et al. 2019). Twitter is used to disseminate information on sustainable soils (Mills et al. 2019) and co-ordinate national scale farmland soil ecology assessments e.g. #WorldWormWeek (Stroud 2019). However, these networks are sensitive to the balance of information and disinformation.

To effectively co-produce knowledge, research into farmer-friendly geostatistical designs is needed to balance information and inconvenience for the farmer (Pringle et al. 2010), for example, on-farm strip trials are convenient (Lawes and Bramley 2012). Developing efficient tools for open-access datasets using common tautology would help to tackle key information gaps efficiently. Communicating results effectively also requires research attention, with verbal, written, and number-based formats impacting perceptions of credibility and correctness (Jenkins et al. 2017). Communicating uncertainty is also an important research need, particularly surrounding the environmental impacts of NT agriculture, which causes tensions in the community. Research indicates that the method of communication depends on the audience, for example, to researchers, verbal scales are more open to misinterpretation than box-plots in reporting estimated greenhouse gas emissions (Milne et al. 2015).

Visual indicators of soil physical, biological and chemical properties are also priority research areas, as they are important at building links between soils and people (Ball et al. 2018). This includes adapting scientific methods for on-farm applications, and research into what changes in these visual indicators mean – for example, it is unknown whether it is better to have a diversity of ecological groups, a diversity of earthworm species, or if there is a keystone species, and thus how to configure the agroecosystem effectively (Briones 2014).

Towards developing effective farmer-scientist partnerships whilst at Rothamsted Institute, UK, I hosted a group of NT farmers from European countries in June, 2016 and asked them to compile a list of research topic priorities (pers comm. with Bill Richie, study tour coordinator). The priorities this group identified were:

- Slug management and control including identification and management of beneficial organisms for control;
- Utilising Integrated Pest Management in NT systems;
- Cover crop utilisation including mixes, seeding rates, and placement in a crop rotation (e.g. interactions between various cover crops and following cash crops);
- The role of soil biology in an arable system, particularly relating to crop health and biological control of common pests (including 1 above).
- The role of crop residue retention in a NT system in relation to the soil as a carbon sink;
- The impact of soil microbial activity in relation to nitrogen "lock-up" and timing of subsequent N release to the growing plant;
- The impact, if any, of glyphosate on soil life; and
- The utilisation of companion crops in NT systems.

Workshops with farmers, researchers and agri-businesses are a primary tool to identify local research needs. For example, in Andalusia, Spain where mal-adoption of conservation agriculture had occurred, research needs to tackle this issue included (Carmona et al. 2015):

- Technical modifications to the NT drills by the machinery dealer;
- Plant density research for weed control; and
- Use of granular insecticides for pest management

A final research and development need is to understand the connections between farming-society-pesticides to inform best policy practices because current policies lead to discrimination, for example, impacting the mental health of the farming community (Coquil et al. 2018). No-tillers have been marginalized for their use of pesticides (Compagnone and Hellec 2015). However, interestingly, organic farmers (who restrict pesticide use) have also been traditionally marginalized in the community (Landesmaki et al. 2019). Stigmatization creates inequality, undermines trust and reduces opportunities to build effective knowledge networks (Landesmaki et al. 2019).

31.5 Outlook

Policy makers dictating change or delegating this role to businesses are indicative of poor quality support to achieve societal demands for the agroecological transition of farming across Europe. New policies are needed to support social learning networks with strategic farmer-science partnerships. Empowering farmers leads to durable increases in stewardship activities, and the quality of environmental management is linked to the quality of feedback during the adoption process, which can be delivered through science. Ultimately achieving a diversity of socially acceptable practices associated with ‘good farming’ will be through effective policy that enables people to work together to achieve sustainability goals.

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Chapter 32
No-Till Farming Systems in North America

Upendra M. Sainju

Abstract The no-till (NT) farming system is one of the prominent conservation management practices used to reduce soil erosion, sustain crop yields, and improve soil health and environmental quality. The NT system has variable effect on crop yields and soil and environmental quality compared to conventional tillage (CT) system, depending on soil and climatic conditions and cropping systems. While crop yields are variable in irrigated cropping systems, yields are similar or greater in NT than CT in dryland cropping systems. As a result, soil organic matter is also similar or greater in NT than CT in dryland cropping systems, but variable with tillage practices in irrigated cropping systems, especially in humid regions. Nitrogen leaching can be greater in NT than CT due to the presence of large pores. Similarly, N_2O emissions can be greater in NT than CT due to increased soil water content, but CO_2 emissions can be lower. However, global warming potential (GWP) and greenhouse gas intensity (GHGI) can be lower in NT than CT. Although NT provides more ecosystem services than CT, adoption of the NT system by producers has been slow due to some social and economic concerns. This chapter discusses the impact of the NT system on crop yields, soil health, and environmental quality compared to the CT system and the challenges and opportunities of adopting NT by producers in North America.

Keywords Air quality · Crop production · North America · Soil quality · Tillage · Water quality

32.1 Introduction

Concerns about soil erosion and nutrient losses due to the actions of wind and water from conventional tillage (CT) in the 1950s led to the adoption of no-till (NT) farming systems in the USA (Fig. 32.1). While CT involves plowing the land intensively to prepare a seedbed, incorporate crop residue into the soil, and control weeds, NT

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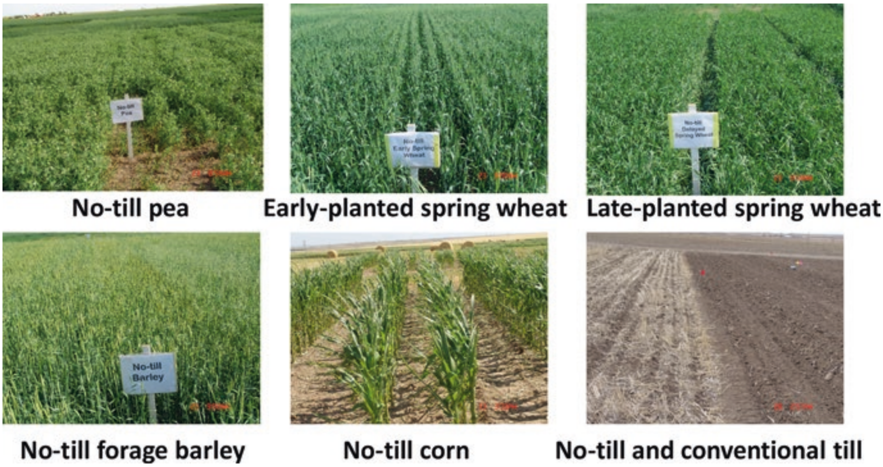

No-till pea

Early-planted spring wheat

Late-planted spring wheat

No-till forage barley

No-till corn

No-till and conventional till

Fig. 32.1 Examples of NT cropping systems in North America (U. Sainju)

involves seeding crops directly over crop residue using a NT drill without disturbing the soil. Exposure of soil at the surface, degradation of aggregates, and mineralization of organic matter due to frequent tillage operations enhance soil erosion in CT, but the reverse is true in NT where crop residue deposited at the soil surface covers the soil. Furthermore, enhanced soil aggregation due to increased organic matter from an undisturbed soil condition helps to reduce erosion in the NT system.

The NT system also has several agronomic and environmental benefits compared to CT. While crop yields in NT are similar to or greater than CT (depending on soil and climatic conditions and cropping systems), soil health is usually enhanced in NT due to increased soil organic matter from decreased mineralization and reduced soil erosion and nutrient losses. Increased soil C sequestration in NT can also reduce greenhouse gas emissions, but N leaching can be greater in NT than CT due to the presence of large pores. Another benefit of using NT is the reduced energy required for tillage in crop production, but increased herbicide input required for weed control may negate this gain. In USA, about 37% of crop production occurs in NT systems, with area under NT increased by 8% from 2012 (39 Mha) to 2017 (42 Mha) (USDA 2017). Although the benefits outweigh the limitations of using the NT system, adoption of the system has been slow in USA primarily due to social and economic reasons, such as difficulty in seeding over crop residue, increased cost of purchasing the equipment, reduced seed germination due to lower soil temperature, and unwillingness to change tillage practices. The objectives of this chapter are to evaluate the impact of the NT system in crop production, soil health, and environmental quality compared to the CT system, and discuss challenges and opportunities in adopting the NT system in North America.

32.2 Crop Production

32.2.1 Irrigated Crop Production

The NT system has variable effect on irrigated crop yields compared to CT in North America. For example, some researchers (Bordovsky et al. 1998; Daniel et al. 1999; Nyakatawa et al. 2000) have reported similar or greater cotton (*Gossypium hirsutum* L.) and sorghum (*Sorghum bicolor* [L.] Moench) yields in NT than CT, while others (Ishaq et al. 2001; Pettigrew and Jones 2001; Schwab et al. 2002) have found lower cotton yield with NT. In some cases, enhanced cotton yield with NT occurred only after 3 years (Triplet et al. 1996). Increased soil water content due to crop residue accumulation has increased cotton yield from enhanced seed germination and root growth in NT compared to CT (Bordovsky et al. 1998; Nyakatawa and Reddy 2000; Nyakatawa et al. 2000). In contrast, lower soil temperature, poor root penetration, and difficulties in obtaining adequate plant stand and weed control have reduced cotton and sorghum yields in some NT systems (Schertz and Kemper 1994; Triplet Jr et al. 1996). Boquet et al. (2004) also reported that cotton yields were lower in NT than CT without N fertilizer, but yields were higher with optimum N rate in NT. Increased N immobilization due to residue accumulation at the soil surface resulted in lower cotton yield in NT than CT when no N fertilizer was applied (Boquet et al. 2004).

32.2.2 Dryland Crop Production

Dryland crop yields also varied with tillage practices. For example, malt barley (*Hordeum vulgaris* L.) yields were lower (Peterson and Potts 1985), similar (O'Sullivan and Ball 1982), or greater (Ciha 1982) in NT than CT. However, NT often increases spring and winter wheat (*Triticum aestivum* L.) yields compared to CT, especially during dry years, by increasing soil water conservation and trapping snow due to increased crop residue accumulation (Halvorson et al. 1999; Lenssen et al. 2007; Miller et al. 2002). Because of improved soil water storage, NT also enhances crop intensification and increases annualized dryland crop yields compared to CT in crop-fallow systems in arid and semiarid regions (Farahani et al. 1998; Halvorson et al. 1999; Miller et al. 2002). Sainju et al. (2009b) reported that NT increased spring wheat grain yield compared to CT in 7 out of 21 years, although mean grain yield across years were not significantly different between tillage systems in the northern Great Plains, USA.

Several researchers have found that NT increased dryland corn yield by 25% and net return by 69% compared to CT (Norwood 2000; Norwood and Currie 2011). In a meta-analysis on the effect of tillage on corn yield, DeFelice et al. (2006) found that corn yield was greater in NT than CT in the southern and western USA, similar in the central USA, and lower in the northern USA and Canada, but overall USA national average yield was not different between NT and CT. They also reported that corn yield was greater in NT than CT in moderate- to well-drained soils, but slightly lower in poorly-drained soils. Delayed germination and emergence of seeds due to lower soil temperature and greater water content can reduce irrigated corn yield from late vegetative growth, time of silking, and flowering in NT compared to CT (DeFelice et al. 2006). In contrast, increased soil water conservation and root growth can enhance dryland corn yield and water use in NT compared to CT (DeFelice et al. 2006). Because of reduced input costs, increased conservation of soil resources through reduced erosion, greater soil C sequestration, and similar corn yield compared to CT, NT corn production has been increasing in USA since 1980 (DeFelice et al. 2006). Lenssen et al. (2018a) found that CT increased dryland corn plant stand compared to NT in 3 out of 6 years, but NT increased corn seed number and grain yield in 4 out of 6 years in the northern Great Plains, USA. Several researchers (Machado et al. 2008; Payne et al. 2000, 2001) in the Pacific Northwest, USA have reported that tillage had no effect on pea (*Pisum sativum* L.) yield. In contrast, NT increased pea yield compared to CT in the Canadian Prairie (Lafond et al. 2006). Lenssen et al. (2018b) observed that CT increased dryland pea plant stand and grain yield in 1 out of 6 years and plant height in 2 out of 6 years compared to NT, but overall pea performance was similar between NT and CT in the northern Great Plains.

32.3 Soil Health

32.3.1 Soil Carbon and Nitrogen

Sound soil health is needed not only for enhancing or sustaining crop yields and quality, but also for protecting the environment by maintaining water and air quality. Soil health is evaluated by examining the physical, chemical, and biological properties of soil that relate to crop yield and environmental quality. Management practices, such as tillage, can affect these properties. Soil organic matter, as measured by organic C and N levels in the soil, is one of the key factors that affect these properties. No-till can enhance soil organic C and N compared to CT by reducing organic matter mineralization and aggregate degradation due to the relatively undisturbed soil condition (Allmaras et al. 2000; Jastrow 1996; Sainju et al. 2002). In contrast, CT can reduce soil organic C and N by incorporating crop residue into the soil, disrupting aggregates, and increasing aeration (Balesdent et al. 1990; Cambardella and Elliott 1993).

Conversion from CT to NT can increase soil C stock by 0.1% at the 0–0.05 m soil depth every year, a total of 10 Mg ha^{-1} in 25–30 years (Lal and Kimble 1997; Paustian et al. 1997a). However, SOC below the 0.075 m depth can be higher in tilled areas, depending on the soil texture, due to residue incorporation at greater depths (Clapp et al. 2000; Jastrow 1996). Tillage can also influence crop residue C input, which effects soil C sequestration (Ogle et al. 2012). For example, when C input is <15% in NT than CT due to reduced crop yields, soil organic C is often lower in NT, especially in regions with wetter and cooler climate, such as in eastern USA and Canada (Ogle et al. 2012). In such regions, tillage often redistributes crop residue in the soil profile, resulting in lower soil organic C in the surface and greater in the subsurface layer, with overall soil profile C similar or greater in CT than NT (Angers and Ericksen-Hamel 2008; Luo et al. 2010). The reverse is true when C input is >15% in NT than CT (Ogle et al. 2012).

In dryland cropping systems, studies have shown that soil organic matter can be increased by using NT with continuous cropping compared to CT with crop-fallow systems (Halvorson et al. 2002a; Sainju et al. 2007; Sherrod et al. 2003). Halvorson et al. (2002b) observed that NT with continuous cropping increased soil C sequestration in dryland farming systems in the northern Great Plains, USA by 233 kg C ha^{-1} $year^{-1}$ compared to a loss of 141 kg C ha^{-1} $year^{-1}$ in CT with crop-fallow. After 8 years, Sainju et al. (2017) reported that NT with continuous spring wheat increased soil total C at 0–0.2 m by 16% compared to CT with 2–4 years crop rotations containing spring wheat, forage barley, pea, and corn. Soil total N at 0–0.05 and 0.05–0.10 m was 6–7% greater in NT than CT. In a long-term experiment (21 years) in eastern Montana, Sainju et al. (2007) reported that soil inorganic and organic C, particulate organic C, and potential C mineralization at 0–0.2 m were greater in NT continuous spring wheat than fall- and spring-till continuous spring wheat and spring wheat-pea rotation due to greater amount of crop residue returned to the soil. Nitrogen loss after 21 years due to N fertilization rate, crop grain N removal, soil surface residue N, and soil total N at the beginning and end of the experiment was lowest in NT continuous wheat than fall- and spring-till continuous wheat and spring-till spring wheat-fallow rotation (Sainju et al. 2009b). After 30 years, soil bulk density was lower, but organic and inorganic C and total N were 12–98% greater in NT and spring-till continuous spring wheat than spring-till spring wheat-fallow rotation (Sainju et al. 2015a). They also observed that both soil organic C and total N declined linearly with time from their original levels in all treatments, but the rate of decline was lower in NT and spring-till continuous spring wheat.

32.3.2 Soil Biology

Several researchers (Arshad et al. 1990; Staley 1999) have reported increased soil microbial biomass C at 0–0.05 m in NT compared to CT, with similar or lower levels below 0.05 m. Similarly, Franzluebbers et al. (1994, 1995) reported that soil microbial biomass C and N and potential C and N mineralization at 0–0.05 m were greater in NT than CT after 9 years in south-central Texas. Doyle et al. (2004) also found greater microbial biomass C and N and potential C mineralization at 0–0.05 m in NT than CT after 27 years in Kansas. Sainju et al. (2012a) observed that particulate organic C and potential C mineralization at 0–0.2 m were 23–54% greater with NT than CT after 4 years in eastern Montana. In the same experiment, Sainju et al.

(2012b) found that soil total N and microbial biomass N at 0.1–0.2 and 0–0.2 m were 5–41% greater in NT with the regular cultural practice (conventional seed rates and plant spacing, conventional planting date, broadcast N fertilization, and reduced stubble height) than CT with the ecological cultural practice (variable seed rates and plant spacing, delayed planting, banded N fertilization, and increased stubble height).

32.3.3 Aggregation

The NT system has been identified as an important practice to increase soil aggregation and C and N sequestration (Six et al. 1998; Wright and Hons 2005). Tillage is more disruptive of larger than smaller aggregates, making soil organic C and N from larger aggregates more susceptible to mineralization (Cambardella and Elliott 1993; Six et al. 2000). As tillage increases the proportion of microaggregates to macroaggregates, there may be less crop-derived C and N in tilled than NT soils (Six et al. 2000). Impacts of tillage on soil aggregation and organic matter often vary due to variations in soil type, cropping systems, residue management, and climate (Paustian et al. 1997b). Sainju et al. (2009a) reported that, after 21 years, macroaggregate (2.00–4.75 mm) proportion at 0–0.05 m was greater in NT continuous spring wheat than spring- and fall-till continuous spring wheat. Soil organic C and total N in aggregates at 0–0.05 m was 34–42% greater and at 0.05–0.2 m were 20–32% greater in NT and spring-till continuous wheat than spring-till spring wheat-fallow.

32.3.4 Soil Chemical Properties

Differences in residue placement in the soil and removal of nutrients by grains due to variations in crop yields from tillage can affect soil chemical properties. For example, NT increased soil Bray-P and CEC, but reduced K, Ca, base saturation, and pH compared to CT at 0–0.05 m, but the trends reversed at 0.05–0.10 m after 27 years under dryland spring wheat-sorghum-corn-fallow rotation in Nebraska (Tarkalson et al. 2006). Similarly, Lal et al. (1994) found greater cation exchange capacity (CEC) at 0–0.15 m in NT than CT after 28 years in Ohio. Sainju et al. (2011) reported lower soil pH, Ca, and Na contents at 0–0.3 m in NT than CT after 9 years in western Montana. Nitrogen fertilizers applied at higher rates at the soil surface to reduce N immobilization and sustain crop yields in NT can reduce soil pH compared to CT (Lilienfein et al. 2000; Zibilske et al. 2002). Moebius-Clune et al. (2008) observed that NT reduced soil pH, but increased soil organic matter and Mg concentration compared to CT after 32 years in Iowa. Sweeney (2017) reported that soil Bray-P and K concentrations at 0.075–0.15 m were lower in NT than CT, but soil organic matter at 0–0.15 m was not affected by tillage after 20 years in the eastern Great Plains, USA. Sainju et al. (2015b), however, did not observe significant effect of tillage on soil chemical properties in dryland cropping systems even after 30 years in eastern Montana.

32.4 Environmental Quality

32.4.1 Nitrogen Leaching

Tillage can accelerate N mineralization from crop residue and soil organic matter (Legg and Meisinger 1982) and increase accumulation of NO_3-N in the soil profile (Randall 1990; Yadav 1997). The accumulated NO_3-N leaches into the groundwater because NO_3-N is soluble in water and easily moves down the soil profile (Meisinger and Randall 1991). Leaching of NO_3-N occurs usually in the fall, winter, and spring seasons when evapotranspiration is low and precipitation exceeds water-holding capacity of the soil (Chichester 1977; Meisinger and Randall 1991). About 15% of N applied to corn, 20% of root zone, and 68% of non-root zone residual soil NO_3-N leaches to the groundwater in Minnesota and Iowa (Hallberg 1989; Yadav 1997). Several researchers (Tollner et al. 1984; Tyler and Thomas, 1977) have reported that NO_3-N leaching is greater in NT than CT because of the presence of greater number of macropores. High concentration (>10 mg L^{-1}) of NO_3-N in the drinking water is considered a health hazard to people and animals (Phillips et al. 1997). Sainju et al. (1999) reported that 74% of NO_3-N at 0–0.6 m was lost from fall to spring in NT compared to 46–62% in chisel till and moldboard plow. The losses in NT compared to chisel till and moldboard plow were 46% vs. 5–9% at 0.6–1.2 m and 58% vs. 22–26% at 0–1.2 m, suggesting that NO_3-N moved from the 0–0.6 to the 0.6–1.2 m layer and was finally lost to the groundwater. Losses were greater in NT compared to tilled systems.

32.4.2 Greenhouse Gas Emissions

Tillage can also influence greenhouse gas (GHG) emissions. In some soils, NT can increase N_2O emissions compared to CT due to denitrification resulting from higher soil water content, thereby reducing the GHG mitigation potential of NT systems (Robertson 1999). In contrast, N_2O emissions can be similar (Decock 2014) or lower (Mosier et al. 2006; Sainju et al. 2012c) in NT compared to CT in semiarid and arid regions. Reduction in tillage intensity decreases soil disturbance and microbial activity, which in turn, lowers CO_2 and N_2O emissions (Drury et al. 2006; Lemke et al. 1999; Mosier et al. 2006). On the other hand, increased tillage intensity enhances CO_2 emissions by increasing soil aeration, disrupting soil aggregates (Roberts and Chan 1990), and by physical degassing of dissolved CO_2 from the soil solution (Jackson et al. 2003). Sainju et al. (2012c) observed that CT increased CO_2

and N_2O emissions, but had no effect on CH_4 emissions compared to NT, regardless of irrigation practices in western North Dakota, USA.

The overall impact of the NT system on radiative forcing in the earth's atmosphere is calculated by using its net global warming potential (GWP). This accounts for all sources and sinks of CO_2 equivalents from farm operations, N fertilization, chemical inputs, soil C sequestration, and N_2O and CH_4 emissions (Mosier et al. 2006; Robertson et al. 2000). Net GWP can also be expressed in terms of crop yield, which is referred as net greenhouse gas intensity (GHGI) or yield-scaled GWP. The net GHGI is calculated by dividing net GWP by crop yield (Mosier et al. 2006). In the calculation of net GWP and GHGI, emissions of N_2O and CH_4 are converted to their CO_2 equivalents of GWP, which are 298 and 28, respectively, for a time horizon of 100 years (IPCC 2014). Various researchers have shown that both net GWP and GHGI were lower in NT than CT, regardless of soil and climatic conditions and cropping systems (Archer and Halvorson 2010; Mosier et al. 2005, 2006; Ruan and Robertson 2013; n and Grace 2004; Sainju et al. 2014). Increased soil C sequestration rate due to reduced soil disturbance and C mineralization reduces net GWP and GHGI in NT (Robertson and Grace 2004; Robertson et al. 2000; Six et al. 2004). In contrast, increased crop residue incorporation and aeration increases microbial activity, which enhances organic matter mineralization, thereby enhancing net GWP and GHGI in CT (Mosier et al. 2005, 2006; Sainju et al. 2014).

32.5 Challenges and Opportunities of Adopting the No-Till System

Although the NT system has many ecosystem services in sustaining crop yields and soil and environmental quality compared to CT, especially in irrigated and dryland cropping systems in arid and semiarid regions, adoption of the system has been slow in North America. The NT system was first developed in the 1950's, yet only 37% of cropping system in the USA utilized NT in 2017 (USDA 2017). The reasons for this slow adaptation include:

- More herbicide applications are needed to control weeds in NT than CT. Energy saved for not using the equipment for tillage, however, can overcome some of the cost of herbicide application.
- Specialized equipment is needed for seeding crops. This is expensive, and most producers cannot afford to purchase it. Either a government financial incentive is required to use the NT system, or non-profit organizations, such as co-operatives, need to help lease equipment to producers at a reasonable cost.
- The NT system cannot be used for crops, such as sugarbeet, potato, sweet potato, yam, carrot, etc., that grow inside the soil. Harvest of such crops can disturb the soil and therefore affect soil and environmental quality. For these crops, a reduced till system is needed.

- Increased infestations by weeds and pests due to crop residue is a problem. Increased application of pesticides are needed to control the pests.
- The NT system is less effective in enhancing crop yields in the humid region due to increased soil water content that reduces soil temperature and seed germination. This delays seeding dates and reduces yields.
- In humid regions and irrigated cropping systems where crop residue production is high, extra residue needs to be removed for direct seeding of crops in the NT system. This discourages producers from using the NT system for crop production.

Although there are some challenges in adopting the NT system, the system can provide many agronomic and environmental benefits compared to CT. As a result, the NT system should be promoted to reduce soil erosion, enhance the resiliency of the cropping system in a changing climate, and sustain soil health and environmental quality. The NT system can also provide additional economic return in a C-credit market by increasing C sequestration in some regions.

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Chapter 33
No-Till Farming Systems in the Canadian Prairies

William Earl May, Mervin St. Luce, and Yantai Gan

Abstract The Canadian prairies account for about 85% of Canada's arable land. Historically, cropping systems were primarily summer fallow-cereal based, which led to severe soil degradation, loss of productivity, and negative environmental consequences. Efforts were taken by all stakeholders to arrest this grave situation, and one of the key measures was retaining crop residues on the soil surface along with standing stubble to conserve soil moisture and enhance soil organic matter (SOM). This mitigation strategy led to the development of the no-till (NT) cropping system in the Canadian prairies. Adoption of NT in the early years was slow due to limitations of seeding equipment, weed control options, and lack of yield advantage over conventional tillage (CT). Since the 1980s, NT has become a routine practice on the Canadian prairie, and currently is adapted on about 65% of the arable land area. The drastic change is largely due to the development of advanced seeding and harvesting equipment and improved weed control options. Although challenges still remain, for example, the increased prevalence of herbicide resistant weeds, wet seedbed in spring, and excessive crop straw on the soil surface, NT systems have significantly contributed to enhancing economic and environmental sustainability on the prairie. In this chapter, we discuss the evolution of NT in the Canadian prairie and the impacts of the decades of NT adoption on productivity, soil health, and challenges.

Keywords Soil degradation · Crop diversification · Glyphosate · Herbicide resistance

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33.1 Introduction

The Canadian prairies account for about 85% of Canada's arable land, making it the most important agricultural region in the country. Native soils on the prairies contained <1% nitrogen (N), and about 15–40% of this N was lost by the 1940s since the land was first broken about 120 years ago (Mitchell et al. 1944). Soil degradation continued into the 1980s, by which time about 35% of the initial organic N was lost (Voroney et al. 1981). To curb the situation, the Science Council of Canada brought multiple stakeholders together (Science Council of Canada 1986) where strategies to reduce soil erosion, salinity, and soil organic matter (SOM) loss were the top priority. Also, many long-term experiments were established to determine the main causes of soil degradation, including the change in SOM, and develop advanced farming technologies. Concerns about the conversion of the prairie grassland to crop land, and overall agricultural sustainability on the Prairies was also a focus (Shutt 1906; Janzen 2001).

In the earlier days, one of the major limitations in crop production was the lack of weed control options and soil fertility technology that would allow for a change from conventional summer fallow-cropping practices to no-till (NT) systems. Continued summer fallowing gave rise to severe and frequent wind erosion events in the 1930s on the prairie (Montgomery 2007). With progressive research, it became evident in the later part of the 1930s that maintaining crop residues on the soil surface (Fig. 33.1) could improve water infiltration, reduce evaporation losses, decrease surface runoff and erosion, and conserve soil moisture because of the increased ability to trap and hold snow and shield the soil surface from direct sunlight (Smika and Unger 1986). This knowledge led to the development and introduction of one-way discs in the later part of the 1930's. While these one-way discs were suitable for primary tillage, they were less aggressive than the conventional ploughs. Tillage with such equipment left a larger portion of crop residues on the soil surface. Subsequently, seed and fertilizer boxes were installed on the one-way discers, allowing seeding and fertilization together with primary tillage. This type of discer seeders created an opportunity to seed into standing stubble and eliminated fall tillage, and was used extensively until the late 1990's.

Starting in the 1980s, air delivery systems for fertilizer and seed placement in the soil became available, known as "air-seeders". These "air-seeders" represented the start of what is known as "high disturbance direct seeding systems", the precursor to NT systems, providing better penetration, residue clearance, and depth control than discer seeders. The rapidly evolving seeding technologies resulted in the development of "low disturbance direct seeding" equipment, currently known as "air drills" (Hood 1990; Memory and Atkins 1990). With air drills, fertilizer banding in the soil was incorporated into the early generation NT drills and eventually led to the development of the one-pass seeding and fertilizing NT systems. This system involved the placement of the fertilizer to the side and below the seed, or in the mid-row between every second seed row. Air seeder technology created a fundamental transformation in cropping practices on the prairie with earlier seeding and less field

Fig. 33.1 Conventional tillage (top) and no-tillage (bottom) plots showing differences in soil coverage. (Photo taken by Mervin St. Luce in Swift Current, SK)

operation passes, thereby extending the growing season by up to 3 weeks. Other factors key to the NT development included government policies, technology transfer forums, innovative farmers, and the introduction of selective and non-selective herbicides, especially glyphosate.

In this chapter, we discuss the impacts of NT systems on crop agronomy in the past and present based on a large number of studies conducted on the Canadian prairies over the past four to five decades. We summarize the effect of adoption of NT practices on crop productivity, soil health, crop diversification, and environmental sustainability.

33.2 Adoption of No-Till Systems on the Prairies

Soil moisture is critical for crop production in the arid and semi-arid Canadian Prairies. Conventional tillage (CT) was traditionally used for seedbed preparation and weed control (Baan et al. 2009; Maillard et al. 2018). However, CT was shown to enhance soil moisture loss, increase soil erosion, and accelerate SOM loss through decomposition (Campbell et al. 1990; Curtin et al. 2000; Lemke et al. 2012; Maillard et al. 2018). In contrast, studies have shown that maintenance of crop residues on the soil surface (Fig. 33.1) improved water conservation through snow trapping and enhanced water infiltration, reduced soil moisture loss through evaporation and surface runoff (Lafond et al. 2014). Thus, minimum tillage (MT) or NT practices that allow crop residues to remain on the soil surface have increased rapidly over the last three decades. Data from Statistics Canada (2019b) showed that land area in the three prairie provinces (Manitoba, Saskatchewan and Alberta) with NT seeding increased substantially from the 1970s to present and in 2016, 65% of the total land prepared for seeding in the prairie provinces used NT practices.

The adoption of NT was slow in the initial years (Lafond and Fowler 1990; Lafond et al. 2014), largely due to (1) limitations in NT seeding equipment; (2) the presence of excessive crop residues on the soil surface, particularly from cereals; (3) cool soil temperatures in spring; (4) lack of weed control options; and (5) lower than expected profit margins. The excessive crop residues reduced soil drying and also provided challenges for the equipment to seed through the residue while accurately placing seed and fertilizer in the soil. Wet and cool soils can lead to the formation of wheel ruts and compaction, as well as plugged seed runs. Furthermore, while NT reduced labor and fuel costs due to less field operations, increased grain yields and prices were mostly offset by the significant rise in input costs, thereby narrowing the profit margins of NT. With the availability of improved equipment, including straw chopping and spreading equipment on combines and increased yield over the years, the economic advantages of NT were gradually realized. Advancement in herbicide technology, especially the availability of glyphosate, contributed to the rapid adoption of NT systems.

Seedling establishment is a major concern with NT systems. Studies have shown that seedling establishment is either not affected by tillage system (Lafond et al. 1992; Lafond et al. 2006), better under CT than NT (Carter and Rennie 1985b; Lafond et al. 1992; Lafond et al. 2006) or vice versa (Tessier et al. 1990). Greater plant heights were reported under NT than CT, reflecting improved surface (0–30 cm layer) soil water (Lafond et al. 2006). Although soil temperatures are typically cooler under NT than CT (Gauer et al. 1982; Carter and Rennie 1985a; Wang et al. 2007), which may delay seedling emergence, the shallower seeding in NT than CT systems provides a means of overcoming potentially low soil temperatures under NT (Lafond et al. 1996; Gan et al. 2002). In addition, the soil temperature difference between NT and CT appears to be dependent on the amount of stubble residue on the seed row and the height of stubble between the seed rows (Carter and Rennie 1985a; Arshad et al. 2002; Cutforth et al. 2006). Hoe type openers move a lot of residue off the seed row and this might be part of the reason for their success and popularity. Moreover, NT can mitigate heat shock and reduce root heat stress during the growing season, leading to higher grain yield and biomass production (Wang et al. 2007).

33.3 Impact of No-Till Systems on Crop Productivity

In one of the first studies on the Canadian prairies to examine conservation tillage practices, Lindwall and Anderson (1981) found higher spring wheat (*Triticum aestivum* L.) yields after fallow for NT than CT in a Dark Brown Chernozem. In a later study in a Dark Brown Chernozem, Brandt (1992) reported higher spring soil moisture in most cases for NT than CT, more so on fallow than stubble, and predominantly higher crop yield for NT than CT. A study on a Black Chernozem (heavy clay soil) showed that NT and MT increased soil water by 9% and 6% in the 0–0.6 m and 0–1.2 m soil layers, respectively, over CT (Lafond et al. 1992), leading to 9 to 23% yield increases in spring wheat, flax (*Linum usitatissimum* L.), and field pea (*Pisum sativum* L.) (Lafond et al. 1992). In contrast, in the Brown soil zone of the semi-arid region, McConkey et al. (1996) found no real advantage of NT or MT over CT on spring wheat yield, while Gan et al. (2003) reported lower pulse crop yields on NT than on CT. Hence, in the past, there was little short-term economic incentive for producers in the semi-arid region to adopt conservation tillage practices, due to the lack of yield advantage of NT or MT over CT and higher herbicide input costs (Zentner et al. 1996).

More recent studies have shown agronomic, economic, and environmental benefits of NT compared to CT, where results depended on several factors including soil type, moisture availability, and NT duration. Higher crop yields under NT than CT are predominantly attributed to better soil moisture conservation and reduced soil water evaporation (Grevers et al. 1986; Soon and Arshad 2004; Malhi and Lemke 2007; Soon et al. 2008). Field pea, flax, and spring wheat yield on cereal stubble on a Black Chernozem was increased by 7%, 12.5%, and 7.4%, respectively, with NT and MT over CT due to an increase in soil water content in the 0–0.3 m soil depth, with water use efficiency of flax being 10% greater with NT and MT than CT (Lafond et al. 2006). In relatively dry years, or years with below-average precipitation on a Grey Luvisol, NT produced significantly higher barley (*Hordeum vulgare* L.) and canola (*Brassica napus* L.) grain yield than CT, particularly where straw was retained, but the reverse was true for spring wheat and canola yield in years with above-average precipitation (Malhi and Lemke 2007). However, Arshad et al. (1998) reported higher grain yield for CT than NT in a Dark Gray Luvisol. Malhi and Lemke (2007) reported that soil moisture content was 1.5% and 1.9% higher in the 0–0.15 m and 0.15–0.30 m depth, respectively under NT than CT. Due in part to soil moisture conservation and build-up of SOM, NT soils may have higher mineralization potentials and net N mineralization than CT soils (Soon and Clayton 2003; Sharifi et al. 2008). This may sometimes contribute to higher crop yields for NT than CT. Conversely, lower wheat yield under NT than CT was associated with greater N immobilization and slower N mineralization from SOM due to less soil disturbance and protection from microbial access within undisturbed soil aggregates (McConkey et al. 2002; Soon and Clayton 2003). Decomposition of crop residues is greatly reduced when left on the soil surface under NT compared to being incorporated in soils under CT (Curtin et al. 2000). Also, greater denitrification and volatilization from excess water (Aulakh et al. 1984), and possibly greater NO_3-N leaching may occur under NT due to a continuous pore system (Izaurralde et al. 1995). In addition, low soil temperatures under NT may delay soil microbial activities at the start of the growing season.

The moisture differences between NT and CT not only influences crop yields, but also nutrient availability, crop response to applied fertilizers, and nutrient uptake. Malhi and Lemke (2007) reported a greater response of barley yield to increasing N fertilizer rate under NT than CT. In an earlier study in the same region, Malhi and Nyborg (1990) noted that barley yield and N uptake were lower under NT than CT at low N rates, but at higher N rates, yield and N uptake were similar or higher for NT than CT at optimum N rates. Lafond et al. (2011) observed 14% and 16% more spring wheat and canola grain yield, respectively for long-term NT than short-term NT due to higher N cycling rates under long-term NT, and the authors concluded that NT production systems will increase soil productivity over time, enhance system resilience, and lower production risks. Due to the retention of crop residues at the soil surface, the major reduction in soil disturbance between the 0–0.1 m soil depths, the near elimination of soil disturbance below 0.1 m, and the placement of fertilizer between 0.02 and 0.1 m below the soil surface, the increased concentration of nutrients, especially N and P, in the 0–0.075 and 0–0.15 m segment of soil profile is a major concern (Lupwayi et al. 2006b; Baan et al. 2009; Helgason et al. 2010; Malhi et al. 2011a), with implications for nutrient cycling, soil testing, and nutrient losses through runoff (Soon and Clayton 2003; Lupwayi et al. 2006a; Cade-Menun et al. 2015). Reduced tillage was shown to reduce cadmium contents in durum wheat (*Triticum turgidum* L.) grains and increase grain yields compared with CT in three of four site-years on an Orthic Black Chernozem in Manitoba (Gao and Grant 2012).

33.4 Impact of No-Till Practices on Soil Health

Soil health can be defined as the capacity of a soil to function as a vital living system to sustain plant and animal productivity and health, and maintain or enhance environmental quality (Doran and Zeiss 2000). The concept of soil health, which one could argue is related to soil quality, a term widely used in the past, is gaining much attention because healthy soils are critical for long-term agroecosystem sustainability and resilience. Soil health encompasses soil biological, chemical, and physical properties, with a greater focus on soil biology in the past few years. Although there is no standardized soil health test available for the Canadian prairies, numerous studies have focused on the impact of management practices, including tillage, on various soil health indices. No-till practices can have significant impacts on soil health indices as they alter soil moisture and temperature, crop residue placement and distribution, and nutrient cycling. Although SOM**,** soil organic carbon (SOC), and total soil N (TN) are integral components of soil health, it may take several years, or even decades, to observe measurable differences between NT and CT for these indices. In an 11 year study in the semi-arid region of southwestern Saskatchewan, Shrestha et al. (2013) found similar SOC content between NT and MT in the 0–0.15 m depth. Other studies also reported no differences in SOC or TN content between NT and CT (Campbell et al. 1998; Malhi and Lemke 2007). However, higher SOC and TN under NT than CT were measured in others (Larney et al. 1997; McConkey et al. 2003; Liang et al. 2004; Campbell et al. 2005; Maillard et al. 2018). After 11 years of NT, SOC content (0–0.15 m depth) increased by about 4 Mg C ha^{-1} relative to CT (Campbell et al. 1996). A review by Campbell et al. (2005) highlighted that SOC gains under NT were higher than under CT, being about 250 kg ha^{-1} $year^{-1}$ higher in the semi-arid Canadian prairies irrespective of cropping frequency, while in the sub-humid Canadian prairies, it was 50 kg ha^{-1} $year^{-1}$ for systems with fallow but 250 kg ha^{-1} $year^{-1}$ for continuously cropped systems. In addition to the heterogeneous nature of SOM, the lack of tillage effect on SOC and TN could be due to several factors, including the failure of tillage to affect crop residue production, the depth of tillage in the case of CT, initial SOC and TN content, cropping system used (e.g., fallow vs. continuous cropping), and site-specific conditions such as texture (Nyborg et al. 1995; Larney et al. 1997; Campbell et al. 1998; Janzen et al. 1998; Curtin et al. 2000; McConkey et al. 2003; Campbell et al. 2005; Maillard et al. 2018).

Responses to management-induced changes, such as tillage, are predominantly detected in the more readily decomposable, dynamic and labile forms or quality attributes (Janzen et al. 1998). For example, while tillage had no effect on SOC and TN content at 0–0.15 m in a Gray Luvisol, Malhi et al. (2006) found higher light fraction organic C (LFOC) and N (LFON) under NT than CT. On a Black Chernozem, Malhi et al. (2008) also found higher LFOC and LFON under NT than CT, however Malhi et al. (2011b) observed higher LFOC and LFON under CT than NT. Campbell et al. (1998) found higher microbial biomass C (MBC) and N (MBN) at 0–0.075 m under CT than NT after 12 years in a silt-loam soil in the semi-arid Canadian prairies. In contrast, higher MBC and MBN were observed under NT compared to CT (Lupwayi et al. 1999; Soon and Arshad 2004). In a study conducted across western Canada, NT was shown to enhance MBC and functional diversity over CT in the rhizosphere in 4 and 5 of 18 site-years, respectively, and 3 and 4 site-years in bulk soil (Lupwayi et al. 2010). Tillage had little impact on LFOC at the 0–0.075 m depth in the Brown and Dark Brown Chernozem soil zones, but significantly decreased LFOC in the Black Chernozem soil zone (Liang et al. 2003). Soil structure can also be impacted by tillage. Several studies reported better aggregate stability (most frequently measured as mean weight diameter) under NT than CT (Malhi et al. 2006; Malhi et al. 2008). Studies also reported lower soil hydraulic conductivity and bulk density under NT than CT (Malhi et al. 2008), while the reverse was true in others (Singh et al. 1996; Singh and Malhi 2006).

Soil microbial diversity and function are integral to sustainable and resilient cropping systems, as microbial-mediated processes support nutrient cycling and other important aspects in cropping systems. Lupwayi et al. (1998) found greater bacterial diversity in NT than CT in the 0–0.075 m depth on a Gray Luvisol, indicating that conservation tillage can support microbial diversity and influence the long-term sustainability of agroecosystems. In a study conducted across four tillage trials located in four different soil zones on the Canadian prairies, with the exception of one site, Helgason et al. (2009) found 8–202%, 26–58% and 0–120% higher total microbial biomass, bacterial biomass, and fungal biomass, respectively, at the soil surface (0–0.05 m) under NT than CT. Hence, while fungal dominance is usually assumed under NT, both fungal and bacterial biomass increased under NT in these soils (Helgason et al. 2009). In a subsequent study, Helgason et al. (2010) found consistently higher microbial biomass at the surface of NT than CT soils but found NT-induced shifts in their relative abundance, except at the driest site (Swift Current). At this semi-arid site, arbuscular mycorrhizal fungi (AMF) was higher under NT than CT while gram positive bacteria was the reverse. This observation at Swift Current was linked to lower crop productivity, crop residue inputs, and decomposition rates resulting from moisture limitations (Helgason et al. 2010). Hence, crop rotation, the quantity and quality of crop residues, soil texture, and environmental conditions may sometimes have a more dominant effect on soil health attributes than tillage system.

33.5 Opportunities of Implementing No-Till Systems on the Canadian Prairie

A significant enhancement with NT technology is fertilizer application. Currently, there are two major configurations for fertilizer application – side banding and mid-row banding. In a side banding, fertilizers are placed in the seed row or in a fertilizer band that is to the side and below the seed. The side banding unit and seed opener are typically on different shanks allowing the operator to independently adjust the depth of the fertilizer band and seed row. In a mid-row banding, the majority of the N is placed in a band between two seed rows and the band is placed in every second spacing between the rows. The phosphorus (P) and potassium (K) fertilizers are usually placed in the seed row. There are some seeder configurations that allow growers to divert some of the P and K fertilizer to the mid-row band if they are concerned that the amount of P and K fertilizer to be applied would damage seed germination and seedling emergence if placed in the seed row. The hoe opener is the most common opener due to its ability to be effective in different environmental conditions. The popularity of the low disturbance disc type openers is more prevalent in the southern regions, where the more semi-arid to arid conditions exist.

The second significant change with the NT system is the implementation of crop diversification using annual pulse crops such as dry pea, lentil (*Lens culinaris* Medik), chickpea (*Cicer arietinum* L.), and fababean (*Vicia faba* L.), as well as oilseeds such as canola (*Brassica napus* L.), mustard, and the other Brassica species. These crops are typically planted between the rows of standing cereal stubble from the previous years (Fig. 33.2). Annual pulses, especially dry pea and lentil, have a shallower rooting depth (Liu et al. 2011) and use less soil moisture than deep-rooting crops like cereals (Wang et al. 2012). With direct seeding into standing cereal stubble, these crops tend to grow taller (Cutforth et al. 2011), mature earlier (Gan et al. 2009), and facilitate a straight combine (Gan et al. 2016). The implementation of NT technology has allowed diversified crop rotations to replace conventional fallow-based monoculture systems on the Canadian prairies (Gan et al. 2010). Many studies have shown that crop diversification with NT management offer many benefits, including (i) enhancing carbon conversion from atmospheric CO_2 to plant biomass, thus, increasing crop productivity (Gan et al. 2014); (ii) enhancing system resilience and robustness (Li et al. 2019), and improving the resistance to biotic stresses due to weeds and diseases (Beckie et al. 2008; Harker et al. 2013, 2015); (iii) improving fertilizer use efficiency (St. Luce et al. 2016) and lowering N_2O emissions (Malhi et al. 2010); and (iv) optimizing soil microbial community structure and functionality to improve soil health (Bainard et al. 2016; Hamel et al. 2018; Niu et al. 2018).

Fig. 33.2 Lentil was no-till planted between the rows of standing cereal stubble, a typical no-till pattern adapted on the Canadian prairie. (Photo taken by Yantai Gan in Swift Current, SK)

33.6 Challenges of Implementing No-Till Systems on the Canadian Prairie

One challenge facing NT cropping systems in the Canadian prairies is the emergence of herbicide resistant weeds since the NT cropping system does not use tillage to manage weeds. All producers in any cropping system will have to improve their cultural management of weeds to address the issues surrounding the control of herbicide resistant weeds. For example, in a recent survey in Alberta determining the distribution and abundance of multiple-resistant [acetolactate synthase (ALS) inhibitor, glycine, and synthetic auxin] kochia (*Bassia scoparia* L. Schrad), researchers found that all populations were ALS inhibitor resistant, with glyphosate and dicamba resistance confirmed in 50% and 18% of populations, respectively (Beckie et al. 2019). The predominate weed species often shift when a cropping system is changed from CT to NT, although overall weed densities may decline with time (Blackshaw 2005; Hansen et al. 2017). The shift towards perennial weeds in NT also presents a specific problem in pea and lentil pulse crops. Perennial weeds such as dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers),) Canada thistle (*Cirsium arvense* L. Scop.), and perennial sow-thistle (*Sonchus arvensis* L.) require herbicide applications in the fall for effective management. A pre-harvest application of glyphosate is a very effective approach in controlling perennial weeds. Unfortunately, with the frequent use of glyphosate as a slow desiccant on a large number of crops in western Canada and with the occasional application at the incorrect stage of plant development, problems are arising with its future use and effectiveness. If a desiccant is used to dry down the weeds so the crop can be combined, there may not be enough green weed tissue left for a post-harvest application of glyphosate to be effective.

While NT is more effective at capturing, storing and maintaining soil moisture than CT or MT (Brandt 1992; Lafond et al. 1992; Halvorson et al. 2019), capturing too much water may delay seeding, reduce germination and stunt growth since the soil may be saturated. The use of intermittent tillage by producers in the highest precipitation regions of the prairies appears to be directly related to this issue. In fact, when recent precipitation levels were above average for a large portion of the prairie region for several years, the amount of intermittent tillage observed increased. Improving the NT cropping system in areas that are more concerned with excess moisture than a moisture deficit is a major challenge facing the continued expansion of the NT production system on the Canadian prairies.

In Saskatchewan the number of farms cropping more than 1400 ha is growing (Statistics Canada 2019a). Average farm size in Saskatchewan has increased from 470 ha in 1996 to 725 ha in 2016; the number of farms that are bigger than 2000 ha and 4000 ha were not captured in the census. In a study on land ownership and concentration, the four top land owners owned between 16–28% of the land in the three rural municipalities studied (Desmarais et al. 2015). At least two of these four entities were family farms in each rural municipality. The size of the rural municipalities studied ranged from 80,000–112,000 ha which puts the size of the largest farms in the 5000–7500 ha. With increased farm size, logistics becomes critical to the success of the farm. The quality of the agronomic practices being used can decrease as producers focus on saving time. Computers combined with sensors and different imagery are now commonly used by producers to increase the intensity of their management to a scale even smaller than one field. The development of self-guided equipment may ultimately determine the level of agronomy used in NT cropping systems in the future.

Currently there is a growing list of ideas on how to improve the environmental sustainability of our NT cropping system including, cover crops, organic farming, reduced inputs, and new crops that are more efficient in utilizing resources. Some of these ideas may lead to large improvements in environmental and economic sustainability of agriculture; however, these ideas may reduce the support and understanding of the critical importance of the NT cropping system to the sustainability of agriculture on the Canadian prairies. There should be a tendency to incorporate these new ideas and approaches into a NT cropping system, but that is not always the case.

33.7 Summary

The adoption of NT on the Canadian prairies was not quick or easy. It was the result of an awareness of the dramatic loss in yield potential and environmental damage, as well as the willingness of governments, non-profit organizations and individuals to do something about this problem. This was followed by technological advancements that were implemented to successfully develop a NT cropping system. Currently, the NT cropping system is a dominant and successful cropping system on the Canadian prairies. In order for NT to continue to be used successfully into the future, we will need to adapt the system to deal with problems as they arise and to combine it with new ideas and approaches that will further improve the economic and environmental sustainability of the farming system of this region of the world.

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Part VI
Perspectives

Chapter 34
No-Till Farming Systems for Sustaining Soil Health

Donald C. Reicosky

Abstract Agriculture in the next decades will have to produce more food on less land and purchased production inputs by making more efficient use of natural and applied resources. The practice of no-tillage (NT) is briefly described and its effect on physical, chemical, and biological properties and processes and how these led the transition from NT only to biodiverse and regenerative NT or Conservation Agriculture (CA) systems is discussed. No-tillage initially evolved as a way of reducing severe soil erosion associated with intensive tillage and favorably impacted soil properties. Further development of NT to also incorporate the use of stubble retention, diversified crop rotations, and cover crop mixes have transitioned us to CA with a wide range of agro-environmental benefits. The positive impact of NT lies in improved carbon (C) management and enhanced aggregate stability that provides for erosion control, more infiltration, and less runoff. The regenerative benefits of minimum soil disturbance, permanent mulch cover, and diversified cropping on yield are best obtained through enhanced C management for climate extreme mitigation and food security.

Keywords Minimum soil disturbance · Mulch cover · Soil carbon · Soil health · Systems · Temporal trends · Biodiversity · Cover crops

34.1 Introduction

Tillage has been an integral to crop production for more than 10,000 years (Lal et al. 2007). However, tillage can result in soil erosion and degradation of soil, water, and air quality which may negatively impact the environment and our food security.

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This paper is a brief review of the development and evolution of no-tillage (NT) systems and their effect on physical, chemical, and biological soil properties and their positive impact on soil health. A secondary objective encompasses the transition from NT practices to biodiverse and regenerative Conservation Agriculture (CA) systems.

34.2 Definition of no-Tillage (NT)

No-tillage (NT), also referred to as zero-till (ZT) or direct seeding (DS), evolved originally as a method of reducing severe erosion associated with intensive tillage. Following Eagle et al. (2012), this review treats NT/ZT/DS as a separate activity representing the minimum soil disturbance required to insert the seed. As NT has evolved over the last 40 years into NT systems farming or CA, it has also grown to include stubble retention and species diversification. No-tillage/zero-tillage is not included under the umbrella term ‘conservation tillage’, which is taken more narrowly to denote a wide range of tillage practices (Corsi et al. 2012; Reicosky 2015). Qualitative terms such as “conventional tillage” (CT), reduced tillage, minimum tillage, etc. are highly problematic; and a more quantitative approach should be considered. To some, NT simply means no plow. A true NT system implies continuous minimum soil disturbance. There is a lack of attention to detail on the tillage and planting equipment used in methods and materials of many research studies, which often do not differentiate between conservation tillage, reduced or minimum tillage, and NT and the use of a minimum soil disturbance NT planter (Baker et al. 2007). As a result of this confusion, it is difficult for authors to differentiate between the studies that meet the “minimum soil disturbance” criteria in CA.

34.3 No-Tillage Effects on Soil Properties

The NT system, leaving the residues on the soil surface with no mechanical mixing of residues and added amendments, will provide a positive modification of soil biological, chemical, and physical properties as compared to plowed soils (Fig. 34.1). A summary of these effects is provided below.

34.3.1 Physical

Aggregation is important for soil structure and functioning, providing physical protection of C and microbial inhabitants destroyed by intensive tillage. Soil structure is stabilized by a variety of different binding agents; however, soil organic matter (SOM) is a primary factor in the development and modification of soil structure

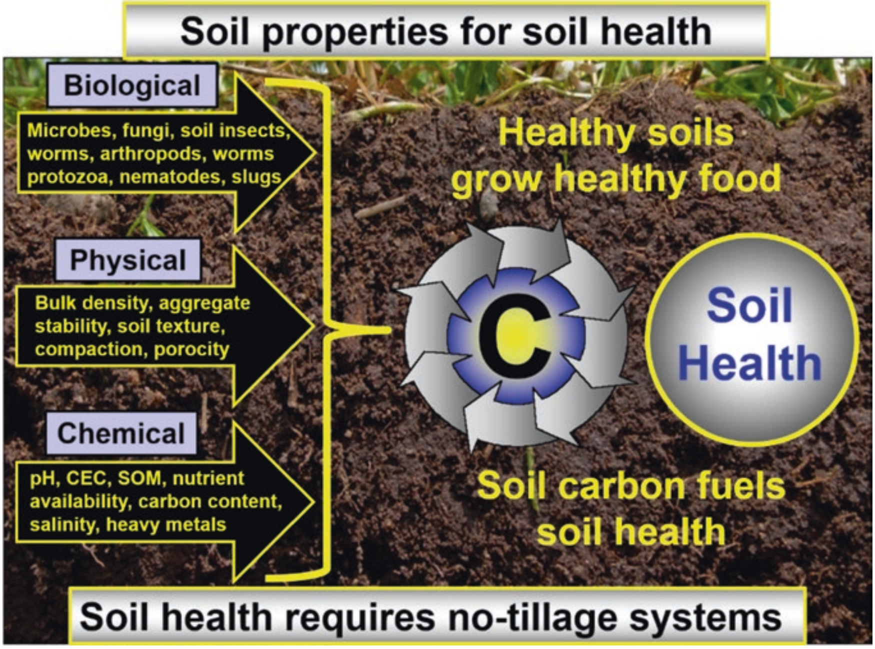

Fig. 34.1 Soil properties impacting carbon management require no-tillage systems for optimum soil health (pH = LOG_{10} Hydrogen ion concentration; CEC = Cation Exchange Capacity; SOM = Soil Organic Matter)

(Kay, et al. 1997; Lal 2015a). Consequently, where increases in SOM are observed under NT systems these have also been associated with improved soil aggregation. For example, Rhoton et al. (1993) conducted a 15-year study on four soils with different textures in four different areas southeast US. Aggregate stability was higher under NT than CT in all soils.

Where NT systems also include practices such as cover cropping, further improvements are also observed. For example, different cover crops, both cereal and legumes, have been shown to improve soil aggregation (Olchin et al. 2008; Finney et al. 2017). However, where NT does not lead to overall increases in profile SOM, improvements may not be observed. For example, Olchin et al. (2008), evaluated tillage-induced influences on aggregate structure, residue-derived C stabilization, and the subsequent efficiency of C stabilization in aggregates of NT and tillage management (TM) (stubble mulch) practices at different depth increments. The negative impact of aggregate disruption through tillage appears counterbalanced with similar efficiencies of C stabilization between the NT and TM practices, possibly due to slower decomposition of residues deeper in the profile (Kumar et al. 2012).

As well as increases in aggregate stability, the increase in soil C content increases soil water retention (Hudson 1994; Rawls et al. 2003; Murphy 2015; Basche and Edelson 2017). Soil organic matter high in C in the form of ‘spongy organic matter’ that releases nutrients to crops on decomposition and holds more than its own weight in water provides resilience in both wet and dry periods. The formation of soil aggregates is possible via the synergistic interactions between plant roots, root exudates, fungal hyphae, and microbial extracellular polysaccharides and proteins that help ‘glue’ soil particles into various sized aggregates (Six et al. 2006), essential for erosion resistance, microbial habitat, and air and water flow. Nouri et al. (2019) found long-term (34 years) incorporation of cover crops in NT significantly improved the infiltration rate, and field-saturated hydraulic conductivity and increased the mean weight diameter of aggregates by promoting the macro-aggregation. Improvement in soil physical properties was associated with an increase in cotton lint yield under cover crop and NT management.

34.3.2 Chemical

Healthy soils are characterized by a diverse and active community of organisms that maintain and drive key chemical ecosystem functions, mainly C and nutrient cycling (Tully and Ryals 2017). The soil is a ‘biochemical or nutrient reactor’ that absorbs, releases (i.e. desorbs), and transforms organic and inorganic and biochemical compounds, including toxic metals. Carbon serves as a chemical buffer against changes in pH and C is being recycled while recalcitrant C in many forms provides chemical stability for the soil system.

A comparison of the long-term trends between NT and CT on a at the University of Kentucky is described in the works of Blevins et al. (1977); Blevins et al. (1983); and Ismail et al. (1994) who compared the effects of 5, 10, and 20 years of continuous NT and CT of corn (Zea mays, L.) on certain chemical and physical properties of the soil. After 5 and 10 years, neither tillage treatment or N treatment had a statistically significant effect on soil bulk density in the 0–0.15 m layer. After 20 years (Ismail, et al. 1994), soil organic carbon (SOC) and N; extractable P; exchangeable Ca, Mg, and K; and pH were significantly higher with NT than CT in the 0–0.05 m depth. They concluded changes in SOM content, with their many ramifications, are probably the most important long-term effects of tillage differences on soil properties.

34.3.3 Biological

The “living soil” is full of bacteria, fungi, algae, protozoa, nematodes, and many other fragile creatures affected by intensive tillage. By modifying soil structure and microclimate, tillage exerts the most important control on soil microbial communities and reflects a fundamental shift in care for our soils. Zuber and Villamil, (2016), evaluated the impact of tillage methods on soil microbial biomass and enzyme activities using a meta-analysis. Overall, microbial biomass and all of the enzyme activities were greater under NT compared to any other tillage type. They found greater enzymatic unity in all NT treatments and concluded that NT, and some reduced tillage, promote larger microbial communities and greater enzymatic activity. Soil C and N indicators were most effective at separating rotation and tillage effects (Zuber et al. 2017).

Tillage negatively affects fungi more than other microorganisms, such as bacteria, because of the physical severing of the hyphal mat or strands that can form after long periods with little disturbance (Six et al. 2004). In NT systems, a higher proportion of fungal decomposers are found, while tilled/cultivated systems favor higher populations of bacterial decomposers. Overall biological activity also tends to be higher in NT systems as indicated by greater CO_2 output from NT compared to CT soils (Hendrix et al. 1990). Jiang et al. (2011), concluded that tillage regulated microbial communities by changing aggregate size distribution.

Tillage management influences microbial community structure within aggregates and may provide a potential explanation for differences in process rates observed in NT v CT soils over the longer-term. Wright et al. (1999) demonstrated a linear relationship between aggregate stability and glomalin, a glycoprotein produced by arbuscular mycorrhizal fungi (AMF), studied during the first 3 years in transition from moldboard plow (MP) tillage to NT maize. This further increased up to 15 years and suggests that plant roots and NT management may have a synergistic effect on glomalin production and aggregate stabilization.

Beare et al. (1994) have also shown that fungal densities and fungal-mediated binding of soil macroaggregates are considerably greater in NT than in CT soils. It is likely that a fungal-dominated microflora produces binding agents that differ chemically from those of other microbial communities, and these differences probably influence their biodegradability. In addition, fungi have higher C assimilation efficiencies and higher C:N ratios than do bacteria (Holland and Coleman 1987), factors that would be expected to lower the C:N ratios of mineralizable SOM and increase the C:N ratios of whole-soil C in fungal-dominated soils of NT.

Tillage creates a priming effect for some microbes with the destruction of the network structure of the mycorrhizal fungi and micro arthropods (Kuzyakov 2010), in addition to letting more oxygen into the soil to stimulate the heterotrophs (Reicosky and Lindstrom 1993). In summarizing the effects of NT on soil fauna, Kladivko (2001) concluded that the larger species are more vulnerable to soil cultivation than the smaller. A review of 45 studies of tillage and invertebrate pests (Stinner and House 1990) showed that for the investigated species, 28% increased with decreasing tillage, 29% did not change with a tillage system, and 43% decreased with decreasing tillage. Reduced populations under CT are likely due, in part, to physical disturbance and abrasion from the tillage operation itself, but the reduction in surface residue cover is probably more significant. Chenu et al. (2019), who reviewed the prominent role of soil microorganisms in the stabilization of SOM, drew the attention to more exploratory potential levers, through changes in microbial physiology or soil biodiversity induced by NT agricultural practices, and concluded that more in-depth research is required.

34.3.4 Temporal Changes in Soil Properties

Soil systems are very complex possessing of a great number of properties related to or correlated with independent variables commonly called “soil-forming factors” that include climate, organisms, topography, parent material and time, with all the properties of the soil system functionally interrelated (Jenny 1941). Depending on one’s perspective, the “time” factor presents major challenges because changes in soil properties can range from nearly instantaneous to geologic time intervals. Soils are fragile and provide many ecosystem functions important to our existence; unfortunately, new soil formation is a very slow geologic process, taking 700–1500 years to form 25 mm of soil (Montgomery 2007b).

Soil erosion is still a major problem in agricultural production systems caused by tillage; soil that is loosened by tillage is more easily transported by the tillage operation and wind or water. Efforts to control land degradation and soil erosion can be traced over the last 10,000 years, humankind has been building on the ruins of the old tillage and monoculture concepts at our peril (Lal et al. 2007; Montgomery 2007a, b). Montgomery (2007b) describes the effect of poor soil management and erosion on several past civilizations and shows that with CT agriculture we are losing soil faster than nature can make it. Several once thriving civilizations eventually collapsed due to erosion, salinization, nutrient depletion, and other types of soil degradation.

Stockfisch, et al. (1999), found after 20 years of minimum tillage (shallow cultivation restricted to stubble cleaning and seedbed preparation, using a rotary harrow or rototiller), a single mouldboard plow (MP) tillage decreased the SOM in one year and negated the previous cumulative beneficial changes in SOM. In contrast, Quincke et al. (2007a, b) found that one-time MP tillage of 10 years of NT can be done without loss of SOC, soil aggregate stability, or grain yield during the 2 or 3 years following the tillage. Wortmann, et al. (2010) concluded that 5 years after a one-time tillage there was no measurable effects on yield or soil properties. The absence of a one-time tillage effect may suggest a resilient system, or that the organisms recovered in a shorter time interval then measured and further research on the time response of the organisms to a perturbation is needed. Considering NT enhanced both microbial functioning and C storage in soil, Mangalassery, et al. (2015), suggested that NT offers significant promise to improve soil health and support mitigation measures against climate change.

The long-term responses of soil microbial processes and community structure to perturbation constitute one critical aspect of soil health. Dimassi, et al. (2014) reported SOC measurements at time 0 and every 4 years out to 41 years and showed that tillage or crop management had no significant effect on SOC stocks both in the old ploughed layer (ca. 0–0.28 m) and deeper (ca. 0–0.58 m). Their results indicated that C storage rate was positive in dry periods and negative in wet conditions and that tillage had no effect on crop yields and residues. Daigh et al. (2018) evaluated tillage-treatment (chisel plow (CP) v NT) durations from eight to 51 years in the Midwestern U.S. Corn Belt and concluded that tillage had no significant effect on long-term crop yields, with a few exceptions. However, NT had significantly lower range of relative yields across the variable-weather years as compared to CP for the corn-corn system and corn-soybean phase. These direct and synthesized data provide evidence of little to no yield differences between CP and NT managed corn/soybean research plots. Nunes et al. (2018) assessed the long-term impacts of continuous (20+ years) NT in comparison to plow-till (PT) management on soil properties and corn (Zea mays L.) yields. The effects of tillage were assessed in combination with different cropping systems. Soil managed under long-term NT showed the most favorable soil biological, physical, and chemical conditions for plant development, with higher levels of SOM, protein, respiration, water aggregate stability, total N, P, Zn, and infiltration rate. Zuber et al. (2015), studied the effect of rotation and tillage on soil physical and chemical properties on two productive soils. After 15 years, bulk density (BD) under NT was 2.4% greater than under CT. Similarly, SOC and total nitrogen (TN) were slightly greater under NT than under CT.

Soil perturbations may alter soil microbiology, metabolic processes, biogeochemistry, and gaseous fluxes. Jackson et al. (2003) indicated that CO_2 emission was high for the first day after tillage, but respiration declines or remains constant, suggesting that physical soil fracturing processes are responsible for the high flux from the soil surface. Tillage caused immediate changes in microbial community structure, based on phospholipid fatty acid (PLFA) analysis (Calderon, et al. 2001), but little concomitant change in total microbial biomass. Jackson et al. (2003) showed that tillage causes short-term changes (2 days) in nutrient dynamics that may potentially result in N losses through denitrification and nitrate leaching, as well as C losses through degassing of dissolved CO_2. These changes are accompanied by naturally associated shifts in microbial community structure, suggesting a possible relationship between microbial composition and ecosystem function.

34.4 Critical Role of Cover Crop Diversity

In addition to the absence of tillage and retention of residue on the soil surface, integrating greater cropping diversity within NT systems contributes to numerous economic and environmental benefits (Liebig et al. 2014; Lal 2015a; Poeplau and Don 2015; Basche et al. 2016; Dudley and Alexander 2017). The greater the range of plants grown, in mixtures or in sequence, the more varied the biodiversity of organisms above-ground and inhabiting the rooting-depth, and the greater the competition that can suppress those detrimental to root function and thus be considered weeds/pests. Diverse crop rotations will further interrupt the infection chain for diseases and may have other pest-repellent and -suppressing characteristics (Stirling et al. 2016). Diversified cropping patterns that minimally incorporate at least three plant species, including one legume, are suggested (Chatterjee et al. 2016). To incorporate more diversity, some farmers simultaneously use 10–14 species in cover crop mixes in the same field (Liebig et al. 2014). Legume cover crops in combination with CA have been beneficial in N accumulation and protecting the soil

(Mitchell et al. 2019). Cover crops can be managed to improve soils through biodiversity input and increased aggregate stability, which helps to (i) increase soil water infiltration and reduce erosion; (ii) improve nutrient cycling and water quality, due to keeping nutrients in the field for increased biological activity; and (iii) improve the control of diseases and pests (Basche et al. 2016; Dudley and Alexander 2017). The previous research demonstrates the health of soil organisms depends on minimum soil disturbance and C input from diverse cover crop mixes, as supported by recent reviews (Jarecki and Lal 2003; Schipanski et al. 2014; Chu, et al. 2017; Kaye and Quemada 2017; Finney et al. 2017).

34.5 Enhanced Soil Properties Lead the Transition to NT Systems/Conservation Agriculture

No-tillage is looked upon by many as a way to enable sustainable cropping intensification to meet conservation ethics and future agricultural demands with initial emphasis on minimizing soil erosion (Montgomery 2007b). The more coherent and complex concept of NT systems or CA, which also incorporate a diversity of crop rotations, has evolved from the practice of NT alone. Although NT suggests merely the absence of tillage, the impact of NT is maximized when combined with the retention of crop residues, increased diversity of crop rotations, and cover cropping that leads to NT or CA systems with equal or higher yields, decreased input costs, and better environmental performance than with CT systems (Friedrich, et al. 2012; Friedrich, et al. 2014; Lal 2015b; González-Sánchez, et al. 2017; Reicosky and Janzen 2018; Mitchell et al. 2019). Multiple species cover crops, in particular, are required for maximum photosynthesis and C capture to nurture the living soil organisms. Integration and synchronization of these fundamental principles enhances the development and functionality of crops' root systems as a consequence of an increased depth and more regular water and nutrient uptake (Chu, et al. 2017). No-till or CA systems have spread rapidly into other regions of the world, and now have become a global agricultural movement (Kassam, et al. 2018).

Although the suitability of NT systems or CA for smallholder farmers in developing countries (e.g. Giller et al. 2009) and in Australia (Kirkegaard et al. 2014) had been questioned, it was not until a study in Nature by Pittelkow et al. (2015) that debate over yield impacts did the relevance of meta-analysis surface. Pittelkow et al. (2015) describe their work as a 'global meta-analysis' which included 5463 yield comparisons from 43 crops across 63 countries with a robust methodological approach. Measured across all data, they concluded that NT (defined as an absence of tillage, and not necessarily including residue retention/ species diversification) lowers yields by an average of 5.7% relative to tillage for a variety of crops, although positive effects were found in more arid climates when rotations and residue retention were applied. Indeed, across climates and observations, the addition of rotations and residue retention to NT reduced yield loss to 2.5%. The article also revealed that combining NT with the other two CA principles of residue retention and crop rotation, minimized its negative impacts and in rainfed and dry climates, crop productivity was significantly increased over NT alone. This work further highlights the importance of implementing NT as an integrated system that combines the absence of tillage with residue retention and species diversification.

The complexity of transitioning from NT alone to a NT or CA system highlights the necessity of farmer involvement in all phases of the innovation process, including on-farm research and evaluation, to ensure successful implementation. The successful development and promotion of NT/CA systems will be essential, given that they will lead to the implementation of the principles and concepts that will be provide a key mechanism for C management to cope with climate extremes (Kassam and Friedrich 2012; Corsi et al. 2012; Lal 2015b; Kassam et al. 2017; Reicosky and Janzen 2018; Mitchell et al. 2019). Diverse cover crop mixes will help ensure adequate C input to NT/CA systems (Corsi et al. 2012; Lal 2015 a, b; Chatterjee, et al. 2016).

34.6 Summary and Conclusions

No-tillage has transitioned from a practice simply referring to the removal of tillage from crop production to more complex and coherent NT or CA system that incorporates stubble retention with biodiversity in crop rotations and cover crop mixes. By permitting higher crop diversification, rotation has a crucial positive impact on weed, pest, and disease control, as well as on crop nutrient management. Improved soil properties can also provide a wide range of agro-environmental benefits. The rate of change of most soil properties with NT alone appears somewhat slower than when diverse rotations and cover crop mixes are part of the comprehensive system. The positive impacts on the physical, chemical, and biological properties in NT lies in improved C management and enhanced aggregate stability that provides for erosion control, more infiltration, and less runoff. The increased C input from diverse rotations and cover crop mixes also provides the necessary root exudates as a readily available short-term form of energy for the soil organisms, in addition to the C supplied during biomass decomposition. Thus, we must understand the regenerative benefits of minimum soil disturbance, permanent mulch cover, and diversified cropping, not just on yields, but also through enhanced C management for climate extreme mitigation/adaptation. The ongoing global evolution and expansion and refinement of NT into a NT or CA system led by younger generations of innovative farmers is an inspiration that provides hope of improved soil health and food security for future generations.

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Chapter 35
The Future of No-Till Farming Systems for Sustainable Agriculture and Food Security

Rattan Lal

Abstract Pre-historic agriculture was based on a basic form of no-till (NT). The invention of a plow, initially pulled by draft animals and later by a tractor, facilitated weed control and incorporation of crop residues; it also exacerbated risks of soil erosion and other degradation processes. Development of herbicides since the 1940s and of a seed drill in the 1960s promoted the use of NT farming, which is practiced on about 180 M ha or on about 12.5% of the global arable land area. The extent of adoption of NT is higher in North and South America, Australia, and New Zealand, but is lower in Asia, Africa, and Europe. The low adoption rate by small landholders of Asia and Africa may be attributed to a lack of access to essential inputs, competing uses of crop residues, and a possible decline in crop yields on soil prone to compaction. Yet a system-based NT technology can facilitate adaptation to, and mitigation of, a changing and uncertain climate by sequestration of atmospheric CO_2 in soil as humus. Incorporation of cover crops in the rotation cycle can also enhance soil structure and improve use efficiency of nutrients. Soil-specific adaptation is needed to promote adoption of NT.

Keywords Climate-resilient technology · Crop residue management · Cover cropping · Soil carbon sequestration · Soil quality

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35.1 Introduction

In pre-historic agriculture, using a stick to make a hole in the ground to drop a few seeds and then covering these with soil pushed in by a toe, is a basic no-till (NT) system used since the dawn of agriculture. This age-old system is still used in several regions throughout the developing countries. However, it is the plow-based system of seedbed preparation that is associated with modern farming. The validity and long-term consequences of plowing came under strong scrutiny during the "Dust Bowl" era of the mid-1930s. The book "Plowman's Folly" by Edward Faulkner (1943) challenged the traditional concept about mechanical tillage by simply stating that "the fact is that no one has ever advanced a scientific reason for plowing". Further, Faulkner also concluded that most problems encompassing the complex process of soil degradation (e.g. erosion, drought, soil impoverishment) and declining agronomic yields are directly attributed to the age-old practice of plowing. The Time magazine dubbed this concept "one of the most revolutionary ideas in agricultural history" (Time 1944). However, the modern concept of NT, which has now evolved into NT systems farming or conservation agriculture (CA), became practical only during the 1940s with the invention of herbicides to control some broadleaf weeds. Subsequently, a NT seed drill was developed in 1960s and the 1985 Farm Bill promoted NT farming in the US through subsidies for soil conservation (Gattuso 1985).

The global spread of NT farming systems, estimated at ~180 Mha or 12.5% of the total cropland area of 1443 Mha (Table 35.1), occurred slowly between 1974 and 1992 (0–10 Mha), moderately between 1992 and 2008 (10–100 Mha), and rapidly between 2008 and 2016 (100–180 Mha) (Kassam et al. 2018). However, the extent of adoption is higher in South and North America and the Australia/New Zealand region (155.8 Mha out of 180 Mha or 86.5% of the global adoption)

Table 35.1 Global spread of cropland area under NT farming/conservation agriculture during 2015–2016

Region	Cropland Area Under CA (Mha)	Percent of the World Arable Land Area
South America	69.90	4.84
North America	63.18	4.38
Australia and New Zealand	22.67	1.57
Asia	13.93	0.97
Russia and Ukraine	5.70	0.39
Europe	3.56	0.25
Africa	1.51	0.10
Total	180.44	12.5

Total Cropland Area = 1443.2 Mha
Adapted from Kassam et al. (2018)

compared with the rest of the world. The adoption rate of NT farming systems is especially low in Asia, Africa, and Europe.

Among the reasons for the low adoption rate in Asia and Africa (i.e. South Asia or SA, Sub-Saharan Africa or SSA) include resource-poor farmers who cannot invest in technologies (i.e. seed drill, herbicides) and are unable to retain crop residues as surface mulch because of competing uses (Lal 2016). The low adoption rate of NT farming systems in Europe may be because of sub-optimal soil temperatures during spring in northern latitudes and high risks of soil compaction (Soane et al. 2012). Adoption of NT farming systems on poorly-drained clayey soils may also be problematic, especially because of relatively low agronomic yield. Uses of NT farming systems on organic farms is another issue that needs an objective consideration (Cooper et al. 2016) because of the need for plowing to control weeds and enhance mineralization and recycling of biomass C. In general, NT farming systems are more applicable in regions with large scale commercial farms (i.e. North and South America, Australia and New Zealand) than in regions with predominantly small-size land holdings and subsistence farmers (i.e. SA, SSA, Caribbean, Central America, the Andean region). Yet, the Agenda 2030 or the Sustainable Development Goals (SDGs) of the UN is aimed at achieving a world without hunger and malnutrition. The SDG #2 (zero hunger) has two specific targets: (target 2.1) ensuring access to safe, nutritious, and sufficient food for all; and (target 2.2) eliminating all forms of malnutrition (UN 2015). To achieve this goal, greater implementation of climate resilient farming technologies, such as NT farming systems, will need to occur.

The objective of this article is to discuss the future of NT farming and its relevance to advancing food and nutritional security and adapting/mitigating climate change. The article also addresses the need to identify specific soil/crop management options that may enhance adaptation of a system-based NT under diverse conditions such as that of the dryland environments, clayey soils, soils of the tropics etc.

35.2 Global Food Security

There are 821 million food-insecure people in the world (FAO et al. 2018) and this number has increased from 784 million in 2014 and 2015 to 804 million in 2016. The percentage of the population vulnerable to food insecurity in 2017 was 20.6% in Africa, (256 million people, of which 236 million were in SSA) 11.4% in Asia (515 million people), 6.1% in Latin America and the Caribbean, 7.0% in Oceania and < 2.5% in North Americas and Europe (FAO et al. 2018). This food insecurity is also on the rise in all regions of Africa and South America. In contrast, 1.5 billion people (mainly located in the developed world) are obese, and this number is also increasing (FAO 2012).

It is feared that some goals of the Agenda 2030 (targets 2.1 and 2.2) may not be met (Lieberman 2018). Furthermore, the vulnerability to food-insecurity may also rise because of anthropogenic climate change (Lobell et al. 2011). Crop yields have been predicted to fall by 3–8% (5%) for each degree (C) increase in temperature, which is equivalent to a 1.5% decrease per decade (Lobell and Gourdji 2011). Not only is climate change already impacting global food production, its adverse impact is rather unequally distributed geographically (Ray et al. 2019).

Developing a resilient food system requires a holistic, long-term perspective (Tendall et al. 2015), with other co-benefits. The latter is important because of the numerous dimensions of hunger, and the fact that anthropogenic climate change may adversely affect progress towards achieving the SDG #2 of the world without hunger (Wheeler and von Braun 2013). Indeed, climate change may impact all four dimensions of food security: availability, access, utilization, and system stability (FAO 2008). The problem of food and nutritional insecurity may also be exacerbated by the growing preference for animal-based diets with the increasing affluence of populations in emerging economies (i.e. China, India). In addition, the risks of food waste may also be exacerbated by current and projected climate change because of the change in temperature and precipitation which affect the shelf life of food (i.e. vegetables, fruits). Thus, there is a strong need for the identification of soil/site-specific climate-resilient technologies, such as NT systems, and to critically evaluate their role in achieving climate-resilient agroecosystems.

35.3 No-Till Farming Systems as a Climate-Resilient Technology

The conversion of natural ecosystems to agricultural ones can have a strong adverse impact on soil physical and nutritional properties (Table 35.2). It can also lead to significant losses of soil organic carbon (SOC), with associated negative impacts on global CO_2 emissions and anthropogenic climate change (Lal 2015). However, the magnitude of this impact can be reduced through residue retention and adoption of a system-based NT (Lal 2015). The latter has four basic components: (1) retaining crop residues as mulch on the soil surface; (2) growing a cover crop during the off-season to capture plant nutrients, provide additional biomass, and improve soil health; (3) eliminating all soil-tillage operations (i.e., primary, secondary, and tertiary) and limiting vehicular traffic to a pre-designed space; and (4) adopting a complex system based on incorporation of a cover crop in the rotation cycle. Furthermore, soil physical properties and processes are extremely important to the sustainable

Table 35.2 Effects of 40 years of cropping on physical properties of Napponee silty clay loam, Paulding County, Ohio

	Bulk Density (Mg m^{-3})		Porosity (%)		N Content (Mg ha^{-1})	
Depth (m)	Virgin	Cultivated	Virgin	Cultivated	Virgin	Cultivated
0–0.305	1.05	1.31	60.3	50.5	7.40	5.01
0.305–0.610	1.13	1.39	58.1	47.6	–	–
0.610–0.915	1.23	1.46	53.5	44.8	–	–

Recalculated from Page and Willard (1947) management of agroecosystems but are neither widely studied nor properly understood. The role of NT in sequestration of atmospheric CO_2 as SOC must also be addressed (Lal 2015).

The widespread adoption of NT is essential to address global issues of the twenty-first century and advance the SDGs of the UN. However, site-specific options must be identified to successfully incorporate all four components of a NT system (Lal 2015). Some key issues pertinent to the future of NT are described below.

35.3.1 Crop Residue Management

Being climate-dependent, agriculture is a risky business. Thus, the judicious management of crop residues is a prudent strategy of risk management in both dryland and irrigated agriculture. The maintenance of crop residues is an important factor affecting soil quality, functionality, and provisioning of numerous ecosystem services. However, the effects of crop residue management (i.e. removal, retention,

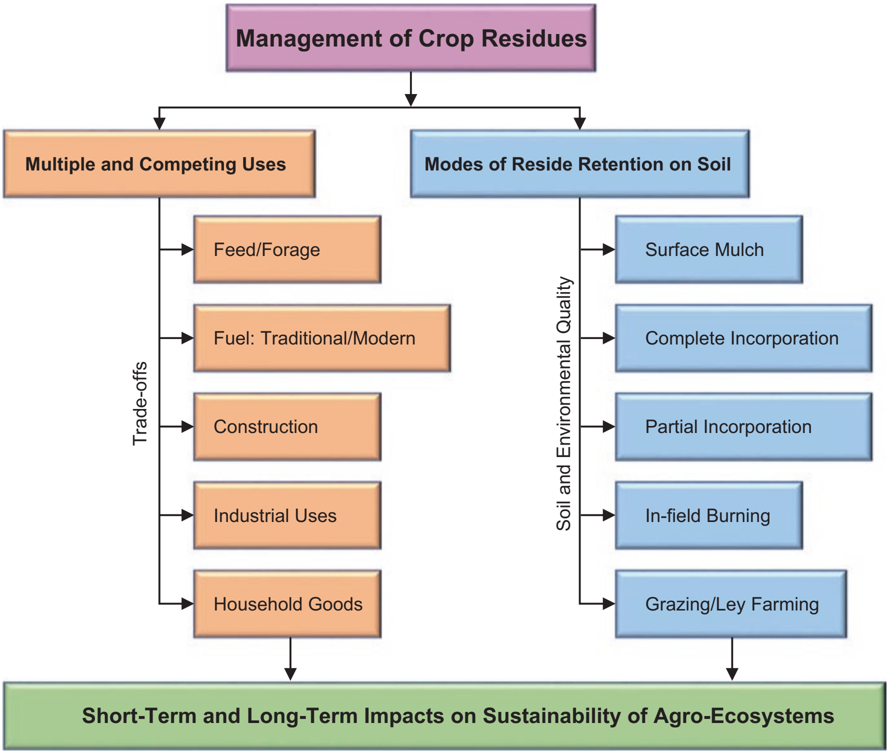

Fig. 35.1 Ramifications of crop residue management

incorporation, in-field burning) are also complex and multi-dimensional (Karlen et al. 2019).

Residue management has two factors that govern its impact on soil, environment, and agronomic sustainability (Fig. 35.1). One is the multiple and competing uses of crop residues, which is a pertinent consideration especially for the small landholders in developing countries. Second is the mode of application. Residues can be retained as surface mulch, incorporated partially or completely, grazed, or burnt in the field. There also exits a strong interaction among these managerial options, with both short-term and long-term consequences (Fig. 35.1).

In general, there are positive effects of residues retention as surface mulch for soil and water conservation, moderation of soil moisture and temperature regimes, and increase in SOC concentration in the root zone or in surface 0.1–0.2 m layer. Residue retention can increase SOC stock, reduce soil bulk density, and increase water retention and infiltration (Chalise et al. 2019). However, in regions with cold and wet springs (high latitude and temperate/ boreal climates), residue retention as mulch may create sub-optimal soil temperatures and excessively wet soil conditions, leading to poor seedling growth and immobilization of nitrogen.

Where residues are incorporated via plowing, the rate of decomposition is increased and SOC stocks may decrease (Turmel et al. 2015). Removal of crop residues for biofuel (traditional or modern) and due to grazing/burning can also deplete SOC concentration and stock (Liska et al. 2014). Indeed, residue removal rates of even 25% can adversely impact soil properties and processes (Blanco-Canqui and Lal 2009), lead to loss of soil fertility, nutrient depletion, and elemental imbalance in the soil (Hiel et al. 2018) and increase gaseous emissions from soil (Zhan et al. 2019). Although it should be noted that these adverse effects are minimized under NT compared with the plow-based system (McGowan et al. 2019) and residue removal may not impact N_2O emission (Johnson and Barbour 2019). However, the magnitude and the specific impact on soil properties depends on site and soil-specific attributes (Blanco-Canqui et al. 2007; Clay et al. 2008). In addition, the magnitude of sustainable crop residues removal rates will also depend on the market value of residues for hay, or other competing uses (Kludze et al. 2013), and the societal value of SOC (Lal 2014).

35.3.2 Cover Cropping

Conversion of natural to managed ecosystems can adversely impact soil physical and nutritional properties (Table 35.2). Increase in soil bulk density, decrease in total porosity, and depletion of soil fertility (especially N) can affect agronomic yield and use efficiency of inputs. This is where cover cropping has an important role. A summary of the benefits of cover cropping is provided below and in Fig. 35.2. Specifically, cover cropping can:

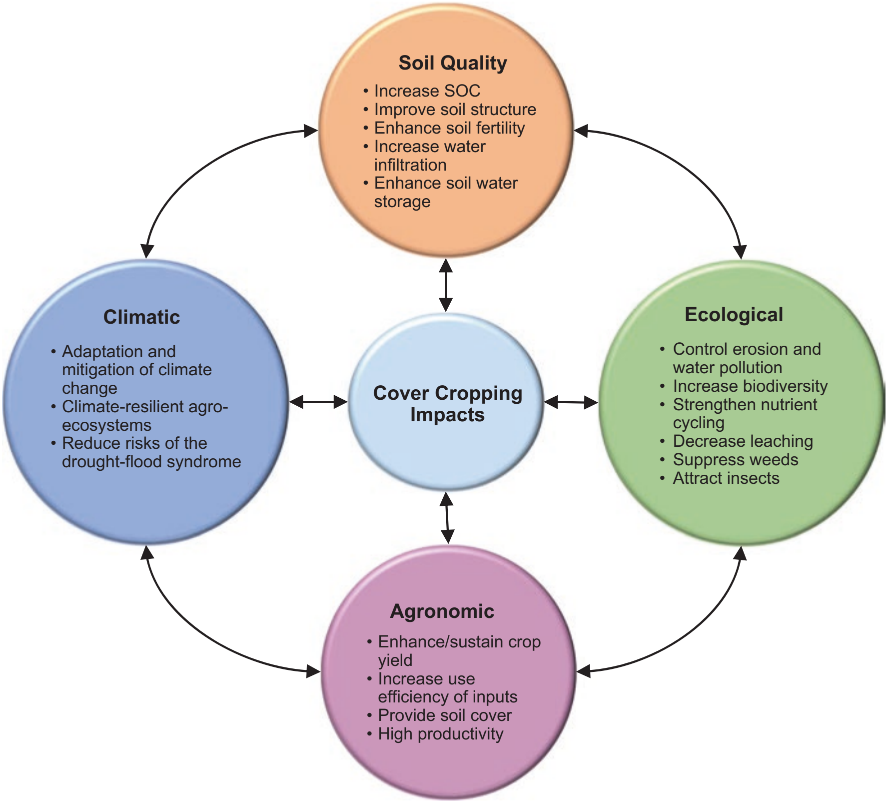

Fig. 35.2 Ecological and agronomic impacts of cover cropping

- Increase the amount of crop residues that can be sustainably removed (Ruis and Blanco-Canqui 2017; Sindelar et al. 2019);
- Help with the restoration and sustainable maintenance of SOC. For example, cover crop shoots, and especially roots, have been observed enhance SOC stock in a NT corn bioenergy cropping system (Austin et al. 2017);
- Decrease soil bulk density, increase water infiltration, improve water content and water storage, increase crop yield (Chalise et al. 2019), and positively impact the soil microbial community (Schmidt et al. 2018). It can also enhance biodiversity, especially populations of pests (Luo et al. 2019) and predators (Rivers et al. 2018);
- Reduce the risk of erosion and water pollution (Kladivko 2016);
- Suppress weeds (Baraibar 2017; Liebman and Gallandt 1997);
- Strengthen soil nutrient recycling (Kladivko 2016; Wagger et al. 1998); and
- Provide agronomic benefits, including enhancing and sustaining productivity and improving use efficiency of soil water (Sanders et al. 2018).

Above all, cover cropping is highly effective at improving adaptation to, and mitigation of, climate change (Fig. 35.2). These co-benefits are harnessed through soil quality interactions in agroecosystems (Reicosky and Forcella 1998), and on water quality (Dabney et al. 2011).

Choice of an appropriate cover crop depends on many factors, especially the climate. In temperate climate of southern Ontario, for example, barley is not a suitable cover crop because of winter-kill, and cereal rye is more suited to the regional climate (Landry et al. 2019). Overall, the selection of appropriate cover crops must be done on a site by site/ region by region basis.

35.3.3 Soil Guide to No-Till/Conservation Agriculture

Not all soils are suitable to direct adoption of a NT system. Some clayey soils in harsh/extreme climates (e.g. cold and wet spring of the temperate/boreal regions) and with slow internal drainage may not be suited to retention of crop residue mulch and the slow warming under NT. Similarly, a NT system may not be directly applicable on severely eroded/degraded soils with compacted/crusted surface layers of massive structure. Under such conditions, restorative measures may be needed prior to adoption of NT system.

There may also be socio-economic constraints to the adoption of NT, particularly by resource-poor and small land holder farmers of the tropics and sub-tropics (Lal 2016). Therefore, the development of a soil suitability guide to help advise farmers on the suitability of their land for the adoption of NT may be useful (Lal 1985). Site-specific packages that incorporate appropriate cultural practices must also be developed to address both the biophysical and socio-economic issues (e.g. land tenure, availability of credit, appropriate tools including seeding equipment, gender considerations) (Table 35.3). The strategy is to make the NT system work through adaptation of the package designed to alleviate the biophysical and socio-economic barriers (Fig. 35.3).

35.3.4 Weed and Pest Management

Weed control is a serious issue that must be addressed in NT systems, especially the control of perennial weeds. In NT systems there can be a shift in weed flora towards perennial species (Nichols et al. 2015) and some weeds may develop resistance to herbicides (CAST 2012; Dang et al. 2015). Similarly, some pests (e.g. slugs) may find shelter in crop residues (Douglas and Tooker 2012).

Table 35.3 Biophysical and socio-economic and cultural factors to be considered in developing a soil guide to adoption of a system-based NT farming

Biophysical Factors			**Socio-Economic and Cultural Factors**		
Soil	Terrain	Climate	Economic	Social	Cultural
1.Physical Attributes: Texture, structure, USA, MWD, clay minerals, water retention and infiltration rate, internal drainage, bulk density, erodibility, soil temperature	1.Slope Length, gradient, shape, aspect	1.Precipitation Amount, type, seasonal distribution	1.Market Access, infrastructure	1.Land Sights	1.Traditions
2.Chemical Properties: pH, CEC, salinity or EC, nutrient reserves, elemental toxicity or deficit	2.Vegetation: Annual, perennial	2.Extreme Events: Drought, flood, dust storms	2.Credit Availability, affordability	2.Equity	2.Social hierarchy
3.Biological Parameters: SOC, MBC, gaseous emissions, enzyme activity, biodiversity (earthworms)	3.Pests and Pathogens: Weed infestation (imperata), nematodes	3.Temperature Soil and air temperatures, heat and cold waves	3.Inputs: Access, price	3.Education	3.Democratic traditions
4.Ecological: Erosion, compaction, surface sealing, water and energy budget, nutrient cycling	4.Drainage density	4.Season: Growing season duration	4.Resources: Availablility, reliability	4.Gender	
	5.Inundation		5.Labor Availability, Technical skills	5.Institutions: Support services, extension	
	CEC = cation exchange capacity				
	MWD = mean weight diameter				
	WSA = water weight aggregation				
	EC = electrical conductivity				
	SOC = soil organic carbon				
	MBC = microbial biomass carbon				

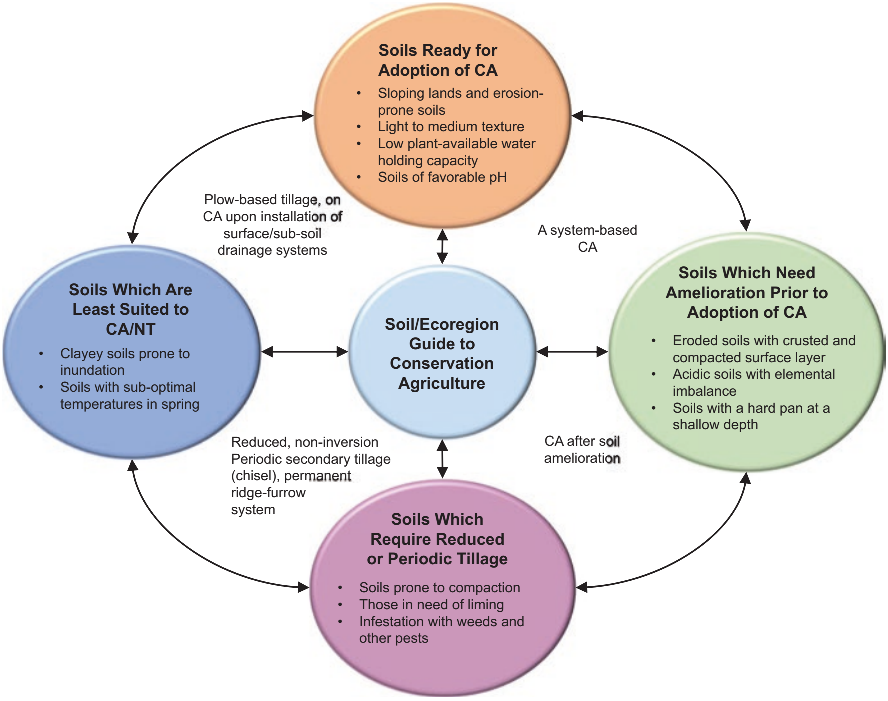

Fig. 35.3 Factors to be considered while developing a soil/ecoregion guide to adoption of NT systems/conversion agriculture (CA)

35.3.5 Agronomic Yield: Quantity and Quality

The objective of NT systems is not to maximize agronomic returns over a short-time period but to optimize and sustain productivity over the longer term. Accepting some yield reduction (~5%) may be acceptable if an optimum yield can be sustained. Similarly, obtaining a minimum assured crop yield during a bad growing season (i.e. drought, heat wave, flood), rather than a high yield during a good season, is an indication of climate-resilience of the production system. In addition to calories, the nutritional quality of the food (i.e. protein, micronutrients) and its shelf life are also useful criteria.

35.3.6 Productivity

The effectiveness of a NT system is indicated by productivity per unit of the resources consumed. In view of the finite nature of essential resources and high environmental footprint of agroecosystems, a preferred approach is of producing more from less. Rather than expanding the land area and increasing the use of limited resources (e.g. irrigation water, energy, fertilizers, pesticides), a preferred option is that of enhancing the use efficiency, reducing wastage and leakage into the environment (in water and air), and decreasing the environmental footprint. Thus, the effectiveness of NT vis-a-vis the conventional/traditional systems of seedbed preparation must be assessed with the criteria of productivity per unit consumption of the limited resources and on the basis of a low environmental footprint (i.e. C, H_2O, N, energy, soil erosion, gaseous emissions).

35.4 Future of No-Till and Conservation Agriculture

System-based NT, following the soil-guide criteria outlined in Fig. 35.3, has a promising future and a vast potential. With adaptation to site-specific conditions, NT is a climate-resilient system with built-in buffers against drought, heat waves, and other extreme events. However, its effectiveness depends on the skill and knowledge of land managers and availability of tools (i.e. seeding equipment, cover crop), other inputs (i.e. amendments), and institutional support (extension services).

Policy interventions may also be needed to develop a system of payments for ecosystem services generated by the adoption of a system-based NT technology. In regions where credible and verifiable rates of SOC sequestration can be made, farmers must be rewarded through payments of a just and fair price of C based on its societal value (Lal 2014). During the 1970s through to the 1990s, NT was promoted primarily as a tool against soil erosion (water, wind) and reduction in non-point source pollution. However, since the beginning of the twenty-first century, focus has been on the importance of NT due to its climate-resilience and importance in assisting with both the adaptation to and mitigation of climate change, improving quality and renewability of water resources, restoring soil health and functionality, improving soil biodiversity as indicated by the activity and species diversity of soil biota, and on multi-dimensional sustainability of agroecosystems. It is precisely in this context that NT has a bright future. Its sustainability and effectiveness is also enhanced by integration of crops with livestock and trees.

35.5 Innovative Approaches to Brightening the Future of NT Systems

The modern NT system has been studied since the 1940s (Faulkner 1943). However, its adoption is slow, and its effectiveness has been a debatable issue during the 2010s due to problems with its implementation under a variety of environmental and socio-economic conditions (i.e. land tenure, gender). In order to promote and drive continued uptake of NT, the concept needs out-of-the-box thinking and innovative ideas. For example, novel and environment-friendly approaches are needed to promote NT in diverse soils, farming/cropping systems, climates, and socio-economic and cultural conditions. Certainly, integration of crops with trees and livestock is a promising option. Controlled and rotational grazing and establishment of enclosures on degraded lands (Mekuria et al. 2018) are also important options to alleviate soil-related constraints prior to adoption of NT systems. However, some protected land areas must also be returned to nature forever in the interest of biodiversity (Kroner et al. 2019), and NT can help save land for nature.

The wide-spread adoption of a system-based NT is in accord with many worldwide policies aimed at improving food security and adapting to the effects of anthropogenic climate change. For example, the concept of "Rights-of-Soil", which states that a soil must be protected, restored, and allowed to thrive and flourish (Lal 2019). Inter-connectivity and nexus thinking is also another ancient concept that has gained modern relevance, and which is needed (Chazdon and Brancalion 2019) in the global effort to mitigate climate change (Lal 2018a, b). In view of the UN's SDGs, it is pertinent to think about the food-energy-water-soil (FEWS) nexus, and within this, the role of soil should not be overlooked (Hatfield et al. 2017). Nexus-based NT is also relevant to achieving the "4 Per Thousand" initiative of the Paris Agreement, which aims to boost carbon storage in agricultural soils by 0.4% each year to help mitigate climate change and is in need of a strong political will (Lawrence and Schäfer 2019). Saving land and returning it to nature through afforestation also is an important land-based solution to mitigation of climate change (Bastin et al. 2019). This approach can reverse the increasing rate of forest loss in the tropics (Sloan and Sayer 2015). Promotion of NT puts us on the path of thinking more about soil and its sustainable management rather than about oil and fossil energy (Gates 2019).

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