Eric Lichtfouse
Editor

SUSTAINABLE AGRICULTURE REVIEWS 3

Sociology, Organic Farming, Climate Change and Soil Science

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Editor
Dr. Eric Lichtfouse
INRA-CMSE-PME
17 rue Sully
21000 Dijon
France
Eric.Lichtfouse@dijon.inra.fr

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Contents

Chapter 1
Society Issues, Painkiller Solutions, Dependence and Sustainable Agriculture

Eric Lichtfouse

Abstract Here I tackle three major issues, climate change, financial crisis and national security, to disclose the weak points of current remedies and propose sustainable solutions. Global warming and the unexpected 2008 financial crisis will undoubtedly impact all nations. Treating those two critical issues solely by painkiller solutions will fail because only adverse consequences are healed, not their causes. Therefore, all sources of issues must be treated at the same time by enhancing collaboration between politicians and scientists. Furthermore, the adverse consequences of globalisation of markets for energy, food and other goods have been overlooked, thus deeply weakening the security of society structures in the event of major breakdowns. Therefore, dependence among people, organisations and nations must be redesigned and adapted to take into account ecological, social and security impacts. Solving climate, financial and security issues can be done by using tools and principles developed by agronomists because agronomy integrates mechanisms occurring at various space and time levels. Agriculture is also a central driver for solving most society issues because society has been founded by agriculture, and agriculture is the activity that provides food, renewable energies and materials to humans. I present a to-do list summarising the major practices of sustainable agriculture based on about 100 recently published review articles. The practices are agroforestry, allelopathy, aquaculture, beneficial microorganisms and insects, biofertilisation, biofuels, biological control, biological nitrogen fixation, breeding, carbon sequestration, conservation agriculture, crop rotation, cover crops, decision support systems, grass strips, integrated pest management, intercropping, irrigation, mechanical weed control, mulching, no tillage, organic amendments, organic farming, phytoremediation, precision agriculture, seed invigoration, sociology, soil restoration, suicidal germination, terracing, transgenic crops, trap crops, and urban agriculture.

E. Lichtfouse (✉)
INRA, Department of Environment and Agronomy, CMSE-PME, 17, rue Sully,
21000, Dijon, France
e-mail: Eric.Lichtfouse@dijon.inra.fr

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Mahatma Gandhi listed seven blunders of humanity: Wealth without work, Pleasure without conscience, Commerce without morality, Worship without sacrifice, Politics without principles, Knowledge without character, and Science without humanity.

1.1 Financial Crisis, Climate Change and the Painkiller Solution

Society is actually experiencing an unexpected financial crisis that will undoubtedly impact all nations (Beyond Growth 2008). It will affect in particular the poorest countries that are already suffering from hunger and diseases. Governments are attempting to heal this issue by injecting large amounts of money in banking systems and major companies. At the same time, effects of climate change are accelerating and deeply altering ecosystems (IPCC 2007). Recent alarming reports even warn that it is already too late to stop global warming, though the forecasted value of the warming in degree Celsius and the date at which it will occur are still debated (Vince 2009). Given the urgency, geoengineering – the notion that to save the planet we must artificially tweak its thermostat by, e.g., firing fine dust into the atmosphere to deflect sun rays – is even gaining cause as a rapid solution to the attempt of cooling the earth (Brahic 2009). Injecting government cash and geoengineering are both urgent actions that may indeed temporarily heal the financial market and the effects of climate change. Nonetheless, those two strategies suffer from the same drawback. Both are “fireman” or “painkiller” solutions, meaning that only adverse consequences are treated, not the cause of those effects (Lal, 2009a; Lichtfouse 2009a).

1.2 Enhancing Politician and Scientist Collaboration

Treating solely negative effects without treating sources will undoubtedly fail in the long run. Therefore, I strongly advice politicians and other policy makers to treat the source of the adverse effects. This can be done by closer collaboration with scientists. It is indeed unacceptable that almost nothing has been done to counteract global warming before 2007, knowing that the Nobel Prize winner Svante Arrhenius has clearly predicted in 1896 – more than a century ago – that temperature will rise of about +5°C as a result of fossil fuel burning (see Lichtfouse 2009b and references therein). In the next section, I discuss dependence, another critical and overlooked factor, and its implication on the security of our society.

1.3 Rethinking Society Dependence

Globalisation of the market for food, fuels and other goods has undoubtedly induced positive effects such as lowering prices and fostering collaborations among citizens and nation. However, it has also induced serious dependence problems such as a sharp increase of maize prices in Mexico following the fast-rising use of maize as biofuels in northern countries. Another striking example is the peak of petroleum prices that has impacted almost all nations. A recent failure of the European electricity grid resulting in thousands of home without current for several days further illustrates the weaknesses of global dependence. We also know that crop control with pesticides is contaminating drinking water, even many years after the ban of those pesticides (Barth et al. 2009), and so on. As a result, though we live at a time of outstanding technology, the excess of dependence created by wild globalisation has strongly weakened our society. In case of major catastrophic events, the society structures were probably more secure 100 years ago because most people were farmers, producing and consuming locally. The fundamental sources of our actual society issues are evidenced in the visionary article by Dr. Rattan Lal, entitled *Tragedy of the global commons: soil, water and air* (Lal, 2009b).

Though this is a very sensitive topic because dependence is the basis of most public and private organisations, the adverse effects of dependence have been largely overlooked because benefits such as growth and profit have predominated until now. Environmental, social and security impacts have indeed not been taken into account. Therefore, we should rethink dependence. More specifically, the production of food, fuels and other goods, their transportation and their selling should be redesigned and controlled to lower dependence among people and nations. For instance, producing and consuming food more locally will both reduce dependence and decrease the ecological footprint of long-range transportation. Switching partly to renewable, locally produced energies will also produce a similar positive effect.

Of course, less dependence does not mean no dependence and no collaboration among people and nations. The degree of dependence should be adapted to the nature of goods or energy, their transportation, selling, ecological footprint, and social impact. Some goods may be distributed globally without weakening the nations, others may not be so. Obviously, the southern, poorest nations should be at the same time supplied with food and helped to produce their own food and energy. Scientists and policy makers should therefore study, assess and enforce the relevant level of goods circulation. Here, the tools developed by agronomists to build sustainable farming systems should be particularly useful because agriculture is the foundation of society (Lal, 2009c; Lichtfouse et al. 2009a). Agronomists are indeed experts at deciphering mechanisms occurring at various scales, from the molecule to the global scale, and from seconds to centuries.

Agronomy should thus be used as a core tool to build a sustainable society. Table 1.1 gathers the major practices of sustainable agriculture, and their main benefits. It should thus help readers to build rapidly an overall vision of the current innovative tools and approaches to build a sustainable world.

Table 1.1 Practices of sustainable agriculture. Most citations are review articles published in the following books: *Sustainable Agriculture* (Lichtfouse et al. 2009b); *Sustainable Agriculture Reviews*, vol 1 Organic farming, pest control and remediation of soil pollutants (Lichtfouse, 2009c); *Sustainable Agriculture Reviews*, vol 2 Climate change, intercropping, pest control and beneficial microorganisms (Lichtfouse, 2009d*); Sustainable Agriculture Reviews*, vol 3 Sociology, organic farming, climate change and soil science (Lichtfouse, 2009e, this volume)

Practices	Benefits	References
Agroforestry Homestead agroforestry	Carbon sequestration Diversification Disease control Employment Food security Higher biodiversity Higher relative plant density Less soil erosion Mitigate climate change Nutrient recycling Pest control Water quality	Carruba and Catalano (2009) Etchevers et al. (2009) Lal (2009e) Malézieux et al. (2009) Miah and Hussein (2009) Palaniappan et al. (2009) Spiertz (2009) Zuazo and Pleguezuelo (2009)
Allelopathy Biofumigation Biopesticides Hormones Plant growth regulators and other biochemicals	Adaptation to climate change Decreasing costs Drought tolerance Food security Increase water uptake Less pesticides Weed control	Aroca and Ruiz-Lozano (2009) Biesaga-Kocielniak and Filek (2009) Farooq et al. (2009a, b) Kalinova (2009) Khan et al. (2009b) Martínez-Ballesta et al. (2009) Runyon et al. (2009) Wu et al. (2009)
Aquaculture	Diversification Food security Recycling farm wastes	Palaniappan et al. (2009)

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Table 1.1 (continued)

Practices	Benefits	References
Beneficial microorganisms and insects	Bioremediation Biosensors Cheaper fertilisation Disease control Drought tolerance Increasing nutrient uptake Increasing plant growth Pest control Phytoremediation Pollinisation	Aroca and Ruiz-Lozano (2009) Bonilla and Bolaños (2009) Deguine et al (2009) Gamalero et al. (2009) Garg and Geetanjali (2009) Ghorbani et al. (2009a) Gregoire et al. (2009) Holb (2009) Joner and Leyval (2009) Khan et al. (2009a, b) Latour et al. (2009) Saha (2009) Viebahn et al. (2009) Wrage et al. (2009) Yair et al. (2009)
Biofertilisation Biofortification Foliar sprays	Disease resistance Drought resistance Higher micronutrient levels Less malnutrition Improving human health Salt resistance	Bonilla and Bolaños (2009) Dordas (2009) Farooq et al. (2009a) Ghorbani et al. (2009a) Viebahn et al. (2009) Wrage et al. (2009) Zuo and Zhang (2009)
Biofuels	Carbon neutral Higher biodiversity Local source of energy Mitigate climate change Renewable fuels	Ceotto (2009) Lal (2009d, e) Hill (2009) Miah and Hussein (2009) Scholz et al. (2009)
Biological control (see also beneficial organisms and insects)	Cheap control Disease control Higher biodiversity Less or no pesticide Pest control Wildlife conservation	Askary (2009) Clergue et al. (2009) Deguine et al (2009) Ferron and Deguine (2009) Ghorbani et al. (2009b) Holb (2009) Latour et al. (2009) Viebahn et al. (2009) Yair et al. (2009)
Biological nitrogen fixation (see also cover crops)	Alternative fertilisation Food security Increases plant growth Increases soil N Less, no mineral fertilisers Local fertiliser Mitigate climate change Nutrient recycling	Bonilla and Bolaños (2009) Garg and Geetanjali (2009) Khan et al. (2009b) Knörzer et al. (2009) Rodiño et al. (2009) Spiertz (2009)

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Table 1.1 (continued)

Practices	Benefits	References
Breeding Recurrent mass selection	Adaptation to climate change Disease resistance Drought resistance Genetic diversity Salinity resistance	Banilas et al. (2009) Carruba and Catalano (2009) Hejnak et al. (2009) Marais and Botes (2009) Martínez-Ballesta et al. (2009)
Carbon sequestration (see also organic amendments)	Decreases erosion Higher nutrient retention Higher soil biodiversity Higher water retention Mitigate climate change Offset CO_2 emissions Prevent desertification	Anderson (2009b) Erhart and Hartl (2009) Benbi and Brar (2009) Bernoux et al (2009) Etchevers et al. (2009) Füleky and Benedek (2009) Ghorbani et al. (2009b) Lal (2009c, d, e, f) Malézieux et al. (2009) Nguyen (2009) Pati et al. (2009) Shaxson (2009) Stagnari et al. (2009)
Conservation agriculture	Air, soil and water protection Biodiversity conservation Decreases erosion Decreases pollution Higher water retention Improves soil structure Mitigates climate change Reduces farm costs Reduces flooding Reduces work time	Palaniappan et al. (2009) Stagnari et al. (2009)
Crop rotation	Biofertilisation Enhances soil organic matter Increases biodiversity Increases soil N Increases water use efficiency Plant disease control Water conservation Weed control	Anderson (2009a, b) Dordas (2009) Erhart and Hartl (2009) Ghorbani et al. (2009a) Kalinova (2009) Lal (2009e) Spiertz (2009) Stagnari et al. (2009)
Cover crops	Improves fertility Improves water availability Nutrient recycling Reduces costs Soil erosion and runoff control Weed control	Kalinova (2009) Malézieux et al. (2009) Pati et al. (2009) Runyon et al. (2009) Stagnari et al. (2009) Wu and Sardo (2009) Zuazo and Pleguezuelo (2009)

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Table 1.1 (continued)

Practices	Benefits	References
Decision support systems Farming systems Indicators Land husbandry Modelling	Assess sustainability Design sustainable practices Integrate various sciences Integrate space and time levels Forecast farming system evolution Forecast impacts Optimise ecological benefits Optimise performance	Barth et al. (2009) Bockstaller et al. (2009a, b) Clergue et al. (2009) Debaeke et al. (2009) Doré et al. (2009) Duru and Hubert (2009) Faivre et al. (2009) Handayani and Prawito (2009) Karami and Keshavarz (2009) Mir and Qadrri (2009) Roger-Estrade et al. (2009) Sadok et al. (2009) Shaxson (2009) Veldkamp et al. (2009) Wu and Sardo (2009) Zamykal and Everingham (2009)
Grass strips Buffering strips Filtering strips Artificial wetlands	Degrade pesticides Reduce soil erosion Reduce water pollution	Gregoire et al. (2009) Lacas et al. (2009) Wu and Sardo (2009)
Integrated pest management	Decreases pesticide input Decreases pollution Decreases cost	D'Addabbo et al. (2009) Deguine et al. (2009) Ferron and Deguine (2009) Holb (2009) Wu and Sardo (2009)
Intercropping Alternative crops	Aesthetic value Biofortification Diversification Decreases erosion Increases biodiversity Increases yield Increases soil nitrogen Recycles nutrients Pest control Plant disease control	Carruba and Catalano (2009) Deguine et al. (2009) Dordas (2009) Etchevers et al. (2009) Kalinova (2009) Knörzer et al. (2009) Malézieux et al. (2009) Palaniappan et al. (2009) Spiertz (2009) Zuo and Zhang (2009)
Irrigation Drip irrigation	Food security Saves water	Hillel (2008) Lal (2009e) Palaniappan et al. (2009) Wu and Sardo (2009)

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Table 1.1 (continued)

Practices	Benefits	References
Mechanical weed control Solarisation Flaming Heating	Disease control Food security Increases yield Increases plant growth Improves water availability Increases soil nutrients Less or no herbicides Weed control	Anderson (2009a) Carruba and Catalano (2009) Chicouene (2009) D'Addabbo et al. (2009) Holb (2009)
Mulching (see also Organic amendments and Carbon sequestration)	Improves soil structure Prevents frost damage Soil water conservation Soil temperature moderation Weed control	D'Addabbo et al. (2009) Kalinova (2009) Lal (2009e, f) Shaxson (2009) Wu and Sardo (2009)
No tillage Reduced tillage Conservation tillage Direct seeding	Disease control Improves soil structure Increases biodiversity Increases carbon sequestration Mitigates climate change Reduces erosion Reduces farm costs Reduces work time Water retention	Anderson (2009a, b) Bernoux et al. (2009) Deguine et al. (2009) Etchevers et al. (2009) Ghorbani et al. (2009a) Lal (2009e, f) Pati et al. (2009) Roger-Estrade et al. (2009) Scholz et al. (2009) Shaxson (2009) Stagnari et al. (2009) Wu and Sardo (2009)
Organic amendments Sewage sludge Manure Organic mulch Biochar Biosolid Compost Crop residues Wood, etc. (see also carbon sequestration)	Buffer soil temperature Cheap fertilisation Carbon sequestration Disease control Decreases erosion Increases microbial activity Increases yield Improves soil structure Mitigates climate change Recycles waste Stores soil nutrients Water retention	Baize (2009) Bernoux et al. (2009) Dordas (2009) Etchevers et al. (2009) Erhart and Hartl (2009) Füleky and Benedek (2009) Ghorbani et al. (2009a, b) Gresta et al. (2009) Holb (2009) Kalinova (2009) Lal (2009e) Palaniappan et al. (2009) Pati et al. (2009) Saha (2009) Scholz et al. (2009) Shaxson (2009) Sigua (2009) Spiertz (2009) Stagnari et al. (2009)

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Table 1.1 (continued)

Practices	Benefits	References
Organic farming	Carbon sequestration Decreases erosion Disease control Food security Increases biodiversity Increases fertility Increases soil carbon Increases soil nitrogen Higher soil quality Improves soil structure Mitigates climate change Recycles nutrients Social improvement	Erhart and Hartl (2009) Füleky and Benedek (2009) Ghorbani et al. (2009a, b) Handayani and Prawito (2009) Holb (2009) Kalinova (2009) Lamine and Bellon (2009) Saha (2009) Spiertz (2009) Winter and Davis (2007) Wu and Sardo (2009)
Phytoremediation (see also grass strips)	Aesthetic improvement Cleans soil, water and air Decreases pollutant bioavailability Decreases pollutant toxicity Decreases pollutant concentration Degrades organic pollutants Extracts metals from soils Low-cost remediation Socially-acceptable reclamation	Al-Najar et al. (2005) Babula et al. (2009) Baraud et al. (2005) Harvey et al. (2002) Joner and Leyval (2009) Khan et al. (2009b) Morel et al. (1999) Rodriguez et al. (2005) Scholz et al. (2009) Wahid et al. (2009)
Precision agriculture Robotic agriculture	Disease control Manages crop variability Manages crop conditions variability Optimises fertilisation Optimises watering Weed control	Sardo (2009) Unibots Wu and Sardo (2009) Zamykal and Everingham (2009)
Seed invigoration	Dormancy management Drought resistance Flood resistance Increases yield Low temperature resistance Salt stress resistance	Farooq et al. (2009a, b)
Sociology Indigenous knowledge	Behaviour, attitude approach Better adoption of practices Eco-protection Ecological modernisation Equity Human dimension, traditions Integrated, holistic approach Integrates economic factors Integrates people culture, religions Resource-conserving practices Tackles sources of issues	Handayani and Prawito (2009) Karami and Keshavarz (2009) Palaniappan et al. (2009) Wu and Sardo (2009)

(continued)

Table 1.1 (continued)

Practices	Benefits	References
Soil restoration	Decreases desertification Decreases poverty and hunger Decreases soil erosion Disease control Food security Increases biodiversity Increases yield Improves water quality Less pollutants	Anderson (2009b) Baize (2009) Barth et al. (2009) Bernoux et al. (2009) Changwen and Jianmin (2009) Etchevers et al. (2009) Erhart and Hartl (2009) Ghorbani et al. (2009a, b) Handayani and Prawito (2009) Knörzer et al. (2009) Lal (2009a, b, c, d, e, f) Pati et al. (2009) Roger-Estrade et al. (2009) Saha (2009) Sigua (2009) Shaxson (2009) Wrage et al. (2009)
Suicidal germination	Parasitic plant control	Runyon et al. (2009)
Terracing	Carbon sequestration Increases yield Soil erosion control	Doumbia et al. (2009) Zuazo and Pleguezuelo (2009)
Transgenic crops	Biopesticide Drugs, vaccines Easier weed control Higher income Increase yield Insect management Less pesticide treatments Reduced tillage	Bonny (2009) Deguine et al. (2009) Devos et al. (2009) Graef (2009) Marvier (2009) Sanchis and Bourguet (2009) Torres et al. (2009)
Trap crops	Pest control	Deguine et al. (2009) Kalinova (2009) Runyon et al. (2009) Torres et al. (2009)
Urban agriculture Local agriculture	Food security Lower prices Less environmental footprint Less transportation Local production and use Mitigates climate change Recycles wastes Provides employment	De Bon et al. (2009) Miah and Hussein (2009)

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Chapter 2
Sociology of Sustainable Agriculture

Ezatollah Karami and Marzieh Keshavarz

Abstract Sustainability is the core element of government policies, university research projects, and extension organizations worldwide. Yet, the results of several decades of attempt to achieve sustainable agriculture have not been satisfactory. Despite some improvement conventional agriculture is still the dominant paradigm. Pollution of water, soil, and air, degradation of environmental resources, and loss of biodiversity are still the by-product of agricultural systems. In light of these crises, based on review of current literature, it is argued that in promoting sustainable agriculture our perception should shift from a technocratic approach to a social negotiation process that reflects the social circumstances and the power conditions. Agriculture should be regarded as an activity of human; therefore, it is social as much as it is agronomic and ecological. Therefore, here we explore the contribution of sociology toward achieving agricultural sustainability. The review reveals that agricultural sustainability can no longer ignore the human dimension and social dynamics that are the core elements of agricultural development. Although the agricultural and ecological sciences are vital, social sciences must play their role to analyze the human dimension, which is central to understanding and achieving agricultural sustainability. The contributions of sociology of sustainable agriculture are exploring the relationship between farmers' attitudes and their sustainable farming practices, understanding the gender impact, offering different sustainability paradigms, providing different models of predicting adoption of sustainable practices, and finally informing decision makers regarding the social impacts of their sustainability decisions. Major findings are discussed and appropriate recommendations are provided.

Keywords Sociology • Sustainable agriculture • Climate change • Attitude • Human dimension • Social construct • Culture • Behavior • Adoption

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E. Karami (✉) and M. Keshavarz
College of Agriculture, Shiraz University, Shiraz, Iran
e-mail: ekarami@shirazu.ac.ir

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2.1 Introduction

Even though agriculture has made great progress in feeding the ever-increasing population, still it faces serious problems and challenges. Some of these challenges such as food production to feed the undernourished and increasing demand for poverty alleviation have been with us for a long time and will continue to be in foreseeable future. Food production will have to increase, and this will have to come mainly from existing farmland. Many predictions are gloomy indicating that gap between demand and production will grow. Population growth, urbanization, and income growth in developing countries are fueling a massive global increase in demand for food.

Sustainability, climate change, and replacing fossil fuels with renewable energy are relatively new challenges for agriculture. Overuse and inappropriate use of agrochemicals have led to contamination of water, loss of genetic diversity, and deterioration of soil quality (Rasul and Thapa 2003). Sustainability is not only a challenge in itself, but also a new worldview, a paradigm, which has changed our understanding of agriculture. This new paradigm seriously questions our conventional ways of solving agricultural problems and challenges. High external input or “modern agriculture,” which once was the promising approach to agricultural production, is now considered to be unsustainable. There is consensus that modern agriculture has diminished the importance of farming as a way of life, and creates certain problems such as ecological degradation (Alhamidi et al. 2003). There is also a growing skepticism about the ability of modern agriculture to increase productivity in order to meet future demand. Sustainable agriculture as a concept has emerged to address the challenges that are facing modern agriculture (Karami 1995).

Some researchers define sustainable agriculture primarily as a technical process. Altieri (1989) defined sustainable agriculture as a system, which should aim to maintain production in the long run without degrading the resources base, by using low-input technologies that improve soil fertility, by maximizing recycling, enhancing biological pest control, diversifying production, and so on. The technological and to a lesser extent economic dimensions of sustainable agriculture have tended to be privileged while the social dimension has been neglected. As a result sustainable agricultural has suffered from limited adoption. This paper argues that the way out of current crisis of promoting sustainable agriculture is to shift our perception from a technocratic approach to a social negotiation process that reflects the social circumstances and the power conditions in a specific region at a specific time (Blaschke et al. 2004). If one accepts the argument that the concept of sustainability is a “social construct” (Webster 1999) and is yet to be made operational (Webster 1997; Rasul and Thapa 2003), then sociology has a great deal to offer toward achieving agricultural sustainability. Understanding what agriculture and sustainable agriculture are, is a prerequisite to understand the sociology of sustainable agriculture.

2.2 Definition of Agriculture

The first point to clarify is: “What is agriculture?,” of course, there is general agreement about the sorts of things, people, plants, and animals that can be called agricultural, but this is not good enough if we are seriously interested in topics such as the role of science in agriculture, the role and importance of agriculture in the world, and how agricultural efficiency can be improved (Speeding 1988). Not many attempts have been made to be more precise and it is quite difficult to arrive at a definition that is both useful and specific. One of the useful definitions is phrased by Speeding (1988, 1996) as follows: “agriculture is an activity *of Man*, carried out primarily to produce food, fiber and fuel, as well as many other materials by the deliberate and controlled use of mainly terrestrial plants and animals.”

The terms “agriculture” and “ agricultural system” are used widely to encompass various aspects of the production of plant and animal material of food, fiber, and other uses. For analysts with a narrow vision, these terms are limited to the cultivation of soil and growth of plants. But for others, the terms also include financing, processing, marketing, and distribution of agricultural products; farm production supply and service industries; and related economic, sociological, political, environmental, and cultural characteristics of the food and fiber system (CAESS 1988). Since agriculture involves economics, technology, politics, sociology, international relations and trade, and environmental problems, in addition to biology it can be concluded that agriculture is social as much as agronomic and ecological. Taking a broad interpretation, agriculture is a system of processes that take place within a threefold environmental framework, biophysical environment, socio-political environment, and economic and technological environment. Together, these three sets of factors set the broad constraints within which individuals, groups, and governments engage in production, distribution, and consumption components of agriculture. These three sets of constraints for agriculture also provide a means of assessing conditions for sustainable agriculture (Yunlong and Smith 1994).

Agricultural sciences can no longer ignore the human intentionality and social dynamics that are the roots of our predicament. Although the natural sciences, and especially the earth and life sciences, remain of vital importance, not least to monitor and analyze the dynamics of “nature” so as to inform normative frameworks for sustained land use (De Groot 1992), social sciences must play their role among the agricultural sciences to analyze human activity as emergent from intentionality and greed, economic systems, human learning, and agreement (Roling 1997). We acknowledge that agricultural systems are human systems, so that “what is sustainable” will also be value laden. Agricultural systems are distinctive in those changes in values and attitudes of farmers, managers, and other stakeholders, and externally imposed risk, e.g., climate interaction (Karami and Mansoorabadi 2008).

2.3 The Human Dimension of Agricultural Sustainability

The human element is not one third of sustainability; it is central to its implementation (Pearson 2003). The challenge of sustainability is neither wholly technical nor rational. It is one of the change in attitude and behavior. Sustainability therefore must include the social discourse where the fundamental issues are explored collaboratively within the groups or community concerned. We do not do that very well, partly because of increasing populations, complexity, distractions, and mobility, but more because of certain characteristics of the dominant paradigm that are seen as desirable (Fricker 2001).

Social constructionists and philosophers have shown that we can never truly "know" nature, as our understandings of nature are shaped by the social and cultural lenses through which we see the world. This is not to argue that "there is no real nature out there," but instead that our knowledge of nature will always be, at least partly, social (see Cronon1996; Escobar 1996). In opening nature to public attention specialists have relinquished their authority over the constitution and meanings of nature and allowed nature to be contested by a much wider variety of stakeholders (McGregor 2004). After all, the construct of a sustainable future may look very different to cultures and individuals with a tradition of a "be all you can be" philosophy as compared with those who ascribe to a "live and let live" philosophy (Goggin and Waggoner 2005). Environmental imaginaries are highly contested and can be thought of as the ways in which a society collectively constructs, interprets, and communicates nature (McGregor 2004).

It is clear that rural sustainability is being undermined by agriculture, particularly as agriculture is the dominant user of rural land. However, in discussing sustainable agriculture, the ecological dimension has tended to be privileged while the social dimension has been neglected. The current economic and ecological crisis for agriculture has, therefore, opened up the space for a discussion of what sustainable agriculture might be, and how it might be operationalized. Social sustainability in much of rural areas is still to be sought through productivity agriculture. Thus, there continues to be a trade-off between ecological priority areas and the productivity pressures of the agricultural treadmill (Ogaji 2005).

Many research works underlined the importance of social and institutional factors for facilitating and achieving sustainable agriculture. Pretty (1995) had considered that local institutions' support and groups dynamics are one of the three conditions for sustainable agriculture. Roling (1994) has used the concept of platforms to emphasize the role of collective decision-making process in the ecosystems sustainability. Sustainable agriculture must be socially constructed on the basis of different perspectives and through stakeholders' interaction. As Roling and Jiggins (1998) observed, "ecologically sound agriculture requires change not only at the farm household, but also at the level of the institutions in which it is embedded" (Gafsi et al. 2006).

It is culture, which ultimately reproduces the heterogeneous pattern of farming and the meaning and shape of locality. There is a tendency to assume that as long as the proposed systems benefit the environment and are profitable, sustainability will be achieved and the whole of society will be benefited. However, what is produced, how, and for whom, are important questions that must also be considered if a socially sustainable agriculture is to emerge (Ogaji 2005).

Ikerd et al. (1998) explained that most farmers have not integrated the economic, ecological, and social aspects of sustainability into a holistic concept of sustainable agriculture. For den Biggelaar and Suvedi (2000), farmers may have a lack of information and awareness about sustainable agriculture and its multiple-dimensions (Gafsi et al. 2006).

The social dimension of sustainability addresses the continued satisfaction of basic human needs, food, and shelter, as well as higher-level social and cultural necessities such as security, equity, freedom, education, employment, and recreation (Altieri 1992). The provision of adequate and secure agricultural products (especially food), supplied on a continual basis to meet demands, is a major objective for sustainable agriculture (Altieri 1989). In the case of developing countries, more imperative demands are often basic household or community needs in the short term in order to avoid hunger. This is known as food sufficiency or carrying capacity problem. In developed countries, meeting demands more often means providing both a sufficient quantity and variety of food to satisfy current consumer demands and preferences, and to assure a safe and secure supply of food (Yunlong and Smith 1994).

The social definition of sustainability commonly includes the notion of equity, including intragenerational and intergenerational equity (Brklacich et al. 1991). The former refers to the affair and equitable distribution of benefits from resource use and agricultural activity among and between countries, regions, or social groups (Altieri 1989). The latter refers to the protection of the rights and opportunities of future generations to derive benefits from resources which are in use today (Crosson 1986). Agricultural production systems, which contribute to environmental deterioration are not considered to be sustainable as they pass on to future generations increases in production costs, together with reductions in income or food security. The two types of equity are sometimes related. For example, many subsistence farmers are forced to employ farming practices that provide immediate rewards, but also degrade the environment and thereby impair future generations' opportunities for sustainability (Yunlong and Smith 1994).

2.4 Achieving Sustainable Agriculture: Role of Sociology

Sociologists and other social scientists have played a significant role in the emergence, institutionalization, and design of sustainable agriculture. Sociologists and other social scientists have done particularly significant research on the adoption of resource-conserving practices. They have also made major contributions through their research into identifying user needs and implementation strategies relating to sustainable agriculture technology (Buttel 1993). For many scholars, sustainable agriculture lies at the heart of a new social contract between agriculture and society (Gafsi et al. 2006).

This paper argues that sociology and the other social sciences play an equally important and constructive role in understanding and achieving agricultural sustainability. Buttel (1993) suggests that this kind of application of sociology may be referred to as the sociology of agricultural sustainability. The major contribution of the environment-development debate is the realization that in addition to or in conjunction with these ecological conditions, there are social conditions that influence the ecological sustainability or unsustainability of the people–nature interaction (Lele 1991). Sometimes, however, sustainability is used with fundamentally social connotations. For instance, Barbier (1987) defines social sustainability as "the ability to maintain desired social values, traditions, institutions, cultures, or other social characteristics." This usage is not very common, and it needs to be carefully distinguished from the more common context in which social scientists talk about sustainability, viz., and the social aspects of ecological sustainability.

Sustainability as a social vision is, on the one hand, not only potentially acceptable, but does, in fact, meet with correspondingly broad approval across all societal groups and political positions, nationally and internationally. On the other hand, sustainability's conflict potential cannot be overlooked. As soon as relatively concrete goals or even strategies of societal action for attaining sustainability are put on the agenda – at the latest – it becomes obvious that the usual antagonistic societal values and interests are lurking behind the programmatic consensus (Grunwald 2004).

Despite the diversity in conceptualizing sustainable agriculture, there is a consensus on three basic features of sustainable agriculture: (i) maintenance of environmental quality, (ii) stable plant and animal productivity, and (iii) social acceptability. Consistent with this, Yunlong and Smith (1994) have also suggested that agricultural sustainability should be assessed from ecological soundness, social acceptability, and economic viability perspectives. "Ecological soundness" refers to the preservation and improvement of the natural environment, "economic viability" to maintenance of yields and productivity of crops and livestock, and "social acceptability" to self-reliance, equality, and improved quality of life (Rasul and Thapa 2003). Sociology of sustainable agriculture deals with the following issues:

Paradigms used to interpret sustainability
Sociological models developed to explain attitudes and behaviors toward sustainability
Adoption of sustainable agriculture practices
Gender and sustainable agriculture
Social impact assessment and sustainable agriculture

These issues will be briefly dealt with in the following sections.

2.4.1 Sustainable Agricultural Paradigms

There are many different schools of thought about how to interpret sustainability (Colby 1989). Sustainable development incorporates the idea of transformations of relationships among people and between people and nature. Batie, however, believes that considerable tension exists between those schools of sustainable development thought that draw their strength from the ecological science paradigm and those from an economic science paradigm (Batie 1991). In her view the assumptions of the two main paradigms have the following differences. First, economic and ecological paradigms differ in their assumption as to relative scarcity. Economics incorporates a belief in almost unlimited possibility of substitution of human-made capital for natural resource capital, while ecologists tend to incorporate the idea of absolute scarcity and hence real limits to economic growth as a key assumption in their respective paradigms. The second major difference between the two paradigms stems from their perspectives of the economic and natural system (Karami 1995).

Another major school of thought can be termed "eco-protection" and is preservationist in nature, that is, it has an objective, the maintenance of the resource base, and it draws heavily from the ecological sciences (Batie 1991). In contrast to the economics of the driving paradigm of "resource management" that works with the world and its values as they are found, the eco-protectionists strive to change the world to be what they desire. Thus, within this perspective there is heavy emphasis on changing people's values, limiting population growth, and on redistribution of society's income and wealth. While the resource managers' goal may be to lift the poor closer to the rich through the adoption of nonpolluting, efficiency-enhancing technology, the eco-protectionist is more likely to advocate pulling the rich toward the poor through land tenure reform, redistribution of income, and adoption of appropriate small-scale technology (Batie 1991; Karami 1995).

Across all literatures, two broad paradigms of sustainability are identifiable: one supporting a systems-level reconstruction of agricultural practice to enhance biological activity, and the other adopting a technological fix, in which new technologies inserted into existing systems can improve sustainability outcomes (Fairweather and Campbell 2003).

Rezaei-Moghaddam et al. (2006) analyzed Ecological Modernization theory and the De-Modernization theory to provide a conceptual framework for sustainable agricultural development. They argue that Ecological Modernization and De-Modernization theories could be used to develop conceptual frameworks for sustainable agricultural development. The two approaches reviewed provided very different explanations of environmental change and they point in very different directions. The conceptual path based on De-Modernization theory has great concern for environmental protection and less attention to increased production. Agricultural development theory based on Ecological Modernization breaks with the idea that environmental needs are in conflict with agricultural production. It argues instead that agricultural productivity and growth and resolution of ecological problems can, in principle, be reconciled. Thus, it assumes that the way out of the negative environmental consequences of agriculture is only by going into the process of further modernizing agriculture. Evans et al. (2002) state that observed trends in agriculture could be viewed as part of a move toward Ecological Modernization and many of the trends with regard to food quality and safety and environmental management fit well into the Ecological Modernization. Contrary to conventional agriculture, an Ecological Modernization agricultural development theory emphasizes on introducing ecological criteria into the production and consumption process. It assigns an important role to science in the production process. Clean technology or what is known as "precision agriculture" is the key to achieve sustainable agricultural development. In contradiction with the De-Modernization agricultural development perspective, sustainable agricultural development under the Ecological Modernization perspective does not mean having less agricultural growth and production.

Rezaei-Moghaddam et al. (2006) emphasize that there is a growing consensus over the need for a shift in paradigm if sustainable agriculture is to be realized. A paradigm shift in agriculture is a change from one way of thinking about agriculture to another. It is a revolution, a transformation, and a sort of metamorphosis in the soft side of agriculture, which eventually will result in changes and the transformation of hard side of agriculture. Ecologically sound agriculture is a complex system, not only in terms of complex interactions among soils, crops, animals, and farming practices (hard system), but also in terms of human knowledge and learning, institutions, and policies (soft system).

2.4.2 Attitudes, Behaviors, and Sustainable Agriculture

Attitudes are defined as a disposition to respond favorably or unfavorably to an object, person, institution, or event. An attitude is (a) directed toward an object, person, institution, or event; (b) has evaluative, positive or negative, elements; (c) is based on cognitive sustainable agricultural attitudes and behaviors beliefs toward the attitude object (i.e., the balancing between positive and negative attributes of an object leads to an attitude); and (d) has consequences for behavior when confronted with the attitude object (Bergevoet et al. 2004; Karami and Mansoorabadi 2008).

Attitude is a predisposition to act in a certain way. It is the state of readiness that influences a person to act in a given manner (Rahman et al. 1999). Therefore, attitude surveys in agriculture could lead to a more adequate explanation and prediction of farmers' economic behavior and have been used on conservation and environmentally related issues focusing on the influence of attitude variables as predictors of conservation behavior (Dimara and Skuras 1999). Dimara and Skuras (1999) concluded from their research that a significant relationship was found between behavior and the goals and intentions of farmers. This relationship is even stronger when statements on attitudes, social norms, and perceived behavioral control are included (Bergevoet et al. 2004)

Calls for the study of farmers' behavior and what motivates that behavior are not new (Gasson 1973). However, the number of studies that have considered farmers' attitudes toward conservation (MacDonald 1984) is small. Fewer still have studied farmers' conservation actions. Potter (1986) points out that a very limited number have tried to link farmers' actions to their underlying motivations, notwithstanding the discourses on the conservation issues in the countryside (Beedell and Rehman 2000). Almost all studies related to the motivational elements of behavior have stressed that the decision to act in a certain way is affected by a "balancing" or weighing of a number of influences. Lemon and Park (1993) concluded that farmers, when trying to achieve "good practice" on their farms, balance environmental, physical, and commercial factors in their decisions about their farming system. Clark (1989) suggested that farmers' decisions about whether to take advice about conservation were affected by three distinct dimensions: the policy environment facing farmers, the advisory structures in place, and the personality of the farmer.

Discussions of the value to be attributed to the preservation of a natural system invoke two distinct sources of value: extrinsic and intrinsic values. Extrinsic value arises from the fact that the environment increases the satisfaction or utility of humans. In this utilitarian philosophy, nature has value insofar as it is useful or agreeable to humans. The intrinsic value of a natural system exists irrespective of its usefulness or amenity to humans. This view explicitly grants rights to exist to nonhuman species or to the environment as a whole. The intrinsic value approach may thus require decision makers to make decisions knowingly counter to their own present on future interests (Pannell and Schilizzi 1999).

Potter (1986) finds any change in the countryside to be, "both 'determined' by policy, institutional, and family influences and 'intentioned' by the farmer acting as a problem-solving individual." This study differs from most previous studies of farmers' conservation behavior as it does not explicitly consider farmers' investment in conservation (Potter 1986); instead, it is concerned with how and why farmers manage the existing features on their farms (hedges, field margins, woods, and trees). This difference is crucial as there is considerable evidence (Potter 1986; Pieda 1993) to suggest that most farmers have a "creative" rather than "preservative" view of conservation. Most of the previous research shows that advice on tree planting, pond creation, and woodlands is most commonly sought, and that leaving seminatural areas undisturbed is not seen as conservation (Beedell and Rehman 2000). Newby et al. (1977) found that farm size alone could not explain farmers' attitudes toward conservation as larger farmers were both more hostile (agri-businessmen) and more sympathetic (gentleman farmers) to conservation than farmers in general. This finding has led further investigations on the topic to consider both a farmer's interest in conservation and his financial constraints as factors that determine his attitude to conservation (Gasson and Potter 1988). In studying voluntary land diversion schemes, Gasson and Potter (1988) found that the financially least constrained and most conservation orientated farmers were the most receptive to the schemes, asked for below average compensation for the land diverted and offered the most acres.

The way farming is presently practiced across the world and the impact of agriculture on wetlands is determined, to a great extent, by the levels of environmental awareness, knowledge and attitudes of farmers, and stockbreeders (Oakley 1991). A stronger "utilitarian" attitude to the natural environment has been found among farmers owing vulnerable ecosystems compared to other population groups (Wilson 1992; Pyrovetsi and Daoutopoulos 1999). Gigerenzer (1996) pointed out that social context of behavior, such as values and motivations, play an important role in the rationality in peoples' decisions. Thus attitudes have causal predominance over behaviors (Heong et al. 2002).

There is consistent evidence in the literature indicating a relationship between farmers' attitudes toward environment and their farming practices (Fairweather and

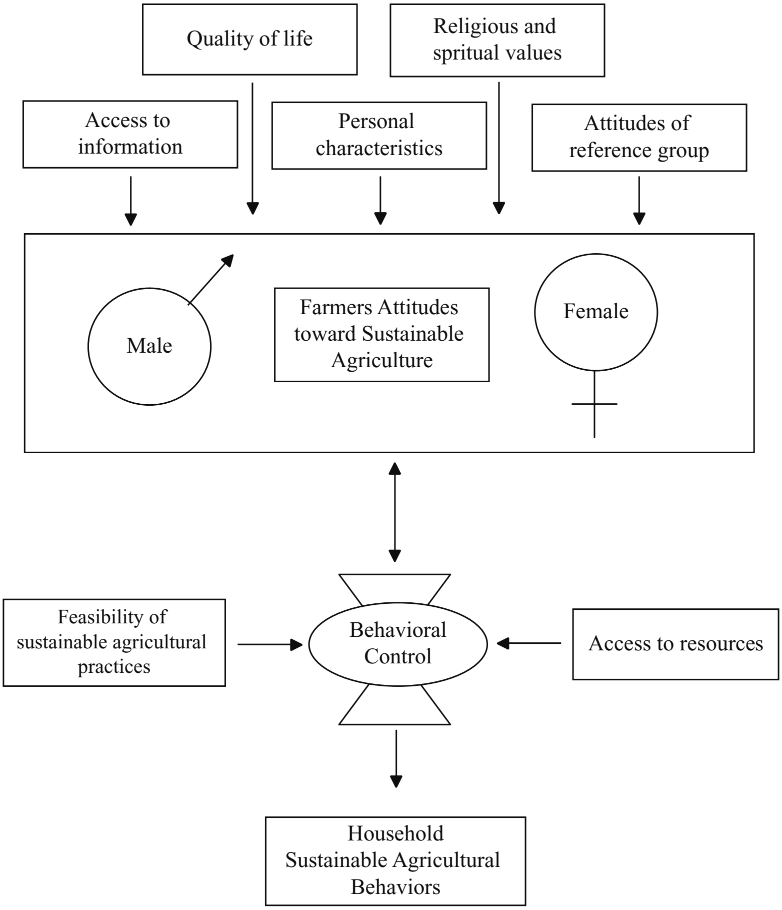

Fig. 2.1 Theoretical framework of factors influencing farmers' sustainable agricultural attitudes and behaviors (From Karami and Mansoorabadi 2008). According to this theoretical framework, farmers' action is guided by two kinds of considerations: attitude toward sustainable agriculture and presence of factors that may further or hinder performance of the behavior

Campbell 2003; Rezaei-Moghaddam et al. 2005; Karami and Mansoorabadi 2008). Karami and Mansoorabadi (2008) developed a theoretical framework to explain the relationship between sustainable agricultural attitudes and behaviors. A schematic representation of the theoretical framework of this study is shown in Fig. 2.1. Briefly, according to this theoretical framework, farmers' action is guided by two kinds of considerations:

Attitude toward sustainable agriculture: Religious and spiritual values, quality of life, access to information, personal characteristics, and attitudes of reference group are the factors, which influence farmers' belief system and contribute toward formation of sustainable agricultural beliefs. The framework assumes that religious and spiritual beliefs contribute to farmers' attitudes toward sustainability, or more specifically that spirituality can be a resource in maintaining environment. Furthermore, a correlation between farmers' quality of life and attitudes toward sustainable agriculture is assumed. Farmers who enjoy a better quality of life are expected to possess more positive attitudes toward sustainable agriculture. One feature of this framework is that access to information and type of information received is a fundamental contributor toward attitude formation. Knowledge and information bring confidence, skills, ability, and experience. If farmers believe that it is easy for them to perform, then they are likely to engage in the behavior. Personal characteristics such as farming experience and education are strong determinants of attitudes. Finally, farmers beliefs about the normative expectations of significant others (attitudes of reference group) is a major determinant of attitudes. The view that women are closer to nature because of their nurturing and caring role, leads the model toward assuming that women, due to gender-based division of labor, and their role in attending to the everyday needs of the household, posses an intimate knowledge of the environment. Therefore, even under similar conditions women may develop different attitudes than men regarding sustainable agriculture.

Control factors: These are beliefs about the presence of factors that may further or hinder performance of the behavior (access to resources and feasibility of sustainable agricultural practices). The framework assumes that behaviors are not within a farmer's control. In their respective aggregates, determinants of attitudes result in perceived social pressure or subjective norms; and control factors give rise to perceived ease or difficulty of performing the behavior. In combination, attitude toward the behavior, subjective norm, and perception of behavioral control lead to the practice of a sustainable agricultural behavior. As a general rule, the more favorable the attitude and subjective norm, and given a sufficient degree of actual control over the behavior, farmers are expected to carry out sustainable agricultural behaviors when the opportunity arises. However, because many behaviors pose difficulties of execution that may limit volitional control, it is useful to consider control factors. To the extent that people are realistic in their judgments of a behavior's difficulty, a measure of perceived behavioral control can serve as a proxy for actual control and can contribute to the prediction of the behavior in question. Farmers, who believe that they have neither the resources nor the opportunity to perform sustainable agricultural practices, are unlikely to form strong behavioral intentions to engage in it even if they hold favorable attitudes and believe that important others would approve of their performing the behavior. We would thus expect an association between perceived behavioral control and actual behavior that is not mediated by attitude and subjective norm. Economic factors, access to resources, and feasibility of sustainable agricultural practices significantly affect sustainable agricultural behaviors.

2.4.3 Adoption of Sustainable Agricultural Practices

While many more farmers now seem to have a better awareness of the negative environmental and social consequences of conventional and social consequences on conventional agricultural systems, this has not translated into a major shift toward the adoption of sustainable practices (Alonge and Martine 1995).

As farmers increasingly confront declining per capita return arisen from miniaturizing land holdings caused by steadily growing population, they are required to make additional efforts to increase agricultural production. They will thus adopt an agricultural system only when it is both economically and environmentally suitable (Rasul and Thapa 2003).

The adoption of sustainable agriculture strategies/technologies has received frequent attention in recent years, both by producers and consumers. Despite economic and noneconomic disadvantages of conventional agriculture, farmers have been slow to adopt these practices, and adoption appears to vary widely by region and crops (Musser et al. 1986).

Attempts to explain the low adoption rate have been many and varied (Alonge and Martine 1995). Lovejoy and Napier (1986), for instance, blamed the little success achieved by past efforts to encourage farmers' adoption of sustainable agricultural innovations on what they termed the American penchant for attempting a technological fix for every problem. They contended that past efforts have concentrated on telling farmers of the negative environmental impact of their production systems in the hope of engendering attitudinal change and as a consequence the adoption of Best Management Practices. They pointed to the futility of such an approach, observing that findings of past research showed that farmers continued to use practices that degraded the environment even when they: (1) were aware of the negative environmental impact of their agricultural practices; (2) believed they had a social responsibility to protect the environment; and (3) had favorable attitudes toward soil and water conservation (Alonge and Martine 1995).

Much of the research effort in adoption of sustainable agriculture has been fragmented, with little coordination and integration. Several issues have not been adequately treated in previous studies. While research on sustainable agriculture systems has produced information on several alternative practices, little substantive research has investigated the structure of belief and motivation that drive farmers' decisions about sustainable agriculture systems adoption (Comer et al. 1999).

Such findings have raised questions about the relevance of the traditional diffusing model for explaining the adoption of conservation technologies. Critics argued that while the study of the adoption and diffusion of technologies under the rubric of the classical adoption–diffusion model have contributed immensely to the understanding of the adoption process as they relate to commercial farm technologies and practices, the model may not provide full explanation of the adoption process when applied to sustainable agricultural practices (Alonge and Martine 1995).

Hence, the need for new perspectives has been called for in the study of the adoption and diffusion of sustainable agriculture, with focus on access to, and quality of information (Lovejoy and Napier 1986), the perception of innovations, and the institutional and economic factors related to adoption (Alonge and Martine 1995). Some studies have concluded that it is likely that the successful adoption of conservation practices would be influenced more by a farmers' attitude and perception, than any other factor (Alonge and Martine 1995).

According to classical technology adoption theory, technology adoption in agriculture is related to demographic characteristics of farmers, and occurs initially among young, well-educated farmers who operate relatively large farms, and own rather than rent land. However, innovations that are primarily focused on environmental benefits ("environmental innovations," e.g., integrated pest management) are fundamentally different from traditional technologies, in that they may be complex groupings of practices, which are not necessarily applicable to all farms, and they may offer more benefit to society as a whole than they do to adopters. The demographic and attitudinal characteristics important in the adoption of environmental innovations may be different than those for traditional technologies. Some studies have found demographic and attitudinal differences between farmers practicing conventional versus reduced-input agriculture. Others have found that farmers interested in reducing pesticide use are demographically and attitudinally similar to mainstream farmers. Farmer support for reduced-input practices has also been reported to be related more to attitudinal than demographic factors. The potential impact of a given pesticide use reduction strategy will be greater if the strategy appeals to farmers with average or typical demographics and attitudes. The adoption of pesticide use reduction strategies can be facilitated through targeted extension if the target group of farmers and farms can be characterized (Nazarko et al. 2003).

A basic assumption of farming systems research is that farmers are intentionally rational in the way they manage their farming operations, including their choice of technology. That is, they choose farming technologies in order to further their goals, subjected to the constraints imposed by resource availability (land, labor, and capital) and environmental conditions (biophysical and socioeconomic) (Cramb 2005). For small farmers who are struggling for food security, current needs are more important than future needs. Even profit-seeking large farmers will not venture into ecological agriculture unless it provides sufficient income (Rasul and Thapa 2003).

Economic considerations are often very important in the adoption of conservation or reduced-input practices. Noneconomic factors can also be important in farmers' decisions to reduce agrichemical use. Also, concern about environmental pollution is consistently positively correlated with farmer's willingness to adopt pesticide use reduction practices; however, economic factors often take precedence over such concerns. Farmers' perceptions of the economic outcome of reduced pesticide use are critical to its adoption (Nazarko et al. 2003).

Kinnucan et al. (1990) observed that there is a relationship between age and farmers' adoption behavior. While younger, less experienced farmers are expected to be more environmentally aware and more likely to adopt sustainable practices, there is no consensus regarding the relationship between farmers' age and environmental concern.

It would therefore be expected that farmers with higher levels of education would be more likely to implement pesticide use reduction. Despite, most comparisons between conventional and organic farmers do not show significant differences in level of formal education (Nazarko et al. 2003). There is conflicting evidence over the role of land ownership in the adoption of sustainable farming practices.

Tenancy (rather than ownership) has been found to be negatively related to the adoption of sustainable practices. However, economic pressures may override incentives for conservation associated with land ownership. Membership in different types of farm organizations may be representative of, or may influence, farmers' perceptions of acceptable farming practices and knowledge of sustainable practices (Nazarko et al. 2003)

The sustainability debate has taught that economic, social, and environmental problems and, more importantly, their solutions are as much cultural as technological and institutional. Cultural diversity, therefore, offers humanity a variety of ways of developmental interaction and avoids the difficulties associated with any monoculture, namely, loss of material for new paths of economic, social, and environmental evolution, and a danger that resistance to unforeseen problems is lowered (Jenkins 2000). In addition to culture, study of the linkage between environment poverty and sustainable agriculture to provide a more realistic picture of the situation has been of great interest to researchers (Karami and Rezaei-Moghaddam 1998; Karami 2001; Karami and Hayati 2005; Rezaei-Moghaddam and Karami 2006).

2.4.4 Gender and Sustainable Agriculture

Women's survival and that of their household and communities depend on access to and control of natural resources, such as land, water, forest, and vegetation. They perform the majority of the world's agricultural work, producing food for their families, as well as other goods that are sold in national and international markets. Women are traditionally the prime participants in the agricultural systems. In agricultural production, the relationship of workers to the production process is different from other types of capital production because it largely flows with the rhythm of biological processes (Meares 1997). Family-based farming adds another element to the relationship of workers to production; that is, boundaries are significantly blurred between the household and the enterprise. Thus, "the unit of production – the agricultural enterprise – is coterminous with the unit of reproduction – the farms household." Such muddy waters make understanding women's and men's work on the farm complex and these difficulties may render women's work "invisible" (Meares 1997).

Women have learned to manage these resources in order to preserve them for future generations (Atmis et al. 2007). Although, the impact of attitude and behavior of rural men on sustainability of agriculture is often acknowledged, the importance of women's attitude in shaping agriculture is ignored (Karami and Mansoorabadi 2008). Because women's different and important contributions to the farm and family are not institutionally recognized and addressed by the sustainable agriculture movement, the movement's goals, vision, and activities are gender-specific, dominated by men's participation and contributions (Meares 1997; Karami and Mansoorabadi 2008). Government and institutional policies often fail to recognize the importance of women's access to natural resources. While research has shown that agricultural productivity increases significantly when female farmers have access to land and technology, women own less than 2% of all land. Women's access to and control of resources is far from guaranteed (Pearl 2003). Women suffer most from environmental disasters and reduced availability of forest products. It is the women and children who collect fuel wood, animal fodder, decayed leaves, and other forest products. Furthermore, they are held responsible for tending sheep, goats, and other domestic animals owned by their families (Boo and Wiersum 2002; CFAN 2005).

Some of the issues that have been addressed by sociologists with regard to women's impact on sustainable agriculture include the following:

- The social construct of gender makes a difference in how farmers perceive quality of life. This social construction, in turn, affects participation in the sustainable agriculture movement. Traditional gender roles assign different responsibilities to women and men. This has resulted in political, cultural, and economic barriers that restrict women's access to natural resources. For example, women are frequently excluded from decision making. Community leaders may not invite women to meetings related to resource use, or expect only the men to present their concerns. Lower levels of literacy and education among women may further restrict their participation (Atmis et al. 2007).
- At the root of these gendered differences in quality of life is the fact that life goals and daily experiences for male farmers within the family have changed significantly as their involvement in the movement has intensified. Much of what men emphasize in describing quality of life reflects the values the sustainable agriculture movement itself espouses: self-empowerment, social justice, balance in economic gain and environmental health, creativity, and autonomy in decision making and problem solving (Meares 1997).
- In many developing countries agriculture is vital for sustainable rural development and recognized as a main means for reducing poverty and ensuring economic growth. In this sense, reducing poverty in rural areas depends significantly on sustainable agricultural development. However, agricultural development should be considered not only in increasing production, but also in developing rural society that includes women (Akpinar et al. 2004). Women seldom have direct access to, or control of, privately held resources, therefore, they are more likely than men to be attuned to common resources and their condition (Chiappe and Butler 1998). Even when women do have legal ownership of land, they are less likely than male owners to make land-use decisions. Women's responsibilities in the domestic sphere give them a different perspective on sustainability. Some authors (Chiappe and Butler 1998) argue that women's limited access to and control over resources – financial, manufactured, human, social, and environmental – often limits their ability to put their values into practice. Women's concern for quality of family is a key part of sustainability. Chiappe and Butler (1998) suggest that not only do the women think that farming in a sustainable manner can improve the health of their families and environment, but also claim that sustainable practices decrease labor time and increase free time to spend in other more valued activities, such as vacationing with the family. Improving the health of the family often involves using safer farming practices, in particular applying fewer or no chemicals (Karami and Mansoorabadi 2008).

- The view that women are closer to nature because of their nurturing and caring role (biological determinism) is another basis for assuming sustainability role for women. On the basis of empirical evidence (Mishra 1994) it would be more precise to say that women are closer to nature because of the gender-based division of labor, and their role in attending to the everyday needs of the household. Women are the primary natural resources managers, and they posses an intimate knowledge of the environment (Karami and Mansoorabadi 2008). Others argue about women's spirituality and how it mediated and required their honoring of nature. Sustainability will require reconnect with the spiritual roots of humanity (Ikerd 2001). Often, women sensed a strong connection between alternative agriculture and their families' spiritual values and beliefs. Spirituality and religion are viewed as "women's work" in many cultures, despite men's formal religious leadership. Women's understanding of harmony with nature emphasized spiritual elements. The transcendence of spirituality is embodied in their active choice to work with nature rather than overcoming it. In some cases, these values and beliefs were deeply rooted in their religious backgrounds (Karami and Mansoorabadi 2008).
- Generally, past studies concluded that young women with high levels of income and education and with liberal political views are the most likely to consider environmental protection a priority (Brody et al. 2004). Most research finds slight evidence that women are more environmentally concerned or possess stronger environmental attitudes than men; however, gender does not appear to be as significant a predictor of environmental concerns or attitudes as other sociodemographic variables (Brody et al. 2004; Karami and Mansoorabadi 2008).
- It is clear that farm women are not a homogenous group. Their position and role in family farming depends on how they participate in the productive process and is contingent on power relations in the household, on personal aspirations, and on other individual characteristics. It is nevertheless useful to observe the element of typological homogeneity amid the heterogeneity of groups characterizing the female farm population. Such observation may help clarify the differences at the level of roles and relationships, the better to interpret notable variations in women's behavior and predict future tendencies (Kazakopoulos and Gidarakou 2003).

2.4.5 Social Impact Assessment and Sustainable Agriculture

Social impact assessment can be defined as the process of assessing or estimating the social consequences that are likely to follow from specific policy actions or project development, particularly in the context of appropriate national, state, or provincial environmental policy legislation (Vanclay 2003; Burdge 2004). It includes all social and cultural consequences to human populations of any public or private actions that alter the ways in which people live, work, play, relate to one another, organize to meet their needs, and generally cope as members of society

(Momtaz 2005). Cultural impacts involve changes to norms, values, and beliefs of individuals that guide and rationalize their cognition of themselves and their society (Burdge and Vanclay 1995). Some have tried hard to define social impact assessment as a process. For example Vanclay (2002) believes that social impact assessment is the process of analyzing (predicting, evaluating, and reflecting) and managing the intended and unintended consequences on the human environment of planned interventions (policies, programs, plans, and projects) and any social change process invoked by those interventions so as to bring about a more sustainable and equitable biophysical and human environment.

Social impact assessment, is an overarching framework that encompasses all human impacts including aesthetic (landscape, development, economic and fiscal, gender, health, indigenous rights, infrastructure, institutional), political (human rights, governance, democratization, etc.), poverty-related, psychological, and resource issues (access and ownership of resources) (Vanclay 2002). The value of social impact assessment in social development, policy making and planning, public involvement, conflict management, and sustainable development has been acknowledged (Barrow 2000).

In line with the triple bottom-line approach from sustainable development (Vanclay 2004), the social impact assessment is of particular importance in considering the social sustainability of agriculture. There is no doubt that the social impact assessment is as important, in some cases even more important than the assessments of biophysical and economic dimensions of sustainable agriculture (Pisani and Sandham 2006). There have been many agricultural development projects in developing countries focusing on rural area in arid and semiarid lands in the past 3 decades. These have faced numerous social challenges such as a growing sense of rural households' dissatisfaction, negative attitudes, and conflicts with the project and as a result unsustainability (Ahmadvand and Karami 2009).

The three main goals of sustainable agriculture are economic efficiency, environmental quality, and social responsibility (Fairweather and Campbell 2003). Certainly, social sustainability is a core dimension of sustainable agriculture. Social impact assessment is necessary to provide information on social sustainability of agricultural development. It makes agricultural sector more inclusive by involving key stakeholders. It makes agricultural projects more socially sound by minimizing or mitigating adverse social impacts, maximizing social benefits, and ensuring that the projects are in line with sustainable development (Becker 2001). It has considerable potential to give social criteria their rightful place alongside economic and environmental criteria in sustainable agriculture. Social impact assessment is important in sustainable agriculture development, because it helps planners, agricultural development project proponents, and the impacted population and decision makers to understand and be able to anticipate the possible social consequences on human populations and communities of proposed agricultural development activities or policy changes. Social impact assessment should provide a realistic appraisal of possible social ramifications and suggestions for project alternatives and possible mitigation measures (Burdge 2004). For sustainable agriculture development, perhaps more than any other application, social impact assessment must integrate with physical impact assessment (e.g., Environmental Impact Assessment), economic appraisal, and other impact assessments (Barrow 2000). The need for such integration with other impact assessments arises because agriculture is being sustainable only if complex of factors are right; if just one is inadequate, production falters and may well fail.

2.5 Conclusion

Agricultural sustainability can no longer ignore the human dimension and social dynamics that are the core elements of agricultural development. Although the agricultural and ecological sciences are of vital importance, social sciences must play their role to analyze the human dimension, which is central to understanding and achieving agricultural sustainability. Sustainable agriculture is a philosophy based on human goal and an understanding of the long-term impact of our activities on the environment and other species. Sociology of sustainable agriculture has contributed to our understanding of sustainability by the following:

- Offering different schools of thought (paradigms) about how to interpret and achieve sustainability. There is a need for a shift in paradigm if sustainable agriculture is to be realized. A paradigm shift in agriculture is a change from one way of thinking about agriculture to another. Sustainable agriculture is a complex system, which requires changes in the hard system as well as soft system.
- Exploring the relationship between farmers' attitudes and their sustainable farming practices. In this regard sociologists have provided theoretical framework and empirical models to explain the relationship between sustainable agricultural attitudes and behaviors. These frameworks are used to guide policy makers, development agents, and researchers on how to design and implement sustainable agriculture.
- Investigating the potential of diffusion and other alternative adoption models in explaining and predicting sustainable farming practices. Although, studies have found that cultural, economics, demographic, and attitudinal variables are important in explaining farmers' sustainable behaviors, the findings in this regards are not conclusive and further investigations are needed to develop more robust models with greater validity.
- Raising awareness regarding women's role in sustainable agriculture. The neglect of women's role is due in part to the assumption of separation of family and work. While in family farms the workplace and the family are often indistinguishable. Women concern for quality of family is a key part of sustainability. It is clear that farm women are not a homogenous group. Their position and role in sustainability is determined by their level of participation in the production process. There is a general agreement that women's actions from local to the global policy-making arenas are a driving force for sustainability of agriculture. Sociologists have explored how women advance sustainable agriculture and

made the role of women visible. It can be concluded that there is support for the thesis that women play an essential role in advancing sustainable agriculture.

- Informing practitioners, researchers, and decision makers regarding the value of social impact assessment in achieving agricultural sustainability. Social impact assessment suggests what social changes are likely and what measures may be needed to establish supportive social institutions crucial for promoting and sustaining sustainable agriculture.

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Chapter 3
Sustainable Versus Organic Agriculture

Juying Wu and Vito Sardo

Abstract Awareness and concern for problems related to environmental quality are growing at a steady pace: climate change, biodiversity, soil fertility decay and above all food quality and pollution are everyday subjects for debates and discussions. The complexity of the problems and the uncertainty about many basic data quite often make discussions inconclusive; even indications issued by scientific authorities are sometimes misleading, and the problems are exacerbated by the frequent influence of ideological positions. In an endeavour to contribute to clarify agriculture-related environmental issues, a review is made here of the principles of sustainable agriculture and of the ways to deal with them. The need is emphasized for a system approach which is able to reconcile economic-productive, environmental and social aspects, the three 'pillars' of sustainability, permitting to consider simultaneously the numerous factors concurring to determine the most appropriate production strategy, and the necessary flexibility in selecting and combining such factors is also outlined. A critical overview is made of the possible options for improving the sustainability of the four principal groups of agricultural operations: cultivation, fertilization, irrigation and pest control. For each of them, the sustainability level of various possible courses of action is estimated as resulting from their expected impact on the three 'pillars' of sustainability and indications are given to avoid risks deriving to agricultural sustainability from misconceptions of non-scientific approaches, including some typical of organic farming. For cultivation, the adoption of some form of conservation tillage is suggested and the various possible options are critically examined. The conclusions for fertilization are that generally the best solution is a blending of organic and mineral fertilizers and that food quality is not influenced by the origin of the fertilizer. Criteria for optimizing irrigation system design and management are illustrated, with reference to energy input, soil protection against erosion and salinity build-up, and reduction in production risks. For pest control, integrated pest management approaches

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J. Wu
Beijing Research Center for Grass and Environment

V. Sardo (✉)
Department of Agricultural Engineering, University of Catania, via Santa Sofia 100,
95123, Catania, Italy
e-mail: sardov@unict.it

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including proactive activities and the parallel reduction to the possible extent of synthetic pesticide applications result in the most sustainable solution. Emphasis is given to those aspects of sustainability, such as soil and water conservation, energy savings, CO_2 balance, which are often overlooked, yet are an important component of sustainability. It is argued that an effective, long-term sustainability of agriculture must primarily gain farmers acceptance and therefore selected solutions must guarantee profit levels and productivity while not increasing risks. It is concluded that since the concept of sustainability is fundamentally dynamic, site- and time-specific, proposed solutions are expected to be flexible, custom-tailored for the single farms and open to technological and scientific progress, avoiding any pre-concocted paradigm and dogmatism; as a consequence, it is evidenced that some rigid principles typical of organic farming are not compatible with sustainable agriculture.

Keywords Cultivation • Fertilization • Indicators • Integrated pest management • Irrigation • Land conservation • Organic farming • Pest control • Sustainable agriculture

Abbreviations

ATTRA	National Sustainable Agriculture Information Service, USA
CTIC	Conservation Technology Information Centre, USA
DRC	Desert Research Center, Egypt
EISA	European Initiative for Sustainable Development in Agriculture
FAO	Food and Agriculture Organization of the United Nations
EIQ	Environmental Impact Quotient
GJ	GigaJoule
IFAD	International Fund for Agricultural Development
IPM	Integrated Pest Management
IRRI	International Rice Research Institute
LD50	Lethal Dose 50% (dose killing 50% of tested population)
MJ	MegaJoule
SARE	Sustainable Agriculture Research and Development, USDA
SAREP	Sustainable Agriculture Research and Development Program, USDA
USDA	United States Department of Agriculture
WHO	World Health Organization

3.1 Introduction

3.1.1 The Problem

In spite of some optimistic or not-so-pessimistic views (e.g. Penning de Vries et al. 1995; Avery 1999; Lomborg 2001), little doubt exists that conventional, high-input agriculture is on the whole unsustainable and that steps must be taken to curb the environmental decay. Although food quality is sufficiently protected, at least in theory, through the existing laws, and indeed no evidence is found in the scientific literature supporting or rejecting a worse quality or taste of conventional food as compared to the 'organic' food, yet the damage to the 'natural capital', not to mention the social aspects very much stressed by Ikerd (1996, 2001a, b, 2008), is certainly high.

It has been reported that in the UK the 'external costs' of agriculture in 1996 amounted to a staggering 89% of the average net farm income (Pretty et al. 2000), that *annual damage by pesticides and fertilizers to water quality is suspected to range in the billions of dollars* (Doran et al. 1996) and that annual off-site damages from soil erosion by water in the USA are over US$7 billion (Pimentel et al. 1993).

Many alternative, more or less fanciful approaches have been suggested to conventional agriculture, all aiming to reduce the input of non-renewable resources and all claiming to permit the achievement of sustainable agriculture, such as integrated farming, ecological farming, permaculture, organic farming, alternative agriculture, biodynamic farming and many others. Of all the above groups, only organic farming can boast an established set of officially coded rules and standards, with minor differences among different countries (European Commission 2000, 2007; FAO/WHO 2001; Australia, Haas 2006; USDA 2007), and enjoys substantial funding; nevertheless, many sound principles deserving full consideration, sometimes more rational than those of organic farming, are suggested by other systems, which can be usefully adopted in the quest for enhanced, more sustainable agro-ecosystems. Conversely some principles of organic farming are potentially hindering the progress towards sustainability, hence the need to objectively evaluate all the possible combinations of cultural practices and then select the optimized strategy for every single farm.

Integrated farming, for instance, developed by the EISA, a group of six European organizations, is based on a set of sound, sensible rules judiciously adopting some principles of organic farming, integrating them when they are *insufficiently* restrictive, e.g. when the need to save energy or protecting the soil is not sufficiently considered, and relaxing them when *unreasonably* restrictive, e.g. when they totally ban synthetic pesticides and fertilizers. EISA released a Common Codex for Integrated Farming which *considers aspects of food production, economic viability, producer and consumer safety, social responsibility and conservation of the environment in a well-balanced manner* (EISA 2000). Later, it also released a European Integrated Farming Framework (EISA 2006) which gives guidelines to progress beyond the National Codes of Good Agricultural Practices.

The intention here is not to debate whether intensive, high-input farming systems perform better or worse than alternative systems – it is out of discussion that they must be actually improved; the point is rather to search procedures for finding out the best combination of seriously based principles and strategies to 'sustain sustainable agriculture'. It is important in fact to work out really sound strategies able to gain a widespread and durable acceptance by farmers and operators, and therefore secure their long-term application, since really convinced farmers can eventually become 'the guardians of sustainability'.

Strategies for determining sustainability in agriculture were analyzed, among others, by Noell (2002), who compared four different approaches, ‘conventional agriculture’, ‘integrated farming’, ‘ecological farming’ and ‘biodynamic farming’, concluding that *[n]either the optimistic basic assumptions of neoclassical economics with regard to the unlimited substitutability of natural capital nor the pessimistic assumptions of the ecological theory on the conservation of natural capital for future human generations (inter-generational fairness) can be scientifically proved. The “mixing ratio” of both positions in the agricultural production models and in their sustainability strategies is therefore an expression of very reasonable subjective risk attitudes in this respect.*

Ekins et al. (2003) report and comment that the four kinds of sustainability proposed by Turner (1993), ranging from ‘very weak’ to ‘very strong’, suggest that the more reasonable are the intermediate categories, ‘weak’ and ‘strong’ sustainability. Their position is balanced, refusing the two extreme positions of totally neglecting natural capital and absurdly protecting it beyond any reason: the problem is to find a trade-off within the two intermediate categories.

3.1.2 The Required System Approach

We are presently going through a critical phase of conversion in agriculture requiring solutions for reconciling widely differing dimensions, namely, agricultural productivity, farm economic sustainability, environmental protection and social aspects.

The need to consider many dimensions simultaneously in a holistic approach was acknowledged at least as early as 1984 (Douglass 1984) and later universally accepted (e.g. Sands and Podmore 2000; Cornelissen et al. 2001; Sulser et al. 2001; Noell 2002) since, as Smith et al. (2000) put it, *agricultural practices that are ecologically sustainable may not be profitable, thereby being economically unsustainable. Measuring crop productivity or animal production alone also is not a sufficient indicator of agroecosystem status because practices that achieve high yields may not be ecologically or socioeconomically sustainable.*

In a SAREP (1997) statement, *[a] system perspective is essential to understanding sustainability. The system is envisioned in its broadest sense, from the individual farm, to the local ecosystem, and to communities affected by this farming system both locally and globally. … A system approach gives us the tools to explore the interconnections between farming and other aspects of our environment.*

Such a need for integrated approaches in agronomic research (integrated in *space and time*, as opposed to the traditional approach, directed to the exploration of *single segments* in *single moments*, such as dose–effect relations in plant nutrition, irrigation or pest protection) led to adopt *system methods*, indispensable to support the required dynamic and holistic approach: *[T]he systems approach can be described as the systematic and quantitative analysis of agricultural systems, and the synthesis of comprehensive, functional concepts of them. The system approach uses many specific techniques, such as simulation modeling, expert systems,* *data bases, linear programming and geographic information systems (GIS)* (Kropff et al. 2001).

The four points listed by FAO in the Framework for the Evaluation of Sustainable Land Management (FESLM) (Smyth and Dumanski 1993) to assess sustainability in land management are: (1) production should be maintained; (2) risks should not increase; (3) quality of soil and water should be maintained and (4) systems should be economically feasible and socially acceptable. They are reasonable and generally accepted, with the only caveat that in view of the forecast of increase in world population from 6 to 10 billions, by 2050 production should not only be *maintained* (point 1) but *increased* accordingly, while of course eliminating to the possible extent any areas of undernourishment. Commenting them, Tisdell wrote: *It appears to be important from an ecological and economic point of view not to have preconceived ideas about the most appropriate agricultural system to achieve sustainability. However it would seem that if FESLM is adopted, it would often be a system requiring external inputs but not necessarily at a high level* (Tisdell 1996).

3.1.3 The Need for Indicators

Since the problem of objectively and effectively assessing agro-ecosystems quality has been impending on scientists for decades, quite a number of indicators have been suggested: indicators are *tools for aggregating and simplifying information of a diverse nature into a useful and more advantageous form* (Sands and Podmore 2000).

Janet Riley, in the preface to a special issue of *Agriculture, Ecosystems and Environment* on indicator quality, highlights the lack of consistency in definitions and the non-comparability of scale, concluding that *the international challenge then is to identify common indicators having consistent definitions across sectors, themes and countries. … More social and political indicators need to be created and tested so that the transfer across different domains or cultures can be validated* (Riley 2001a), and elsewhere she judiciously adds: *There is little problem with finding an indicator; the problem is to find an appropriate one* (Riley 2001b).

Doran comments that *the use of simple indicators of soil quality and health which have meaning to farmers and other land managers will likely be the most fruitful means of linking science with practice in assessing the sustainability of management practices* (Doran 2002). Prato (2007) suggests the use of fuzzy logic for assessing and ranking ecosystem sustainability and management, also highlighting its possible shortcomings, and his approach addressing protected area ecosystems can be also used, within limits, to obtain indicators for agricultural systems.

Since indicators for energy balance have been less explored than the others, some consideration will be devoted to them: Spedding et al. (1981) stated that the single most important aspect of agricultural efficiency in the future is likely to be that of energy use.

3.1.4 Indicators for Energy Balance

One important aspect in evaluating agricultural systems, which has been regrettably overlooked with only a few exceptions (e.g. CLM 1996; Gomez et al. 1996; Uhlin 1999b; EISA 2000; Hülsbergen et al. 2001; Hülsbergen et al. 2002; Tzilivakis et al. 2005) is that related to energy input, since *energy intensity is a measure of the environmental effects associated with the production of crops (consumption of fossil fuel and other resources, emission of carbon dioxide and other combustion gases)* (Hülsbergen et al. 2001).

An indicator based on *energy ratio* or *energy productivity* (namely, the output/input ratio) is not always meaningful, first because the energy in output, namely in agricultural products, may have a negligible interest as explained by Pimentel (1980), like in the case of ornamentals, and second because an extremely high energy ratio can easily be achieved at the expenses of production whenever a very low input, even close to zero, is adopted; in this sort of budget, the input of solar energy is generally not considered, nor is that of human labour. The same consideration applies to *energy intensity*, defined by Biermann et al. (1999) as the ratio of energy input to that contained in the product and by-product, expressed in units of Grain Equivalent (GE); production in terms of GE parallels to some extent dry matter production (Biermann et al. 1999).

Energy gain, namely the difference between output and input, is a more significant indicator: to illustrate this point, consider two examples referring to a low-input and a high-input farming system (A and B system, respectively). In system A, an energy input of 2 GJ (GigaJoules)/ha gives origin to an output of 12 GJ (about 0.8 t dry matter); in system B, an input of 20 GJ produces an output of 60 GJ (about 3.5 t dry matter). Clearly, the low-input system A has a better (higher) energy ratio, namely, 12/2 versus 60/20, than system B; a better (lower) energy intensity than high-input system B, namely, 2/0.8 versus 20/3.5, but such better performance in terms of energy ratio and energy intensity masks the poorer productivity, as revealed by energy gain, 10 GJ in system A and 40 GJ in system B. If agriculture must feed evermore people without expanding the arable area, namely without further loss of forests, biodiversity, wildlife and recreational areas, increasing the unit output is of paramount importance.

Biermann et al. (1999) comment this point writing *maximizing energy gains ranks first, also from the angle of energetic use of renewable resources. The energy intensity is particularly suited for rating product-related impacts on the environment (resources and energy consumptions, CO_2 emission) and for deriving optimal fertilizer and production intensity levels.* Their long-term research, comparing effects of fertilization with only mineral N, only organic N and combined mineral plus organic N, shows that the best results in terms of both energy intensity and energy gain were obtained when a combination of organic and mineral nitrogen was applied.

An analysis of energy indicators for Swedish agriculture (Uhlin 1999a) evidenced that, contrary to what many maintain, intensive systems are more energy productive than low-input, self-sufficient systems: compared to 1956, outputs in 1993 had a 40% increase as opposed to an input increase of only 14%, with a parallel enhancement in energy gain. Considering the solar energy productivity of plant production, namely the gross biomass in plant production divided by total solar energy, a 75% increase can be appreciated passing from 1956 partly traditional agricultural systems to 1993 specialized, mechanized and fully fertilizer-based systems.

Illuminating indications can be obtained if the ‘emergy’ analysis is applied, since it can supply guidelines for the improvement of the ‘Best Management Practices’ (Cavalett et al. 2006) and for logically linking environmental and economic evaluations (Hau and Bakshi 2008). In the words of the latter authors, in fact emergy analysis *provides a bridge that connects economic and ecological systems. Since emergy can be quantified for any system, their economic and ecological aspects can be compared on an objective basis that is independent of their monetary perception* thus permitting to eliminate the highly subjective factors afflicting present economic researches related to environmental factors. They explain: *Through the last two decades, economists have developed techniques to assign monetary values to ecological products and services. However, this assignment typically relies on consensus of boards of experts, often with tenuous physical and biological foundations, and generally scaled to some market-derived values that may be, for example, highly skewed by advertising. In contrast, emergy analysis is meant to be independent of human valuation, but based on the principles of thermodynamics, system theory, systems ecology and, ultimately contribution to survival.*

Synthesis of Section 3.1 **– Conventional, high input agricultural systems are not sustainable, but sustainability is difficult to define and reach. System approaches are required to flexibly combine solutions best fitting any specific condition, in order to satisfy the three pillars of sustainability. To evaluate solutions in turn indicators are required. Since energy input is a highly significant indicator of pollution, it deserves special attention. Emergy analysis is an excellent indicator, permitting to simultaneously evaluate economic and environmental aspects.**

3.2 Striving for a Sustainable Agriculture

The discussion above leads to the following considerations: (1) today’s agriculture has achieved the scientific and technical ability to provide food for a steadily increasing world population, but the price paid to achieve this success, in terms of environmental decay and quality of life, cannot be accepted and there is ample reason to fear an irreversible decay of agro-ecosystems in the future; (2) strategies for a sustainable agriculture are urgently needed and an arsenal of sometimes contrasting ways to achieve sustainability is available, but sustainability is an elusive concept widely varying with the various farms and agricultural systems; (3) progress towards sustainability can be achieved provided that prejudice-free, flexible *system approaches* are adopted, apt to the diverse circumstances and objectively supported by appropriate *indicators*.

Although thoroughly validated, really holistic system approaches are not immediately available; it is possible today to significantly improve present agricultural systems by enhancing the knowledge of the multifarious aspects of agricultural reality and their implications rather than passively accepting pre-concocted, all-purpose solutions.

Sustainability is a moving target wrote Hoag and Skold (1996) and as such it requires flexibility in selecting the practices to be adopted.

The coordinated combination of practices and techniques selectively picked from those tested and suggested by the 'alternative agriculture' groups, so defining all those groups exploring ways to alleviate the high burden imposed by the high-input agriculture, can offer sound, although not formally optimized, solutions, provided that the necessary *holistic* and *synergic* approach be maintained by selecting and combining the best from the various proposing groups rather than embracing any of them as a religion, rancorously rejecting the others.

The costs and benefits of various agricultural practices must be based on local values and local constraints, causing sustainable practices to be region and culture specific (Tilman et al. 2002): no universal recipe exists.

In the following part a necessarily incomplete review will be exposed of the possible impacts of the principal farming practices that must be simultaneously evaluated in order to avoid neglecting some important aspects while giving too much emphasis to others. Only for the sake of clarity, although admittedly the close interrelationships linking them all should not be overlooked, the management practices to be examined will be grouped under four headings:

- Cultivation
- Fertilization
- Irrigation
- Pest control

Practices in every single group will be analysed for their impact on the three 'pillars' of sustainability:

- Economy
- Environment
- Society

Again, since the economic, environmental and social impacts are closely interlocked, a separate analysis is in principle incorrect; however, it is deemed necessary for sorting out the outcomes of the various possible actions. Furthermore it must be considered that conflicting indications may result for every single impact, such as, for instance, the need to associate no-tillage positive effects for protecting soil fertility, sequestering CO_2 and minimizing off-site damages with the negative effects of spraying herbicides, depending on the risk of local and downstream pollution. Similarly, social aspects to be privileged can include increasing labour, which conflicts with farm net profit and above all environmental pollution, human energy being notoriously by far the most polluting of all.

A win–win solution can be found rather easily when only a couple of aspects are considered, but finding the 'best compromise' solution can become a difficult task when three or more conflicting aspects are simultaneously considered and a weight must be assigned more or less arbitrarily to each of them. The scope of the present review is to present a down-to-earth framework at farm level and evidence some rather diffuse misconceptions, with the aim of assisting farm operators in selecting sustainable management strategies and rejecting charlatanisms.

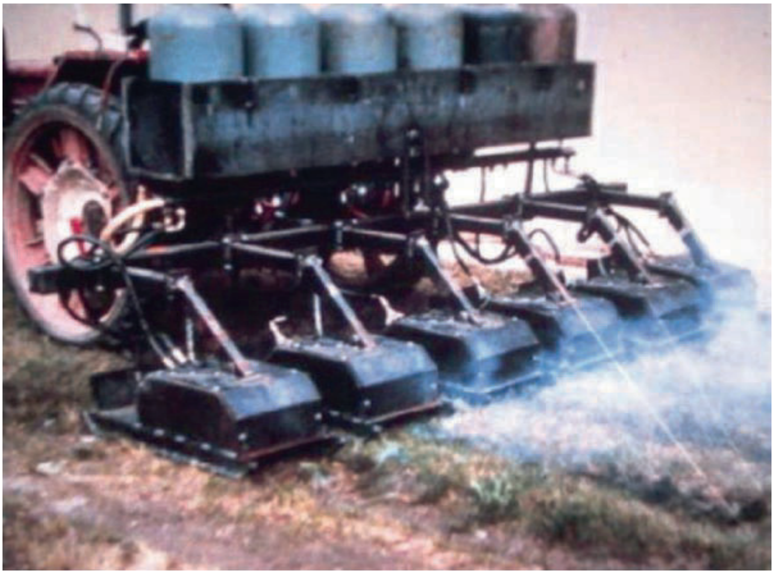
3.2.1 Cultivation

Various forms of soil cultivation, or non-cultivation, exist ranging from mouldboard ploughing to no-tillage, as listed below (from CTIC and Conservation Technology Information 1998):

- *Conventional tillage*: mouldboard ploughing is followed by disking or harrowing, implying soil inversion
- *Mulch tillage or mulch ripping*: the soil is tilled prior to planting with chisels, disks, sweeps or blades; weed control is obtained with herbicides and/or cultivation
- *Ridge tillage*: the soil is left undisturbed from harvest to planting except for nutrient injection; planting is completed in seedbeds prepared on ridges with sweeps, disk openers, coulters or row cleaners. Residue is left on the surface between ridges. Weed control is accomplished with herbicides and/or cultivation. Ridges are rebuilt during cultivation
- *No tillage or zero tillage*: the soil is left undisturbed from harvest to planting except for nutrient injection. Planting or drilling is accomplished in a narrow seedbed or slot created by coulters, row cleaners, disk openers, in-row chisels. Weed control is accomplished primarily with herbicides. Cultivation may be used for emergency weed control

It is worth to report preliminarily the conclusions of a research conducted in Canada by Clements et al. (1995), who found no significant relationship between the yields for a corn–soybean–winter wheat rotation and the energy expended for the frequency and depth of cultivations, which implies that with intensive cultivations there is ample room for energy saving and input reduction.

Conservation tillage, defined as *any tillage and planting system that maintains at least 30% of the soil surface covered by residue after planting* (CTIC and Conservation Technology Information 1998), encompasses a variety of solutions, basically those defined above as mulch tillage, ridge tillage and no tillage. Although attractive under several points of views (in the USA about 40% of corn is conservation tilled according to Uri 1998; similar advantages can be expected in vast European areas, Tebrügge and Düring 1999), conservation tillage finds limitations in *soils* – heavy, clay soils as well as soils prone to crusting are not apt to be conservation tilled, Adeoye 1986; *climate* – conservation tillage cannot be adopted in humid climate areas, due to excessive water intake rates consequent to macropores from large earthworm burrows and root holes, Dunham 1979, as reported in Fowler and Rockstrom 2001; and *crops* – vegetables, potatoes, beets, tobacco, peanuts cannot be conservation tilled (Peet 2001; Uri 1998). As a consequence, a careful assessment



of local conditions is required before embarking in a conservation tillage program. Obtaining clear-cut and definitive information on the comparative efficiency of the various solutions is not easy, not only because of the impact of local conditions – soil, climate, crops – but also because real differences in results can be appreciated only after a long-term experimentation; however, there is general consensus supported by some experimental evidence that reduced tillage and even more so no-tillage are more advantageous than conventional systems not only in terms of environmental protection and energy savings but also in terms of farm profit. The results of a long-term experience conducted in Spain, for instance, demonstrated that zero-tillage with only 0.72 kg/ha of glyphosate outperformed both conventional and minimum tillage (Hernanz et al. 2002); opposite to that, a long-term trial in Argentina could detect no significant difference in yield between conventional and no-till management (Diaz-Zorita et al. 2002).

In plantations on a sloping land, environmental damages from erosion due to mechanical cultivation, namely in-site and off-site effects, are certainly higher than those from one or two yearly sprayings with glyphosate at the dose of less than 1 L/ha, which demonstrates that pollution from physical origin can be more harmful than that from chemical origin. Mulching with polyethylene sheets, permitted in organic farming (Haas 2006) is certainly much more polluting than spraying glyphosate. Similarly the flame weeders permitted in organic farming are not only more costly than glyphosate (Kang 2001), but also much less efficient in the control of perennial weeds and more demanding in terms of energy; therefore, they are ultimately much more polluting.

Anderson (2007) reports encouraging results obtained with field crops in the semi-arid steppe of the USA through the adoption of no-till in a *dualistic approach of prevention and control* which permitted to reduce to about 50% the amount of herbicides.

Cover crops, often suggested as a means for weed control, are certainly attractive but unfortunately can be applied only under certain conditions, since they compete with the main crop for water, disturb water distribution patterns with some irrigation systems, increase frost risk in some areas and are unable to compete with some perennial weeds such as *Cynodon dactylon* (bermudagrass) or *Sorghum halepense* (Johnsongrass). Cover crops are usually, but not necessarily, associated to conservation tillage, concurring to enhance the system sustainability, thanks also to their potential in enriching soils in organic matter and nitrogen and their action in combating weeds. Their acceptance is limited by their opportunity cost adding to the explicit costs and in some regions by their competition with limited water resources. The potential of plant cover in reducing water erosion is well acknowledged: for instance Rizzo et al. (1994) demonstrated that increasing plant cover from 15–40% to 50–90% reduced run-off from about 25 to about 3 mm after 1 h simulated precipitation with the intensity of 48.7 mm/h on 9% sloping plots.

Buffering strips, otherwise called *filtering strips*, are one further method suggested to protect the agro-ecosystems (e.g. Parsons et al. 1995; Vought et al. 1995). They are based on the plantation of vegetated strips at some interval (varying with land slope, soil intake rate and precipitation intensity), which check overland flow and diminish water speed; this in turn entails the deposition of transported solids with their load of pollutants, thus avoiding their accumulation. Additional benefits of filtering strips include the encouragement of water infiltration into the soil and the uptake of some chemical pollutants by protecting plants. The suggested width of strips usually ranges from 5 to 50 m, particularly when they are used as riparian buffers along a watercourse (e.g. Lal et al. 1999); however, examples can be found of narrow grass hedgerows not wider than 50 cm (Huang et al. 2008), very effective in reducing run-off and soil erosion. More forms of non-conventional agriculture exist, aiming at reducing inputs and protecting the agro-ecosystem, including *precision agriculture.* Although attractive, promising and sound in its principles since it is not rational to manage entire fields uniformly, ignoring soil variability, it presently does not enjoy a vast acceptance, requires a high-tech equipment, for instance linking GIS to GPS, and a skilled management and can only be applied under special conditions (e.g. Verhagen et al. 1995; Power et al. 2001; Precision Agriculture and University of Minnesota 2002).

In those cases that conservation tillage, particularly no tillage, can be adopted, advantages can be appreciable under diverse aspects:

- *Economic*: reduced tillage operations automatically reduce costs; particularly with no-tillage, when feasible, root system in tree plants is not disturbed and yield is often increased; grain yield is enhanced through the encouraged rainwater infiltration; costs for irrigation are reduced; in-site and off-site damages depending on erosion and downstream pollution are mitigated;

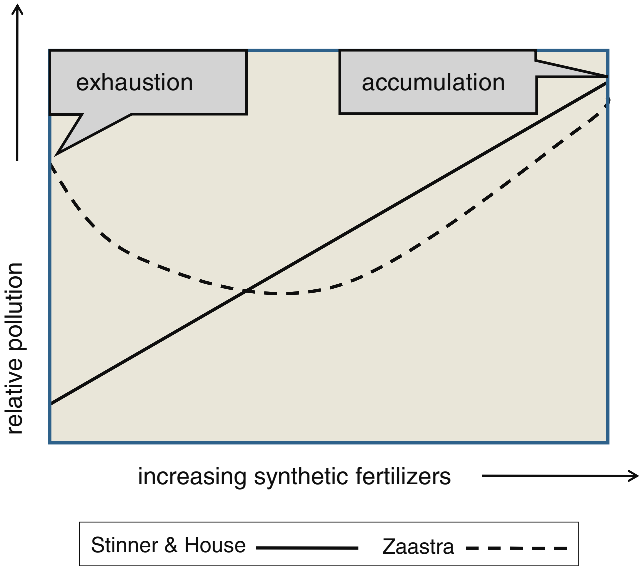
- *Environmental*: reduced cultivation implies reduced energy inputs (e.g. Swanton et al. 1996), therefore determining less pollution; soil is less disturbed and its structure is protected; accumulation of organic matter, a fundamental component of fertility, is encouraged; microbial biomass and soil fauna are increased; CO_2 releases to atmosphere are much reduced (e.g. Halvorson et al. 2002), with a potentially appreciable alleviation of greenhouse effect; soil erosion and downstream pollution are mitigated; wildlife habitat is remarkably improved; chemical contamination is lessened, in spite of the herbicide use required by conservation tillage, in particular by zero-tillage;
- *Social*: workers conditions are improved due to the reduced/eliminated tractor trips; a wide-ranging alleviation of pollution is achieved, from local fertility decay consequent to erosion to off-site damages such as reservoirs siltation, recreational areas impairments, rivers eutrophication, gas emission, water body quality impairment, etc. It is worth to mention here that there is a general consensus that off-site damages consequent to erosion far exceed in-site damages: consequently, the advantages to the society of adopting a large-scale soil conservation program implying the adoption of herbicides when necessary exceed those to single farmers.

***Synthesis of Subsection 3.2.1* – The possible cultivation modes range from mouldboard ploughing to mulch tillage, ridge tillage, zero tillage and each solution has pros and cons. Generally the trend is to reduce cultivation adopting some form of weed control. Well-managed herbicides are less polluting than plastic mulches and flame weeders. Cover crops and buffering strips can be very useful solutions. Factors to be considered in the choice include fertility maintenance, CO_2 sequestration, aquifer protection, erosion control and gas emissions.**

3.2.2 Fertilization

Stinner and House (1989) suggested an inverse relationship between the levels of chemical input and the system sustainability, and their principle is widely, more or less implicitly, accepted; Zandstra (1994, as reported by Hansen 1996), however, proposed a different scheme, with insufficient chemical inputs leading to *exhaustion* of natural resources and excessive inputs leading to *accumulation* and eventually to pollution.

The two principles are not as opposed as it can appear at first sight and can be reconciled to some extent observing that Stinner and House suggest to reduce chemical inputs through information and biological control, which implies avoidance of exhaustion. Anyway it is worth reporting the conclusion in a paper of Shapiro and Sanders (1997): *Everywhere else in the world that food crop yields have been substantially increased, inorganic fertilizers have been a principal component of those yield increases. The other soil-fertility measures, especially organic fertilizers and rock phosphate, are complements not substitutes for inorganic fertilizers.* Some problems related only to nitrogen and phosphorus are briefly discussed below; however, we cannot omit to comment the obligation by the Codex Alimentarius (http://www.fao.org/DOCREP/005/Y2772E/y2772E0c.htm) to use for organic farming sulphate of potash *obtained by physical procedures but not enriched by chemical processes to increase its solubility*: this is a blatant example of single-mindedness putting an unnecessary limitation, conducive to physical pollution for the greater energy required in transporting and hauling more fertilizer to compensate for its lower solubility. Energy for transport cannot be overlooked, in fact: it is estimated that big container ships use about 0.04 MJ/t/km, and trailers



use 1.9 MJ/t/km (Refsgaard et al. 1998; PréConsultants 2004). The same consideration applies to other substances suggested by organic norms, such as phosphate rocks, peat and guano, just on the ground that they are 'natural', without the due consideration to pollution depending on shipping along thousands of miles.

3.2.2.1 Nitrogen

Nitrogen is the most widely used fertilizing element and is also the most highly polluting. The principles of organic farming ban the use of synthetic fertilizers – which gave origin to a flourishing industry of 'organic' fertilizers of uncertain composition, dubious effects and extravagant cost – on the assumption that green or animal manures enrich soil in organic matter and reduce nitrogen leaching.

While enrichment in organic matter by animal or green manure is unquestionable – but with other so-called organic fertilizers it is highly dubious – avoiding nitrogen leaching has been demonstrated a wishful thinking, since the lack of synchronization between N release by organic matter and N uptake by crops can lead not only to an insufficient supply to crops in the critical phenophases (e.g. Myers et al. 1997; Pang and Letey 2000) but also as a consequence to the leaching of unused nitrogen (e.g. Bonde and RosswallT 1987; Yadvinder-Singh and Khind 1992; Kirchmann and Thorvaldson 2000; Russo et al. 2008).

Environmental considerations for animal manure include the criticism of Wilson (2003) who remarks that *the potential or real negative aspects of animal traction include…the additional labour needed for feeding and care, degradation of land and vegetation due to heavy grazing pressure and major additions to global warming gases* and suggests that costs can outweigh the benefits. Gapper (2006) reports that bacterial contamination of *Escherichia coli* by animal faeces was found under almost 10% of organically produced vegetables versus 2% of other produce.

Sieling and Kage (2006) highlight the possibility of achieving very reduced rates of N losses from mineral fertilizers with an appropriate management, while *more serious problems may arise from the use of organic manures and slurries* concluding that *slurry, especially when applied in autumn, increased N leaching more than inorganic fertilizers.*

More cautiously Tilman et al. (2002) wrote: *Reliance on organic nutrient sources is a central feature of organic agriculture, but it is unclear whether the 'slow release' of nutrients from organic compost or green manures can be adequately controlled to match crop demand with nutrient supply to increase nitrogen-use efficiency in intensive cereal production systems, thereby decreasing losses to leaching and volatilization.*

One further consideration is worth reporting: the type of fertilizer does not affect the quality of the crop since when up-taking nutrients, plants do not care if they are of organic or mineral origin, as reported among others by Evers for carrots (Evers 1989a, b, c), Stamatiadis et al. for broccoli (Stamatiadis et al. 1999), ATTRA for wheat (ATTRA 2006), Russo et al. for lettuce, chicory and celery (Russo et al. 2008). Further evidence is supplied by Colla et al. 2000; Bulluck III et al. 2002;

Williams 2002; European Commission, Directorate-General for Agriculture 2002; Tomassi and Gennaro 2002.

Ali (1999) lists several rice-producing countries, including Taiwan, the USA, Japan, India, Nepal, the Philippines and Pakistan where the adoption of green manures (GM) has been nearly abandoned in favour of the more economic mineral N. It is somewhat surprising his finding, referring to rice and supported by analogous findings in researches conducted at IRRI by Ventura and Watanabe (1993) and Cassman et al. (1996), that *the hypothesis that the continuous use of GM enhances productive capacity of soil better than inorganic fertilizer cannot be accepted.* Naturally it is expected that such results apply only to the tropical lowlands where they operated and not to other lands since an abundance of experimental work supports the utility of GM, but this discrepancy underlines once again the importance of abandoning any pre-constituted approach in favour of flexible solutions, fitting the particular conditions of specific areas. Referring to southern Africa, for instance, Abalu and Hassan (1999) comment that *harvested crops mine the soil of its nutrients unless they are replaced with plant residues, manures or fertilizers. Southern Africa does not have and is unlike to have the capacity to produce the quantity of plant residues and manures that would be adequate to replace the mined nutrients. Indeed, as suggested by Borlaug (*1995*), raising the average use of fertilizers in southern Africa from its present low levels to something like 100 kg/ha cannot be an environmental problem, only part of an environmental solution.*

Impacts

- *Economic*: reducing nitrogen doses to the possible extent appears as a typically win–win solution, with reduced costs and reduced pollution; however, it is not 100% true because the reduced physical input should be at least in part economically balanced by the costs for monitoring, analysing soil and leaves and accurately managing the fertilization. Compared to organic manure, mineral fertilization is somewhat cheaper due also to the opportunity costs of green manures and permits a more targeted and time-efficient action, thus reducing the risk of temporary crop malnutrition. Several experiences in very different environments (e.g. Kenya: Tisdell 1996; USA: Larson et al. 1998; southern Africa: Snapp et al. 1998; southern India: Victor and Reuben 2000; Punjab, India: Aulakh et al. 2001; Germany: Hülsbergen et al. 2001) concur to demonstrate that the highest yields are obtained when a basic organic manure is integrated by a mineral fertilization in moderate doses at the right crop phase. This practice was already known in Europe by the nineteenth century, under the name of 'sideration' (Lampertico 1899).
- *Environmental*: the main environmental risk of nitrogen fertilization is depending on the pollution of water bodies, which equally applies to both organic and inorganic forms (Russo et al. 2008). Mineral N is notoriously one of the most energy-demanding factors in farming activity; however, recent technological progresses in fertilizer manufacturing have substantially reduced the energy

required, passed from about 80 MJ/kg in 1972 to about 40 MJ/kg in 1997 (Uhlin 1999a). This makes energy requirement to obtain organic N from a green manure very similar to that for mineral N; however, of course, green manure has the additional advantage of enriching the soil in organic matter. Ammonia volatilization depends much more on organic manure than on mineral nitrogen while N leaching can be higher with green manure than with mineral N (Yadvinder-Singh and Khind 1992). Furthermore, Witter and Kirchmann (1989a, b) demonstrated that the addition of peat, basalt powder, magnesium and calcium failed to reduce appreciably ammonia losses from animal manure.

- *Social*: a mixed organic/mineral fertilization as described above, with appropriate doses of mineral N applied after controlling the nutrient level in the plant tissues and the soil, permits to achieve the safest results in terms of pollution avoidance; this in turn brings about a better fruition of recreational areas, fishing ponds and water courses, and a reduction in emissions. Exchanging large N applications for more analyses, monitoring and accuracy in management entails a more qualified and rewarding job for operators. From the standpoint of food nutritional quality the origin of N, whether mineral or organic, is not relevant (e.g. Tomassi and Gennaro 2002). From the standpoint of consumer health, it has been claimed, but not conclusively demonstrated, that animal manure can be dangerous due to the contamination of fresh-consumed vegetables.

3.2.2.2 Phosphorus

Solid phosphoric fertilizers are available as mono-ammonium phosphate, di-ammonium phosphate, triple superphosphate and single superphosphate; additionally, high-grade liquid phosphoric acid is available.

Furthermore, phosphorus is available as phosphate rocks (PRs); Rajan et al. (1996) give a review of PRs use for direct application to soils, listing advantages and disadvantages as follows.

Interest in phosphate rocks (PRs) as direct application fertilizer stems from the facts that

i. *Per kilogram of P, PR is usually the cheapest fertilizer;*
ii. *Direct application, with or without amendments, enables utilization of PRs which are unsuitable for manufacturing phosphoric acid and other soluble fertilizers such as triple (TSP) or single superphosphate (SSP);*
iii. *Because PRs are natural minerals requiring minimum processing they are environmental benign (Schultz* 1992*); and*
iv. *PRs could be more efficient than soluble fertilizers in terms of recovery of phosphate by plants, even for short term crops in soils where soluble P is readily leached, as in sandy soils (Yeates and Clarke* 1993*) and possibly for long-term crops also in other soils (Rajan et al.* 1994*).*

In spite of this, PRs are not widely used as direct application fertilizers. The reasons are:

i. *Not all soils and cropping situations are suitable for use of PRs from different sources;*
ii. *The large number of factors controlling their dissolution in soil and availability to plants coupled with the inability to predict their agronomic effectiveness in a given soil climatic and crop situation; and*
iii. *Their lower P content compared with high-analysis fertilizers which makes PRs more expensive at the point of application if long-distance transportation is required*

Total phosphorus content of phosphate rocks is relatively unimportant, since what really matters is its reactivity in the soil, which in turn depends on the soil itself, the rock mineralogy and the level of rock grinding.

Phosphate rocks are acknowledged as non-active in alkaline soils and in those soils on a calcareous matrix which are so common for example in the Mediterranean region; to alleviate this problem, it is suggested to apply them in combination with green manures or in the composting process. Grinding ('micronization') is supposed to enhance their reactivity to some extent; however, *it was not possible to convert an unreactive to a reactive PR, even by ultrafine grinding to a size <0.02mm* (Khasawneh and Doll 1978). Gosling and Shepherd (2005) reporting the results of a research conducted in four arable soils in England where organic farming had been practiced for 15–54 years conclude: *[T]he results … indicate that soils in England under mixed organic arable rotations are able to maintain concentrations of total soil organic matter and N at similar levels to those found under typical conventional systems, though there was no evidence of the increase reported by other authors. However, the results do offer support to the argument that organic farming is mining reserves of P and K built up by conventional management. This situation is not sustainable in the long-term.*

Impacts

- *Economic*: assessing a priori which is the most economic form of P fertilizer is difficult. Excluding the use of phosphate rocks which can indeed be considered as inert rocks in most areas and are a support at best (in alkaline soils they can be only modestly reactive when combined to organic matter, which entails an additional cost for hauling and handling), the selection is limited to the high-grade or low-grade, more or less soluble solid forms. Of course liquid phosphoric acid, which is the most costly, is only used in those cases where a permanent irrigation system, particularly a microirrigation system, permits to distribute it to the crops uniformly and inexpensively; it has in this case the additional advantage of cleaning pipelines and emitters and discouraging the entry of insects into the emitters while not being polluting because it is closely controlled.
- *Environmental*: cadmium accumulation through the application of mineral P has been a matter of concern; however, through novel manufacturing and refinement processes, the Cd concentration has been reduced to <5 ppm P (HydroAgri 1998), whereas untreated phosphate rocks keep intact their Cd content. Energy

considerations are one further factor against the adoption of phosphate rocks: in fact although considerable savings in energy are achievable in their manufacturing process compared to soluble forms, the required fine grinding and their transport and application are highly energy-demanding, since a much higher quantity of rocks is required compared to soluble forms. Edwards-Jones and Howells (2001), referring to phosphate rocks approved for organic agriculture in the UK, state that evidently *their use is not sustainable.*

- *Social*: once again, environmental considerations are closely interlocked with social aspects. All those practices and technologies permitting to mitigate fertilizer environmental impact are simultaneously of benefit under social aspects. Like in the case of nitrogen, the mineral or organic origin of phosphorus does not impact the quality and nutrient value of food.

Synthesis of Subsection 3.2.2 **– Environmental pollution can be brought about by excessive or insufficient nutrient availability. Yield quality is not affected by the source of nutrients, organic or mineral. The best results are achieved through a combination of organic and mineral fertilizers. Organic nitrogen is potentially more polluting than mineral. Phosphate rocks are often useless as fertilizers and polluting due to their cadmium content and the energy required for their treatment and hauling.**

3.2.3 Irrigation

Irrigation can be the most expensive operation both in monetary terms and in terms of energy input. The cost of a cubic meter of water in the Mediterranean area, for instance, can exceed €0.50 (desalinized sea water costs in Cyprus €0.70/m^3, Y. Papadopoulos 2002, personal communication) while the direct energy input to lift and pressurize water from deep wells can exceed 4 MJ/m^3, with a corresponding cost, just for electric energy, of over €0.2/m^3. Furthermore, water availability is ever decreasing and competition is mounting among the various uses – domestic, agricultural and industrial – with agriculture taking the lion share, namely, up to 90%, and using it rather inefficiently on the average. As a consequence a careful assessment of real crop water requirements, an enhancement of conveyance and application efficiencies, a better management and whenever possible the adoption of a deficit irrigation schedule are needed: again, human inputs for plant water status monitoring, correct irrigation management, irrigation system maintenance, participatory irrigation management and capacity building are called in substitution of physical inputs.

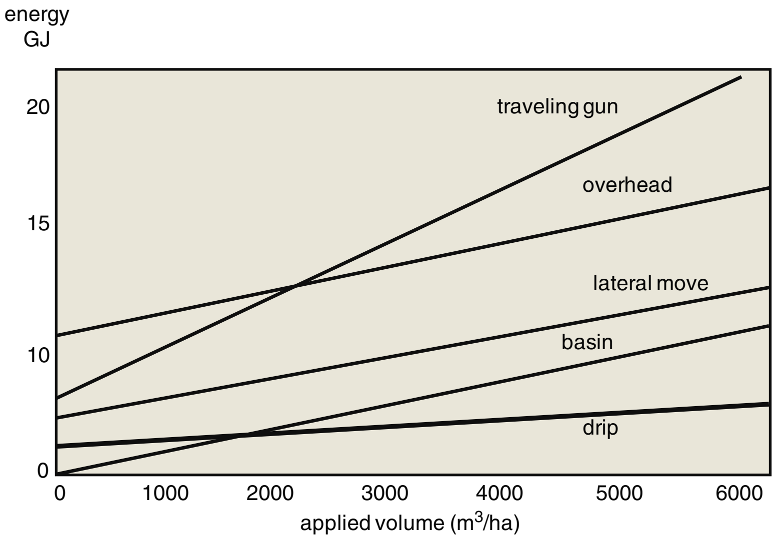
More research and demonstration activity should be devoted to water harvesting, which can be considerably useful not only in reducing irrigation requirements but also in the reduction of overland flow and consequently in the protection of soils from water erosion, as well as in leaching soils from salts accumulated with irrigation water. The solution of tied ridges, or diked furrows, to be obtained either by animal energy or when possible with the use of mechanical equipment, has been demonstrated to be very useful under a variety of conditions (e.g. Rizzo et al. 1994; Shapiro and Sanders 1997).

The attitude of ‘alternative agriculture’ movements to irrigation ranges from outright refusal ‘not to alter natural conditions’, to prohibition of using plastic pipes, maybe in the belief that metal or asbestos-cement pipes are less polluting, to reject of re-using treated domestic wastewaters, to acceptance, in a more realistic mood.

The selection and sizing of the most appropriate irrigation system, as a function of specific human, climatic, economic, agronomic conditions are critical in the process of optimizing the resources. Energy requirement, resulting from the sum of *direct* energy to lift and pressurize water plus *indirect* energy for manufacturing and installing the irrigation system, is a generally overlooked, yet important factor in the selection of irrigation methods (Sardo 1982). To fully appreciate the data in Fig. 4 it is useful to consider (a) that water is considered available without any need for lifting, e.g. from a well, and (b) as a reference, that in the UK the overall energy input for beet production ranges between 15.72 and 25.94 GJ/ha (Tzilivakis et al. 2005).

The negative water balance of hydrological basins in many areas is a factor inducing to manage water more carefully and take advantage whenever possible of the available non-conventional water resources. In particular, irrigating with domestic wastewaters after a primary or secondary treatment can offer several advantages, including the availability of nutrient-rich water, generally free of pollutants dangerous to crops, unlike industrial wastewaters, and the savings linked to the elimination of the expensive tertiary treatment (Hamdy and Karajeh 2001).

Also irrigation with brackish and saline waters is actively explored, with teams studying plant response to irrigation at various salinity levels and implications on the soil and the environment (e.g. INCO-DC 2001; DRC 2002). Results so far achieved show that unsuspected possibilities are open for the use of large, till now neglected unconventional water resources and that traditional guidelines based on crop salinity



tolerance are often exceedingly restrictive. An accurate management when using brackish waters is required to make sure that a correct salt balance is maintained in order to protect soil fertility (Hamdy 1999). This is particularly true with supplemental irrigation, when reduced volumes of irrigation water are applied while the bulk of incoming water is provided by rains, securing a sufficient salt leaching.

Wallender (2007) gives a very interesting example of an integrated model permitting a simulation linking hydrologic, agronomic and economic aspects of irrigation in San Joaquin Valley in California, taking into account soil and water salinity. In his words *the agricultural production model simulates agricultural production decisions at the water district level. It is assumed that growers maximize profits subject to the pertinent resource and environmental constraints. Given initial conditions on surface water allocation and soil, surface water, and groundwater salinity, the agricultural production model simulates agricultural production on an annual basis and produces spatially distributed information on cropping patterns, water applications, groundwater pumping, irrigation efficiencies, and crop yields. The output from the agricultural production model is subsequently used by the hydrologic model to simulate the impacts of these management decisions on the natural system.* His optimistic conclusion is of particular interest: *[T]his decade long effort to develop an integrated, scale dependent analysis is the start of an effort to define sustainability of irrigated agro ecosystems in terms of the quantity and quality of the soil, deep vadose zone, groundwater, and surface water; the agronomic and ecosystem productivity; and, finally, the economic viability.*

3.2.3.1 Impacts

- *Economic*: in order to achieve the highest net income, when designing an irrigation system a trade-off is required between application uniformity, labour requirement and system cost: a higher uniformity and a lower labour requirement are in fact linked to higher capital costs but permit subsequent savings in terms of water and costs for labour and energy. One further aspect to be considered is the cost for pressurizing the irrigation system, which may be not relevant in those regions where only supplemental irrigation is practised, or whenever pressure is obtained by gravity, but influences heavily the budget when volumes of about 5,000 m^3/ha/year or more must be lifted and pressurized. Third, evaporation losses depending on the selected system can be of importance, particularly in those arid or semiarid regions where they can account for 30% or more. A typically 'win-win' solution in many cases can be to reduce to the possible extent water pressure at the nozzles, thus saving energy and money while reducing evaporation; however, the risk is enhanced of large water drops splashing and forming a crust on the soil surface and higher precipitation intensity due to the reduced jet radius determining some overland flow. When carefully managed, irrigation can be economically useful even in humid areas since it determines a reduction in production risk.

- *Environmental*: all those considerations applying to economic impact apply to energy input as well, since savings in water quantities or in required pressure automatically translate into energy savings. Furthermore, savings in water volumes alleviate the burden on the often negative balance of water resources and reduce the risk of water logging and salinization: it is not necessarily true that excess water is beneficial for salt leaching – it is beneficial only under some conditions while it can magnify the risk of salinization whenever a high water table or a low-permeability soil horizon is present. When associated with fertilizer application irrigation permits to increase fertilizers efficiency, provided that application uniformity is sufficient, thus reducing the applied quantities and avoiding/reducing leached amounts.
- *Social*: irrigation is a powerful tool in the improvement of farmer's social conditions, not only in increasing their income and productivity but also in reducing the risk depending on climate vagaries. It also adds to social stability by enhancing the employment and food security, and concurs to enhance the cultural level of irrigators. Further aspects refer to the quality of aquifers and watercourses, which can be protected or impaired by an appropriate/inappropriate irrigation management.

***Synthesis of Subsection 3.2.3* – Irrigation is necessary for achieving high yields in arid or semiarid areas and reducing risk in humid areas; however, it is very demanding in terms of economic and energetic costs. It is necessary to find a trade-off between capital investment and management costs depending on local conditions. A sustainable irrigation management requires to consider salt balance and soil erosion. Water harvesting is very useful to reduce irrigation requirements and erosion risk. A reassessment of water quality for irrigation is needed, particularly when applied volumes of irrigation water are modest compared to rainfall.**

3.2.4 Pest Control

Modern agriculture uses worldwide about 2.5 million tons of pesticides annually (Wijnands 1997), and out of such quantity only about 0.4% reaches the targeted pests, according to Pimentel (Pimentel 1995), while losses through volatilization are on the order of 80–90% (Taylor and Spencer 1990).

Pesticides are considered a necessary evil; however, it has been estimated that without their use food expenditure for western families would more than double (Zilberman et al. 1991) and, much worse, food shortage would be more acute in many third world countries: about 40% crop production would be lost, according to FAO. Pest and pesticide control is probably the sector where a really integrated view of farm management is most required: certainly, pest treatments by calendar as largely in use till a few years ago and still in use today here and there are unsustainable. The principles of targeting interventions according to real need as advocated

by the Integrated Pest Management (IPM) are much more reasonable, entailing only the shortcoming of some degree of risk.

It is not easy to define precisely IPM, since there is a variety of different definitions, originated by different approaches (almost 80 definitions can be found on the Web site of the Integrated Plant Protection Center, Oregon State University, http://www.ippc.orst.edu/IPM); IPM, however, is generally seen as a component of *integrated* farming systems rather than a component of *organic* farming. It must be clearly appreciated that *IPM is not organic farming. This is a critical point. IPM may provide a bottleneck to the adoption of organic farming and vice versa* (Jeger 2000). IPM as advocated by the principles of organic farming in fact is a restricted version where the use of synthetic pesticides is totally banned, whereas IPM as commonly intended aims at *reducing* their use to the possible extent.

The principles of IPM are presently being objected in favour of a still more advanced view, somewhat integrating IPM, namely, the ‘pro-active approach’ seeking *to minimize pest outbreaks by avoiding conditions conducive to their growth and dispersal* (Chellemi 2000). Lewis et al. (1997) state in fact that *the attempted solution becomes the problem … application of external corrective actions into a system can be effective only for short term relief … the use of pesticides and other* ***treat-the-symptoms*** *approaches are unsustainable and should be the last rather than the first line of defense*.

The main trouble with IPM in its presently adopted forms is how to determine the threshold beyond which an intervention is warranted, since the threshold depends on a multitude of factors such as pest population and its likely increase, the intensity of predators and their likely increase, crop damage functions for individual pests, crop susceptibility according to the particular phenophases, weather conditions and forecasts. The lower the threshold fixed for starting the intervention, the lower the risk of pest damage to the crop but the higher the cost in terms of economy and impact on the environment and the society, and as a consequence the threshold cannot be decided with a priori rules of thumb. The principle of a 'dynamic economic threshold', based on the modelling of the crop and pest evolution as impacted by pesticide sprayings and aimed to maximize profit, was developed by Bor (1997); the author suggested that future studies should enlarge the scope to include health and environment-related aspects. Doubtless, an intense scouting and management can greatly assist in safely raising the threshold level and reducing the external input.

Some objection is raised against the advocated solution of crop rotating to control pest development (Jeger 2000; Way and van Emden 2000). Leaving weeds grow on field margins to encourage predators can be a sound practice but can also encourage pests which nest there, according to Peet (1995), Gurr et al. (1998), Way and van Emden (2000). Opposite to these views, crop rotation and the presence of hedges are listed among the *[k]ey aims, principles and management practices of organic farming for pest and disease control* in a sort of handbook published by Greenpeace Environmental Trust (Parrot and Marsden 2002, p. 12). While this suggestion can be accepted, although with some limits, their final suggestion of 'hand picking' the pests (p. 12) is obviously absurd.

Successes of integrated pest management in the USA are illustrated by the leaflets released by SARE (http://www.sare.org/10yrsofsan/pest/pestmgt.htm); on the other side, the intensive monitoring, the relatively costly and sophisticated equipment required by IPM and the inherent higher risk for crops make it unsuitable for many developing countries, particularly in those areas where subsistence crops are grown to sustain the farmer families. It can also be argued that IPM has few probabilities of success at the other extreme, with very high-value crops, where no producer is willing to take a chance: at both extremes a realistic target which can be reasonably expected in the near future is just a reduction in pesticide input. An encouraging paper by van Lenteren, however, reports a considerable trend towards biological control expansion in Dutch greenhouses, even in the case of high-value ornamentals (van Lenteren 2000); he also comments that cost–benefit analyses in greenhouses show that biological control is the most cost-effective control method.

Sustainable approaches are those that are the least toxic and least energy intensive, and yet maintain productivity and profitability. Preventive strategies and other alternatives should be employed before using chemical inputs from any source. However, there may be situations where the use of synthetic chemicals would be more ***sustainable*** *than a strictly nonchemical approach using toxic* ***organic*** *chemicals* (SARE 1997). Lewis et al. (1997) stress this point: *the fact that a product is natural and/or nontoxic does not necessarily mean it is less disruptive than synthetic products. The important thing is to work as much in harmony as possible with the system's inherent defenses.*

Way and van Emden state that *appropriate conventional synthetic insecticides will remain as important IPM components in many crop systems for the foreseeable* *future, as is evident from their continuing vital roles in some of our case histories. … In summary, insecticides will continue to be widely used for the foreseeable future, but more as relatively expensive stilettos, never again as cheap panaceas* (Way and van Emden 2000).

The efficacy of IPM in disease control, as opposed to pest control, is debated: while Jeger is pessimistic (*Biological control by natural enemies is a major component in the control of arthropod pests in IPM programmes. By contrast biological control of plant pathogens is still in its infancy and according to some sceptics will never be weaned let alone reach adolescence,* Jeger 2000) van Lenteren is optimistic, at least for crops grown in greenhouses (van Lenteren 2000). Since the copper and sulphur-based fungicides can be noxious under various respects, the adoption of synthetic fungicides, at least under some circumstances, is presently unavoidable.

Recent progress has focused on the reduction of broad spectrum insecticides, toxic also to useful insects, and on the development of selective alternatives; on the use of pheromone traps, bails and phenology models; on the accurate monitoring of the crops to protect, including also the control of climatic conditions such as the relative humidity and the summation of degrees/day. Doubts can be cast, however, on the accuracy of the summation of degree/days procedure which fails to acknowledge the differences in temperature between the atmosphere and the plant canopies, the latter being during the day several degrees warmer or colder than atmosphere in dependence of plant water status.

The cost of the intensive scouting and monitoring may or may not exceed the savings from pesticide reduction (Fenemore and Norton 1985; Peet 2001; Walker et al. 1997, as reported by Way and van Emden 2000).

3.2.4.1 Impacts

- *Economic*: Pimentel et al. (1993) compared economic results for conventional and alternative pest management practices in tomato, concluding that potential reductions in herbicides were on the order of 80%, in conventional insecticides also of 80% and in fungicides of 50%, with corresponding cost increases (for mechanical cultivation, scouting and management) of 30%, 0% and 10%, respectively; apparently, they did not consider additional shortcomings depending on mechanical cultivation as mentioned above, however. An interesting research conducted by Clark et al. (1998) with tomato and corn showed that economic results obtained with organic and low-input management were basically the same, and both were differing from conventional management negatively for tomato (i.e. with higher costs) and positively for corn. Peet (1995, updated October 2001) reports that insect control with 'botanicals', namely chemicals extracted from plants, is more costly than with conventional pesticides both for the higher cost of botanicals themselves and for their shorter persistence requiring more frequent sprayings.
- *Environmental*: Clark et al. (1998) and Edwards-Jones and Howells (2001), applied the environmental impact quotient (EIQ) developed by Kovach et al.

> (1992) to evaluate the environmental hazard of pesticides suggested for organic farming; the EIQ analyses three distinct categories of hazard, to farm workers, consumers and the environment. The conclusion of Clark et al. (1998) was that EIQ with organic farming is about half that with conventional farming in corn while it is zero in tomato. The somewhat surprising conclusion of Edwards-Jones and Howells (2001) was that *generally, pesticides and fungicides permitted for use in organic farms are less hazardous than those used in conventional systems, but there are some clear exceptions to this rule. However, some evidence suggests that when toxicity and volume are considered in an overall pest management strategy, organic practices may have greater environmental hazard than conventional ones (Kovach et al.* 1992*). For these reasons, we can state that the crop protection activity of organic farming, and hence organic farming itself, is not absolutely sustainable.*

Further objections can be moved to the rationale of permitting the use of broad-spectrum organic insecticides while prohibiting the more environmental-friendly selective synthetic insecticides: energy saving, which is sometimes given as an explanation, is not tenable because actually *more* energy is required by the production, the more frequent spraying and more intense scouting requested by the 'botanicals'. Furthermore, although it may come as a surprise, it must be acknowledged that 'botanicals' can be more toxic than conventional, super-blamed synthetic pesticides. Rotenone has an oral and dermal LD50 lower than both malathion and sevin, and a shorter persistence (Peet 2001), but the shorter persistence, in turn, obliges to more frequent treatments, which are not only *directly* harmful, but are also *indirectly* polluting for the energy requirement and the soil compaction, not to mention their higher cost.

The quotation of Edward-Jones and Howells reported above applies to insecticides and fungicides, since no herbicide is approved for organic farming: objections against this unreasonable banning were illustrated above when discussing the case of environmental damages from mechanical cultivation overwhelmingly exceeding those from the use of herbicides. Solomon et al. (2000) worked out an ecological risk assessment method based on the probabilistic theory, which permits to make decisions according to the accepted agrochemical risk level; their approach is interesting not only for the method itself but also because it implicitly emphasizes the principle, basic to probabilistic theory, that some level of risk, however small, is unavoidable. Including evaluation of hazards to the workers and the consumers, EIQ as mentioned above is a good indicator of social impact; however, focusing only on the pesticide action, it fails to consider the side impact of alternative solutions. For instance, the EIQ value of an alternative, organic, ecologically benign pesticide may well be less than that of the equivalent conventional, synthetic pesticide, but it is also important to evaluate the impact of the practices required to support the action of the environmentally benign pesticides, such as more cultivations or more targeted fertilizations (for instance, silica addition). In conclusion an *integrated approach to the integrated management* is needed, which is still missing

- *Social*: by far the most important social aspect is of course related to food safety and the permissible residue amounts. Tomassi and Gennaro (2002) report in their review that no pesticide residue above permitted limits was found in fruits of peach, plums and pears in a 2-year research conducted by the Italian Ministry of Agriculture. Leaving to ongoing research the difficult task of determining the safe limits to the presence of chemicals, it is worth quoting Haines (2000), referring to the risk of non-chemicals, i.e. 'botanicals': *botanicals are often claimed by proponents to be environmentally safe and non-toxic to consumers because they are* ***natural*** *products. Such generalizations are clearly fallacious since many botanicals in crude or purified form (e.g. opium, nicotine, curare) have pharmacological, hallucinogenic or acutely toxic effects on humans and other organisms.*

In order to issue reliable safety norms, the tolerable amounts of residues in the food must be assessed with certainty and the risk of the 'cocktail effect' must be fully evaluated. To this scope the ongoing updating of the 'Codex Alimentarius' standards, aimed at best serving *the concerns of all (the rich and poor) regarding health, safety and trade in food* (http://codexalimentarius.net/evaluation-en.stm) gives reasonable hope of a major progress, since the core FAO and WHO commission is collecting suggestions from a large number of governmental and non-governmental organizations worldwide.

Synthesis of Subsection 3.2.4 **– Only a minor fraction of sprayed pesticides hits the intended target, while most of them pollute the environment; however, pesticides cannot be abandoned. IPM helps to enormously reduce their use and is presently progressing towards the 'proactive approach'. It is impossible to totally ban chemical pesticides, also because 'botanicals' and the other pesticides permitted by organic agriculture are less effective and/or more polluting. One major problem is the determination of 'threshold values' for the treatments.**

3.3 Discussion and Conclusions

Too many principles have gained dogmatic acceptance just because they have been endlessly repeated and acritically accepted, for instance that diversity is mandatory for ecosystem stability (*experimental evidence and theoretical analysis reveal the notion that diversity causes stability as oversimplified at best, if not dead wrong*, Dover and Talbot 1987; *there is no reason to expect simple natural monocultures to be unstable*, May 1975); that 'small is beautiful' (small can be beautiful but certainly is not useful if scale economies are disregarded); that organic food is richer in nutrients and vitamins (which results untrue); that reducing any external input to farms is highly desirable (the opposite is true, as demonstrated by Uhlin 1999a); that *in large holdings, when capital (mechanization) is substituted for labor, this lowers yields more often than it raises them* (Altieri 2002), which needs no comment, etc.

Certainly a wise solution to contrast such a flood of absurdities is to invest in multidisciplinary research and intense demonstration, and parallel activities of capacity building with the active participation of the stakeholders. When convinced producers become the sentinels of environmental quality obvious and durable advantages on the ground of *social* and *environmental* impacts will be achieved.

Considerations on the *economic* impact are clear-cut: unprofitable agricultural systems quite simply will never be accepted, and securing at least the same profit and the same risk of conventional systems is a prerequisite for the large-scale success of any sustainable system. The fact that growers accept for a while the rules of subsidized organic farming does not imply that they really support the organic farming principles: they just support the subsidy. The premium prices paid for organic products are volatile and not guaranteed in time, since *while organic premiums are very high in a few markets, the global experience is somewhat less promising as more and larger producers enter this lucrative niche. … Promises to farmers about enormous market profits may prove to be misleading, especially after the two-three years it typically takes to be certified* (IFAD 2005).

And it is easy to observe that an agriculture based on subsidies is not sustainable, as demonstrated by many farmers who revert to conventional farming after the period of subsidy.

In any case, it can no longer be tolerated that such an important issue as sustainable agriculture falls prey to unskilled amateurs and dreamers (at best), while taxpayers' money goes to funding activities of a dubious utility or even harmful to the environment such as some of those supported by organic farming. It is reasonable to expect that the objective of the norms and subsidies be no longer to privilege niche producer and niche consumers who can afford to pay premium prices for an undemonstrated better food, but rather to (1) protect everybody's health; (2) encourage food production; and (3) effectively conserve the environment.

In the light of what has been discussed, pursuing sustainability in agricultural systems appears as a still ill-defined but inescapable task, to be based as far as possible on a global approach to farming systems, harmoniously combining all the resources offered by science and technology.

It is striking that, unlike in the USA where much attention is dedicated to soil, water and energy protection, in the rigid rules issued by the European Commission for organic agriculture (European Commission 2007), organic production and labelling of organic products, and in Regulation No 2092/91 and amendments (European Commission 2000, 2002) no specific, explicit provision is made for conserving soil, water and energy, nor to combat physical pollution. Only generic, nebulous principles are enunciated to contrast physical pollution in spite of the so often displayed EU concern for the environment, while an obsessive care is dedicated to chemical pollution.

Although results obtained by researches are sometimes contradictory, due also to the enormous variety of experimental conditions and the uncertainty in some data, and their indications are sometimes biased, there is enough solid ground on which is possible to work confidently.

The complex problems require a cautious and flexible approach; however, a down-to-earth, information-rich paper by Reardon gives an illuminating example of the particular conditions to be faced when coping with a resource-poor agriculture and the possible need for adopting opposite solutions in contrasting situations (Reardon 1995). He comments that low-input systems are not necessarily benign to the environment: *[P]oor farmers stay poor when they use few external inputs; but population still grows, so food demand rises, pushing farmers to crop marginal lands of lower quality, which are easily degraded.* Also Snapp et al. (1998), referring to Malawi and Zimbabwe, outline the shortcomings in single-minded approaches: *Extension departments and non-governmental organizations have promoted the use of organic matter technologies such as green manures for over 70 years in southern Africa. … Adoption of organic matter technologies has been nil. … The technologies promoted require considerable labor inputs, and have often not met criteria of farmers.* As Rasul and Thapa observe (referring to Bangladesh, but the observation is valid for most developing countries): *Bangladesh cannot afford to provide subsidies to farmers to make up shortfalls in crop production caused by environmental conservation-orientated agriculture* (Rasul and Thapa 2004). Of course their consideration applies to those strategies overlooking the ‘economic pillar’ of sustainability.

To some idealistic supporters of alternative farming, including the Soil Association (2002), Altieri (2002) and Ikerd (2008), increasing labour input and disregarding scale economies and reducing external inputs and fragmenting large farms into small family units are highly desirable, but elementary economic considerations as well as practical experience demonstrate the fallacy of their principles, both in developing and developed regions, not to mention the environmental damages which would be brought about by the advocated increases in highly polluting human energy input.

Man is ideally a governor, not a producer of energy for at least two good reasons: for a matter of human dignity (it is preposterous to insist that man should do the work that can be done by a donkey or a machine) and because man-developed energy is enormously more polluting than any other. This apart, any consideration on work affects economy and productivity.

Similarly, some idealistic supporters of alternative farming systems claim the goal of a totally unpolluted environment, unaware that *in most cases it does not make economic sense to eliminate pollutants completely. That is, the cost of eliminating a minuscule level of contaminants may well exceed the benefits. … The difficulty in assessing benefits of reductions in environmental damages has led the Environmental Protection Agency to establish maximum levels of acceptable pollution or environmental damage and to seek mechanisms to reach these levels at least cost* (Zilberman et al. 1999). Kristin Kuntz-Duriseti (2004) with an acute analysis suggests solutions for a logically based integration of the precautionary principle into the cost–benefit analysis and presents three methods for *incorporating a precautionary response to uncertainty into cost-benefit analysis in ways that balance economic growth and environmental protection.*

Way and van Emden, in the discussion to their excellent review on IPM (Way and van Emden 2000), wrote: *The most important message from this review is that priority should be given to application of the right kinds of applied ecological and associated behavioural work in real situations in the field. At present, the balance is wrong, with too high priority given to fashionable technologies.* Yielding to fashion is probably one major reason for the inexplicable blind acceptance of illogical theories, while objecting to them is perceived as 'politically incorrect'.

Our duty, as responsible researchers, committed environmentalists and components of the civil community, is to seriously pursue the solutions appearing objectively more sustainable, without yielding to fashions, obtuse philosophies and, even worse, lobbies, be they on the side of industries or on that of the extreme environmentalists.

Organic farming can appear at a first glance as ideally suited to achieve a sustainable agriculture, and actually it is for some respects; the problem is that, in spite of the claims of its supporters, not always organic farming *can reasonably be regarded as sustainable* (Hodge 1993). Hodge's criticism lists only a part of the objections that can be raised against organic farming sustainability, as illustrated among others by MacCormack (1995), Kirchmann and Thorvaldson (2000), Rigby and Càceres (2001) and Edwards-Jones and Howells (2001). Elliot and Mumford (2002) comment that *organic agriculture relies on price premiums in a niche market and prescribes certain technologies on ideological rather than pragmatic grounds* and suggest the adoption of integrated farming, abandoning the more harmful technologies of conventional farming.

In order to counter criticism on the 'organic' term (all the agricultural systems are organic, it was objected), Scofield (1986) argued that 'organic' refers to the *wholeness* of the principles, which leads to the *systematic connexion or co-ordination of parts in one whole*. The explanation can be accepted, but then, as a consequence, the organic farming enthusiasts for a matter of coherence must accept to *organically* consider in their 'wholeness' *all* the factors that concur to sustainability, including those so far eluded or anecdotally and nebulously treated because they collide with some of their principles, such as energy saving and the impact of direct and indirect energy used in the farming systems, the sequestration of CO_2 in soils and plants, soil protection against water and wind erosion, water conservation and of course the productivity level and the economic aspects of farming activity. Also some aspects of integrated pest management as advocated by organic farming principles are not exempt from criticism, as illustrated above and no satisfactorily, rational explanation yet has been given to their total refuse of synthetic chemicals (in the SAREP Web site it is reported: *However, there may be situations where the use of synthetic chemicals would be more* ***sustainable*** *than a strictly nonchemical approach or an approach using toxic* ***organic*** *chemicals*, SAREP 1997).

In this chapter there is no attempt to elaborate a new system for reaching sustainable agriculture: it is just an endeavour to work out a conceptual framework for focusing and organizing some basic principles. The principal of them is not to supinely accept any pre-conceived 'philosophy', but select in total freedom what is perceived the best solution for any particular case (admittedly, this too can be considered a philosophy). A rational, sustainable farming system in fact must be ‘open’ since farming systems are multi-purpose and multi-method and therefore highly dynamic; as a consequence, the process of elaborating an ‘optimized’ farming system must be able to flexibly integrate in a synergic mode all the relevant aspects, must be free from prejudice and dogmatism, and ready to promptly include any useful new principle or technological innovation and to reject less-than-rational solutions.

Only the adoption of elastic, advanced, rational strategies, to be selected in a participatory process from all the stakeholders, principally well-informed farmers, can secure a long-term and widespread acceptance of sustainable agriculture; this appears the only way to transform ‘pragmatic’ into ‘committed’ producers (Fairweather and Campbell 1996), or better to make the two categories overlap.

The task is evidently too challenging and the stake too important to indulge in emotional, non-rational approaches: all the resources of science and technology should concur in a coordinated, synergic effort towards the Holy Grail of sustainable agriculture. It seems fitting to report here in conclusion Thompson’s warning that *our society may collapse because of shortsighted stupidity on the part of the pro-growth, resource-exploiting power elites, but the collapse will only be tragic if it is shortsightedness or ignorance on the part of environmentally and ethically concerned people that helps bring it around* (Thompson 1992).

Synthesis of Section 3.3 **- To achieve sustainability cultural practices must be selected and combined independent of mainstream beliefs. Organic agriculture principles are unbalanced: too conservative for chemical pollution and too lenient for physical pollution, and this makes it unsustainable. Most organic farmers do not really support organic farming but accept it for the sake of the state subsidy. It should not be permitted that taxpayers fund unreasonable practices: funding should be aimed at encouraging really sustainable farm management by convinced, educated, committed technicians and farmers free from obtuse ideological constraints.**

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Chapter 4
Organic Agriculture and Food Production: Ecological, Environmental, Food Safety and Nutritional Quality Issues

Reza Ghorbani, Alireza Koocheki, Kirsten Brandt, Stephen Wilcockson, and Carlo Leifert

Abstract Conventional agricultural systems should not only produce much greater amounts of food, feed, fibre and energy to meet the global needs, but also challenge problems to improve health and social well-being of man, reduce dependence on fossil fuels, adapt to climate change and extreme weather, reduce environmental degradation and decline in the quality of soil, water, air and land resources throughout the world as well. The present one-dimensional physical and chemical production systems should be replaced by an agricultural paradigm that rely more on biology, ecology and sociology, and meet global food needs based on the soil, water, land and fertility resources without compromising the capacity of future generations in meeting their environmental, food and resource needs. Organic agriculture as an alternative to conventional systems of food production should contain features of agricultural systems that promote the environmentally, socially and economically sound production of food and fibre, and aim to optimize quality at all levels. The underlying principles are to minimize the use of external inputs as far as possible and use of resources and practices that enhance the balance of ecosystems and integrate components of farming systems into an ecological system. Organic agriculture is developing rapidly and the organic land area is increased by almost 1.8 million hectares compared to the consolidated data from 2005. Worldwide, in 2006, over 30.4 million hectares were managed organically by more than 700000 farms, constituting 0.65 percent of the agricultural land of the countries surveyed. Recognizing the ecological principles, self-regulating

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R. Ghorbani (✉) and A. Koocheki
Department of Agronomy, Faculty of Agriculture, Ferdowsi University of Mashhad,
P.O. Box 91775-1163, Mashhad, Iran
e-mail: ghorbani43@gmail.com

K. Brandt and S. Wilcockson
School of Agriculture, Food and Rural Development, Newcastle University,
Agriculture Building, Kings Road, Newcastle upon Tyne, NE1 7RU, UK

C. Leifert
Nafferton Ecological Farming Group, School of Agriculture, Food and Rural Development,
Newcastle University, Nafferton Farm, Stocksfield, Newcastle upon Tyne, NE43 7XD, UK

E. Lichtfouse (ed.), *Sociology, Organic Farming, Climate Change and Soil Science*,
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ability and system stability, agro-biodiversity, climate change and global warming, soil nutrients and soil biology, erosion, nonchemical crop protection and generally agroecosystem health are the most significant ecological and environmental issues regarding production systems. Organic agriculture in farming, processing, distribution or consumption is to sustain and enhance the process of food safety and health at all stages and levels of the agroecosystem in order to prevent serious food safety hazards such as pathogens like prions (BSE), allergens, mycotoxins, dioxins, GMOs, pesticide residues, growth hormones, food additives like colorants, preservatives, flavours, process aids, nitrite added to processed meat, salt, added sugar and saturated fat. There are growing evidences suggesting that organic agricultural systems produce enough quantity and quality foods and have a number of ecological, environmental and health advantages for consumers over food from conventional systems.

Keywords Organic farming • Biodiversity • Climate change • CO_2 • Soil carbon • N_2O • Methane • Soil microbial biomass • Erosion • Food quality

4.1 Introduction

The intensification of agriculture in conventional production systems has resulted in major ecological, environmental and sociological, health and food safety problems in the recent decades. Low stability, climate change and global warming, decreasing biodiversity, accelerated soil erosion by wind and water, chemical fertilizers mainly nitrogen, phosphorus and pesticides in groundwater and on food, the pesticide ‘treadmill’ caused by development of pest resistance to pesticides, routine use of antibiotics for animals leading to antibiotic-resistant strains of organisms, pesticide contamination of farm workers and agroecosystem health are some examples of those problems. Additionally, an overreliance on grain crop monocultures and loss of crop diversity in the aftermath of the ‘green revolution’ has resulted in a loss of well-balanced diets (Magdoff 2007). On the other hand, the conventional approach of increasing dependence on off-farm inputs, including fertilizers, pesticides and energy for food, feed and fibre production, is of questionable sustainability resulting in environmental degradation. Therefore, development of alternative production systems that can preserve productivity and minimize the negative biological and environmental consequences and long-term sustainability problems associated with agricultural practices has a high priority in agriculture worldwide.

It is believed that organic agriculture addresses these public demands and has the potential to improve the agricultural system’s biological functionality and diminish some environmental pollution aspects of agricultural production (Boer 2003; Dabbert 2003). The ecological, environmental and food safety and nutritional benefits of organic farming systems together with growing consumer demand for organic food in many countries, show that organic production systems might be appropriate and desirable alternatives to conventional systems (Poudel et al. 2002). The principal guidelines for organic production are to use materials and practices that enhance the ecological balance of natural systems and integrate the parts of the farming system into an ecological whole (Liebhardt 2003). In practice, this is achieved mainly by excluding or prohibiting the use of most synthetically manufactured fertilizers, pesticides, growth regulators, livestock feed additives and food additives, antibiotics and genetically modified organisms. Greater reliance is placed upon crop rotations including legumes and green manures, crop residues, animal manures, organic fertilizers and mineral-bearing rocks to maintain soil fertility and productivity and biological and mechanical control, for crop protection. However, it should be understood that organic agriculture is not only using nonchemical instead of chemical products or replacing only technology, but also is managing the whole system under particular regulation and certification systems according to specific standards.

Whether the mentioned needs in our production systems can be met by ‘organic’ agriculture is still unknown and under discussions. This article is a review of some of the current state of knowledge regarding ecological, environmental, food safety, human health and quality aspects of organic agriculture.

4.2 Definition and Global Situation of ‘Organic Agriculture’

Organic agriculture has a long history with guidelines developed in 1924 to formalize an alternative to conventional production systems (Hovi et al. 2003). This was associated with Rudolf Steiner and the development of biodynamic farming and agriculture, which has unique features in addition to those of organic farming in general, and a certification scheme established in 1928. This still operates today and is identified by the Demeter and Biodyn labels on foods (Lampkin 1999). Organic farming can be defined as a method of production, which places the highest emphasis on protecting and enhancing the environment and minimizing pollution (Liebhardt 2003). Organic farming systems focus on soil fertility as the key to successful production and reduction of external inputs by refraining from the use of chemosynthetic fertilizers, pesticides and pharmaceuticals. Instead, natural resources and processes are relied upon to manage soil nutrient status and pests, diseases and weeds and hence to influence animal and crop product yields and quality under certain standards and regulations. The International Federation of Organic Agriculture Movements (IFOAM) is the worldwide umbrella of the organic movement and works to coordinate and unite the organic food and farming at the international level. IFOAM described organic agriculture as ‘*all agricultural systems that promote the environmentally, socially and economically sound production of food and fibres by adhering to globally accepted principles*’. These are implemented within local socio-economic, geoclimatical and cultural settings and indeed, IFOAM stresses and supports the development of self-supporting systems at local and regional levels.

Codex Alimentarius Commission, the international food standard body established by the Food and Agriculture Organisation of the United Nations (FAO) and the World Health Organisation (WHO), describes organic agriculture in great detail: ‘*Organic agriculture is a holistic production management system which promotes* *and enhances agroecosystem health, including biodiversity, biological cycles and soil biological activity. It emphasizes the use of management practices in preference to the use of off-farm inputs, taking into account that regional conditions require locally adapted systems. This is accomplished by using, where possible, agronomic, biological and mechanical methods, as opposed to using synthetic materials, to fulfil any specific function within the system.*' (Sligh and Christman 2003).

Products labelled as organic must be certified by a third-party organization as having been produced according to specific standards. The first standards on organic agriculture were developed by private organizations, and the IFOAM basic standards were first published in 1980 and have been continuously developed. Today, the basic standards of IFOAM are applied worldwide, with minor differences in interpretation in different countries. For example, the European Union has a common set of minimum standards (European Commission 1991), while individual European countries or organizations have additional requirements or limitations. The need for clear and harmonized rules has not only been taken up by private bodies, IFOAM and state authorities, but also by United Nations Organizations. The FAO/WHO Codex Alimentarius Commission approved the Guidelines for the Production, Processing, Labelling and Marketing of Organically Produced Foods in June 1999, and animal production guidelines in July 2001. Throughout 2005 and 2006, IFOAM updated and integrated the Organic Guarantee System (OGS) and 'harmonization' programme to provide greater assistance to governments and private bodies worldwide, which are cooperating on organic standards and regulations. Currently the annex lists, which define what substances can be used in organic systems, are under revision, and in the future the discussion about alternative treatments for food processing will continue (Willer et al. 2008).

Organic agriculture is practised in most countries of the World and the extent has continued to expand as more producers have realized that organic production is often a legitimate and economically viable alternative enterprise (Creamer 2003). Worldwide in 2006, over 30.4 million hectares were managed organically by more than 700,000 farms, constituting 0.65% of the agricultural land of the countries surveyed (Willer et al. 2008). Table 4.1 shows that the Australia/Oceania continent accounted for the majority with almost 12.4 million hectares, followed by Europe with almost 7.4 million hectares, Latin America, Asia, North America and Africa. Australia is the country with most organic land. China is second and Argentina is third.

Table 4.1 Land area in organic production in the world in 2006 (Willer et al. 2008)

Continent	Land area (million hectare)	% of global total
Oceania	12.4	42
Europe	7.4	24
Latin America	4.9	16
North America	2.2	7
Asia	3.1	10
Africa	0.4	1
Total	30.4	100

Global demand for organic products remains robust, with sales increasing by over US$5 billion per year. Organic Monitor estimates international sales to have reached US$38.6 billion in 2006, double that of 2000, when sales were US$18 billion and have grown at a rate of 24% per year for the last 8 years (Willer et al. 2008). Consumer demand for organic products is concentrated in North America and Europe. These two regions comprise 97% of global revenues. Asia, Latin America and Australasia are also important producers and exporters of organic foods. The global organic food industry has been experiencing acute supply shortages since 2005. Exceptionally high growth rates have led supply to tighten in almost every sector of the organic food industry: fruits, vegetables, beverages, cereals, grains, seeds, herbs, spices (Willer et al. 2008).

In Europe, while the area under organic agriculture has risen rapidly over the last decade, it represents only 3% of all agricultural land. However, organic agriculture is the most dynamic sector within the whole of European agriculture, with production increasing by 30% per year since 1998. The UK organic market has increased rapidly in recent years, with a growth rate of 30–50% per annum. For example, in the UK sales amounted to £802 million in 2000–2001, and increased by 33% on the previous year (DEFRA 2002) and had exceeded £2 billion in 2006 (Soil Association 2007). Clearly, although organic farming's share of the total agricultural area and food production in the world may still seem very low, it is continuing to expand and might play an increasingly significant role in future throughout the world.

4.3 Ecological and Environmental Issues

The ecological principles underlying different management practices must be understood in order to predict the impact they might have on natural resources. This is a key step towards an agriculture system that reconciles productivity with environmental conservation (Abbona et al. 2007). The intensification of agriculture has resulted in major ecological and environmental problems in recent decades, notably decreases in biodiversity of ecosystems and their associated food resources. This is likely to continue with more intensification dependent on the use of synthetic chemicals and genetically modified crops (Kleijn and Sutherland 2003). On the other hand, organic agriculture aims to preserve the integrity and stability of the biotic community, building or at least sustaining soil productivity and biological resources used in the production process of high-quality, safe food (McCann et al. 1997; Conacher and Conacher 1998; Lampkin and Measures 1999). This is achieved by exploiting self-regulating ecological and biological processes and interactions to sustain productivity and reduce environmental degradation. From the environmental point of view, a farming activity is sustainable if its polluting emissions and use of natural resources can be supported in the long term by the natural environment (Payraudeau and Vanderwerf 2005). Diagnosis of the environmental impact of agriculture therefore constitutes the first step in the overall assessment of the sustainability of agriculture. Efficient methods combining suitable indicators are needed to comprehend and assess agricultural impacts on the environment (Haas et al. 2001) such as the conversion of conventional or intensive agriculture to organic and extensive farming.

4.3.1 Self-regulating Ability and System Stability

Agriculture is under pressure to reform towards a greater degree of sustainability (Oborn et al. 2003), which can be achieved by conversion from conventional to organic farming systems (Condron et al. 2000) that adopt approaches that stimulate the self-regulating capacity of the agroecosystem as much as possible (Lammerts-van-Bueren et al. 2002). Organically grown crops should have characteristics that fit and support those self-regulating capacities such as natural resistance, natural pest control and biotic regulation of soil fertility. Self-regulating ability of organic ecosystems can be defined as the capacity to resist the effects of small and large perturbations or as the presence of enough resilience to counter them without high external chemical inputs (Lammerts-van-Bueren et al. 2002). This self-regulating ability increases system stability and reduces risk of reduction in the agroecosystems' productivity. Organic agriculture bases its sustainable self-regulating production system on the concept of a farm as an agroecosystem. An agroecosystem is shaped by the strong interaction between the biotic and nonbiotic environment, the genetic composition of species involved and the management of resources available to the farmer (Swift and Anderson 1993; Almekinders et al. 1995; Lammerts-van-Bueren et al. 2002). The biotic diversity includes associated organisms (pests, diseases, antagonists, predators and beneficial organisms) that contribute to the self-regulating capacity through balancing or feedback mechanisms (Almekinders and Struik 2000). Organic farmers support all these interactions at different levels of the production system in such a way that the farm can utilize ecosystem functions provided by agro-biodiversity, such as nutrient cycling, water and soil conservation and applying biological control strategies (Altieri and Nicholls 1999). For example, application of integrated pest management (IPM) rather than individual control methods is highly emphasized by organic agriculture. However, many agroecologists believe that IPM is not just about management of pests alone; it is a sustainable crop production approach based on sound ecosystem analysis (Speiser et al. 2006).

4.3.2 Biodiversity

Biodiversity is the sum of all living organisms including plants, animals and microorganisms in the world or in a particular area (Raven 1994). An additional strength of organic farming systems is their diversity – including the diversity of crops, fields, rotations, landscapes and farm activities (mix of various farm enterprises). Positive effects of enhanced biodiversity on pest prevention have been shown by several authors (Pfiffner and Luka 2003; Wyss et al. 2005; Zehnder et al. 2007). Similar effects of diversified agroecosystems on diseases and better utilization of soil nutrients and water are also likely to occur (Altieri et al. 2005).

In sustainable agricultural systems, biodiversity has fundamental importance by providing a range of biological services including natural enemies. In conventional farming systems, these services are effectively substituted by external inputs.

As biodiversity and consequently genetic diversity are reduced, the integrity of the agro-ecosystem in terms of disease resistance and optimal resource cycling is eroded. The most extreme loss of biodiversity is represented in monocultures. The inherent genetic uniformity in monocultures, especially those with a single uniform variety, is highly susceptible to and unstable against pests, diseases, weeds and all environmental stresses (Geier 2000). Therefore, from a yield point of view, crop diversity is an important tool to minimize crop losses due to diseases, pests, droughts, floods and other adverse external factors and significantly reduces the risk of food shortage in case of crop failure of a particular species within a rotation or mixed-crop stand. Most diseases and pests affect only one crop, and often propagate faster and more extensively if this crop is grown on large, continuous areas. For soil-borne pests and diseases, it is well known that the best prevention is simply to avoid growing the same plant species on the same field too often and the same applies to some pests and diseases that affect the foliage. Such well-established practices within farming systems have long contributed to biodiversity, sustainability, protection of the abiotic resources and nature preservation, but the effectiveness of other practices is often unknown (Oppermann 2003). For example, the potential risks of transgenic crops, which are also called genetically modified organisms [GMOs] for biodiversity and the environment were overshadowed by the potential benefits in the early phases of commercialization. However, recent scientific assessments concluded that some risks posed by transgenic crops are unique, and that the regulatory system has not been functioning effectively. The major risks include increased resistance to particular pesticides, gene flow into related plant species, and negative effects on non-target organisms. Significant gaps in knowledge, often stemming from missing markets for ecological services, warrant a cautious environmental regulatory approach for transgenic crops (Ervin et al. 2003).

Creating biodiversity within a crop is an organic cropping technique that improves the reliability of food supply. Some communities that traditionally depend on vegetatively propagated root crops such as potatoes, e.g. in the Andes mountains of South America, carefully mix many different genotypes in the field. The most popular ones that give the highest yields or the most palatable tubers are usually the most susceptible to diseases and pests and hence crop failure. However, by mixing them with resistant but lower yielding or less desirable genotypes, a reliable food supply is ensured. The same applies to mixtures of other crop genotypes, which usually have less disease and higher average yield than the same genotypes grown separately (Wolfe 1997). In practice, however, seed is rarely sold as mixtures of species or varieties. Most conventional seed is sold as single genotypes primarily to ensure that intellectual property rights of the breeder and phytosanitary regulations can be regulated and controlled. Production and processing is also simplified and using a single variety ensures completely uniform ripening in the field, which is particularly important for large-scale mechanical harvest, but more difficult to achieve with mixtures. In contrast, for the subsistence farmer, who does not purchase new seed every year anyway, complete genetic uniformity is neither realistic nor particularly desirable; in fact the most important characteristics are local adaptation to the prevailing conditions of soil and climate (Brandt and Kidmose 2002).

Mixture cropping may provide both organic and conventional producers with a more sustainable approach in reducing weed pressure, crop rotation flexibility, improved yield stability, buffering against pests and diseases, minimizing soil variability and increasing animal feed value (Kaut et al. 2008). Intercropping, multiple cropping and other interspecies biodiversity such as the number of different crops grown in the rotation within and between years could encourage higher numbers of related micro-organisms, insects, worms, weeds and soil fauna. This is not the case in intensive, conventional systems, which can lead to extreme losses of biodiversity and to combat this trend, agri-environment schemes have been introduced, in which farmers are paid to modify their farming practice to provide diversity and ecological benefits.

Organic agriculture is an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity (Haas et al. 2001; Vetterli et al. 2003) and organic growers promote diversity at all levels (Liebhardt 2003). There are evidences showing that insect pest control is enhanced as a consequence of greater biodiversity on organic farms, and an increase in the diversity of insect predators and parasitoids can have positive or negative effects on prey consumption rates (Letourneau and Bothwell 2008). By adopting mixed cropping, applying organic fertilizers such as composts and farmyard manures, using mulches and cover cropping and avoiding synthetic chemicals, habitats are provided for a variety of macro- and micro-organisms. Some of these may be beneficial and keep pest and disease damages below economically damaging levels (Liebhardt 2003). Therefore, the organic farming systems regard biodiversity as an irreplaceable production factor or even a driving force at different levels of the farming system, and as an instrument for preventing pests, diseases and weeds (Geier 2000). Such a self-regulating, stabilizing force in agroecosystems provided by biodiversity is not simply governed by the number of species involved, but mostly by a selective number of specific, functional species in an appropriate ratio. Therefore, depending on the quantity and quality of species in the agroecosystems, the organic farmer faces the challenge of managing site-specific diversity and identifying the correct combinations of species (in time and space) that through their biological synergism achieve the self-regulating capacity of his individual farm ecosystem (Lammerts-van-Bueren et al. 2002).

4.3.3 Global Warming and Climate Changes

Climate models predict that a doubling of current atmospheric carbon dioxide (CO_2) levels will cause a global increase of 1.4–5.9°C in mean surface air temperature by 2080 (Houghton et al. 2001). This increase in temperature is also likely to be accompanied by an increase in temperature variance. Moreover, extreme weather events that were previously rare for example, heavy precipitation or long droughts may become more frequent (Hulme and Jenkins 1998; Houghton et al. 2001). However, changes in temperature, precipitation and atmospheric CO_2 levels could lead to mistaken conclusions about the magnitude and direction of environmental impacts (Abler et al. 2002).

Nevertheless, such changes have implications for pest, disease and weed outbreaks in agroecosystems (Risch 1987) through effects on physiological development, migration and dispersal. Although external inputs such as chemical fertilizers, pesticides and genetically modified varieties may provide some buffering against climate change in conventional agriculture, organic agriculture is far more dependent on internal resources within the system (Stacey 2003) and this has important economic implications for both conventional and organic farmers.

Atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) contributing to climate change are increasing at a rate of approximately 0.4, 0.6 and 0.25% per year, respectively (IPCC 1997). There is a growing interest in quantifying the significant sources and sinks of these trace gases and the international community has taken steps to reduce these emissions (Flessa et al. 2002).

The greenhouse gases and atmospheric loading due to agricultural production may be strongly influenced by the type of farming and land management system used (Flessa et al. 2002; Dalgaard et al. 2003). Agriculture plays a major role in the global fluxes of these greenhouse gases (Robertson et al. 2000; Flessa et al. 2002) and is assumed to be one of the major sources (Figs. 4.1 and 4.2), particularly of N_2O and CH_4. Nitrous oxide emissions from agriculture are estimated to account for more than 75% of the total global anthropogenic emission (Duxbury et al. 1993; Isermann 1994), the major part being produced in soils as an intermediate during nitrification and denitrification (Hutchinson and Davidson 1993). Overall, agriculture accounts for approximately one fifth of the annual increase in radiative forcing (IPCC 1997), which is a measure of the change in balance between incoming and outgoing radiation at the earth's surface.

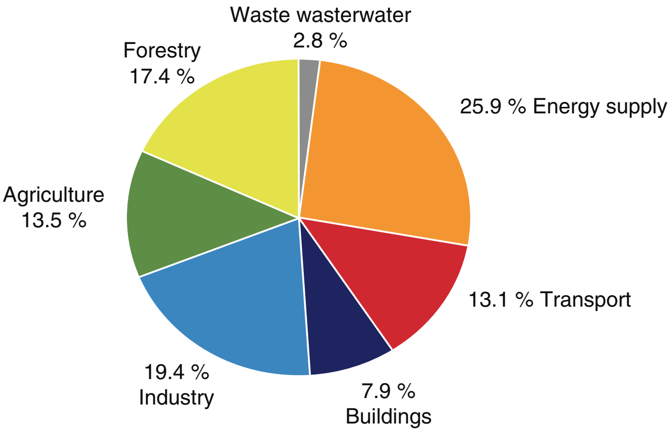

Fig. 4.1 Greenhouse gas emission such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) converted to CO_2 equivalents, by sector in 2004 (Barker et al. 2007). Agriculture and forestry together play a major role in the global fluxes of the greenhouse gases carbon dioxide, nitrous oxide and methane

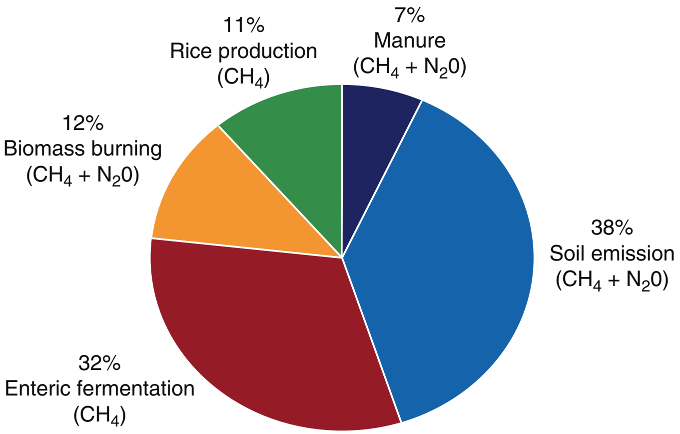

Fig. 4.2 Main sources of greenhouse gas emissions in the agricultural sector in 2005 (Smith et al. 2007). Soil emission and enteric fermentation are the main sources and agriculture is assumed to be one of the major sources particularly of nitrous oxide (N_2O) and methane (CH_4)

Composting and biogas production are often suggested as measures for mitigating climate change. In this context, benefits of aerobic fermentation of manure by means of composting are ambiguous: while a shift from anaerobic to aerobic storage of manure can reduce CH_4 emissions, nitrous oxide emissions increase by a factor of 10 (Kotschi and Müller-Sämann 2004).

4.3.3.1 Carbon Dioxide

Agriculture can help to mitigate climate change by either reducing emissions of greenhouse gases (GHGs) or by sequestering CO_2 from the atmosphere in the soil. The global warming potential (GWP) of agricultural activities can be defined as GHG emissions in CO_2 equivalents per unit land area or per unit product. The global warming potential of organic farming systems is considerably smaller than that of conventional or integrated systems when calculated per land area. This difference declines, however, when calculated per product unit, as conventional yields are higher than organic yields in temperate climates (Badgley et al. 2007). Under dry conditions or water constraints, organic agriculture may outperform conventional agriculture, both per crop area and per harvested crop unit. Typically, conversion from conventional to organic farming leads to a lower total fossil energy use (Flessa et al. 2002). Organic farming practices may result in a lower amount of CO_2 production per area of agricultural land; but in most cases the reductions in the energy input were higher than the reductions in CO_2 output from the production. Consequently, there are reports that energy efficiencies, defined as output per energy input, are higher in organic than in conventional farming. Reductions in fossil energy use lead to similar reductions in the emissions of CO_2, which cause less GHG contribution (Dalgaard et al. 2003). Artificial nitrogen fixation for synthetic fertilizer manufacture and use in conventional agriculture consumes large amounts of non-renewable energy supplies responsible for CO_2 emissions and contributes to the greenhouse effect. The same is true for emissions of N_2O, which is approximately 300 times more powerful than CO_2 in its contribution to the greenhouse effect (Vetterli et al. 2003).

Organically farmed soils are likely to be a larger sink for CO_2 compared to many conventionally farmed soils (Jareckia et al. 2005). This is mainly because of their higher biomass levels fixed in the form of root material. Restoration of soil organic carbon (SOC) in arable lands represents a potential sink for atmospheric CO_2. Strategies for SOC restoration by adoption of recommended management practices include conversion from conventional tillage to no-till, increasing cropping intensity by eliminating summer fallows, using highly diverse rotations, introducing forage legumes and grass mixtures in the rotation cycle, increasing crop production and increasing carbon input into the soil (Jareckia et al. 2005).

Arable cropland and permanent pastures lose soil carbon through mineralization, water and wind erosion and overgrazing. Global arable land loss is estimated to be 12 million hectares per year, which is 0.8% of the global crop land area or 1,513 million hectares (Pimentel et al. 1995). This rapid loss is confirmed by experimental data from Bellamy et al. (2005) in England and Wales. Between 1978 and 2003, they found carbon losses in 92% of 6,000 soil samples. Annual CO_2 emissions from intensively cropped soils were equivalent to 8% of national industrial CO_2 emissions. Therefore, if agricultural practices remain unchanged as it is in current intensive production systems, the loss of organic carbon in typical arable soils will continue and eventually reach a lower level than present. The application of improved agricultural techniques, e.g. organic farming, conservation tillage and agroforestry, however, stops soil erosion (Bellamy et al. 2005) and converts carbon losses into gains (Reganold et al. 1987) particularly due to the use of green and animal manure, conserving crop rotations with intercropping and cover cropping and composting techniques. Long-term field trials showed that organically managed soils have significantly higher organic matter content (Foereid and Høgh-Jensen 2004). Consequently, considerable amounts of CO_2 may be removed from the atmosphere.

4.3.3.2 Nitrous Oxide

The global warming potential of conventional agriculture is strongly affected by the use of synthetic nitrogen fertilizers and by high nitrogen concentrations in soils. The primary reasons for enhanced N_2O release from cultivated soils are increased N inputs by mineral fertilizers, animal wastes and biological N fixation (IPCC 1997). A constant emission factor of 1.25% for the amount of N applied to agricultural land is recommended for calculating global and national emissions from fertilized soils (IPCC 1997). Global nitrogen fertilizer consumption produced by fossil energy in 2005 was 90.86 million tonnes (International Trade Centre and FiBL 2007), which required approximately 90 million tonnes of diesel equivalents fossil fuel to produce or about 1% of global fossil energy consumption (Cormack 2000). Emissions of nitrous oxide are directly linked to the concentration of easily available mineral nitrogen in soils. High emission rates are detected directly after fertilization and are highly variable. For example, denitrification is additionally enhanced in compacted soils. According to IPCC, 1.6% of nitrogen fertilizer applied is emitted as nitrous oxide. In organic agriculture, the ban on the use of mineral nitrogen and the reduced livestock units per hectare considerably reduce the concentration of easily available mineral nitrogen in soils and thus N_2O emissions. Immediate application of manure and slurry from dairy, beef, pig and poultry farms have also become an environmental problem because nutrients are often available in excess and over-fertilization of forage and arable crops occurs during its disposal. Emissions of carbon dioxide, nitrous oxide and methane are likely to be very high and water pollution may also occur when manures are not properly matured before application. Composting of farm manures and vegetable wastes according to the organic standards and regulations can thus help to reduce the global warming potential of food production.

4.3.3.3 Methane

Methane accounts for about 14% of the greenhouse gas emissions of which two thirds are of anthropogenic origin and mainly from agriculture (Duxbury et al. 1993; Barker et al. 2007). Even in highly industrialized countries such as Germany, the agricultural sector belongs to the most important national sources of CH_4 and N_2O emissions (Flessa et al. 2002). Biological CH_4 production in anaerobic environments such as enteric fermentation in ruminant animals, animal waste processing and flooded rice fields are the principal sources (IPCC 1997). In addition, agricultural practices may also influence atmospheric concentration of CH_4 by affecting its consumption in aerated soils. To a large extent CH_4 emissions are directly proportional to livestock numbers. In Western Europe around 17% of CH_4 emissions come from animal excrement. Organic animal husbandry methods commonly use straw for bedding and feeding, which becomes a component of manure, but much less is used in intensive conventional systems where liquid manures or slurries present great emission potential for methane and ammonia (Vetterli et al. 2003). Avoidance of CH_4 emissions of anthropogenic origin and especially of agricultural origin is of particular importance for mitigation. Organic agriculture has a potentially important impact on reduction of CH_4 emissions, as the overall population of livestock on organic farms is relatively small and breeding animals are replaced less frequently than in conventional systems (Kotschi and Müller-Sämann 2004; Olesen et al. 2006; Weiske et al. 2006). On the other hand, lower milk yields of organic cows and a higher proportion of roughage in the diet might increase CH_4 emissions per unit of yield.

4.3.4 Soil Nutrient Balance

In conventional systems four frequently used elements, nitrogen, phosphorus, potassium and calcium are often applied as synthetic fertilizers in relatively heavy concentrations that frequently exceed crop requirements. This can cause soil imbalances in two ways: (1) by increasing or decreasing availability of some elements essential for crop growth and also by changing soil pH, and (2) by increasing productivity over the short term; but in decreasing productivity over the longer term due to imbalances and deficiencies for some other essential elements that are not replaced. For example, high levels of phosphorous fertilization can lead to a deficiency of both zinc and iron causing adverse effects on plant growth. Organic systems use organic fertilizers such as manures, compost, crop residues, legumes, rock phosphate and rock potash, containing minor and trace elements as well as moderate amounts of the primary elements.

In general, organic soils contain superior average and balanced levels of nutrients, which have indirect, beneficial effects for pest, disease and weed management (Lampkin 1999). For example, of the nine farms studied by Berry et al. (2003) seven had a positive N budget, six had a positive P budget and three had a positive K budget on the organic part of the farm compared to the conventional part. Derrick and Dumaresq (1999) found that soil in an organic farm contained higher concentrations of exchangeable potassium, calcium, sodium and lower concentrations of exchangeable molybdenum. Joo et al. (2001) found that available phosphorus values were 986 and 935 mg/kg in organic and conventional farm soils, respectively. Average total phosphorus values were 2,973 mg/kg in the organic fields and 1,830 mg/kg in the conventional fields. Oehl et al. (2002) reported that after 21 years of organic management an adequate level of available phosphorus was maintained. Wells et al. (2000) also reported that after 3½ years of vegetable cropping, available phosphorus increased on the organically managed field. Fumigation extractable carbon and nitrogen, mineralizable N, arginine ammonification and substrate-induced respiration were significantly higher in organic and low input than in conventional systems (Gunapala and Scow 1998). However, the results of some studies contrast with these findings (e.g. Derrick and Dumaresq 1999; Loes and Ogaard 1997; Haraldsen et al. 2000).

Organic farming encourages the reduction of agrochemicals and promotes soil conservation principles (Saha et al. 2007). Those production systems are associated with positively enhanced soil physical, chemical and biological characteristics (Brown et al. 2000). Organically managed soils do not contain readily soluble nutrients except K, and normally have slow-release properties. They are more fertile with higher total N, total P, humic acid, exchangeable nutrient cations, water-holding capacity and microbial biomass, than conventionally managed soil (Wells et al. 2000). When organic fertilizers are incorporated into the soil, a greater reliance is placed on chemical and biological processes to release nutrients in plant available forms in soil solution (Stockdale et al. 2002); in other words, ‘feeding the soil not the plant’.

Conventional farming systems are often associated with nutrient leaching from arable lands and ground water pollution (Hansen et al. 2000). Application of farm yard manures, legumes, compost and other organic fertilizers in organic farming systems causes lower nutrient input and less nutrient leaching than conventionally managed fields (Hansen et al. 2000; Kirchmann and Bergstrom 2001; Vetterli et al. 2003). Similarly, phosphate pollution in surface and ground water could be less in organic agriculture due to the absence of any highly soluble phosphate fertilization (Vetterli et al. 2003).

4.3.5 Soil Microbial Biomass

Field and laboratory experiments have demonstrated that soil microbial activity can create soil conditions favourable to sustainable production (Andrade et al. 1998). Bolton et al. (1985) found that microbial activity and microbial biomass were higher under organic management systems. Soil microbial communities are strongly influenced by agricultural practices. Many farming practices such as intensive tillage, application of chemical pesticides and mineral fertilizers and monoculture are directly or indirectly harmful to soil microbes. Microbial population density and diversity are affected by the level of organic matter, which provides energy for soil micro-organisms. Peacock et al. (2001) reported that soil management practices that result in differential carbon inputs also affect the size and structural community of soil biomass. One such practice is the use of organic amendments and cover crops, which increase carbon availability to micro-organisms. Non-pathogenic and plant growth stimulating micro-organisms in the rhizosphere increase plant root exudation. This will in turn improve root growth and thereby plant nutrient availability. It has been shown to occur in the presence of free-living bacteria such as *Azospirillium* spp. and *Azotobacter* spp. and in the presence of symbiotic organisms such as mycorrhizae (Lundegardh and Martensson 2003).

Dynamics of microbial communities during two growing seasons were significantly negatively correlated with amounts of soil mineral N in the conventional system, whereas they were positively correlated with mineral N in the organic system (Gunapala and Scow 1998). Another study showed that total bacterial biomass was highest in conventional field soils while the ratio of active to total bacterial biomass was highest in organic field soils (Glenn and Ristaino 2002). After long-term organic management, e.g. >40 years, microbial biomass C was higher than in conventionally managed farm soils (Schjonning et al. 2002). Carbon released from crop residues contributes to increasing soil microbial activity and so increases the likelihood of competition effects in the soil.

4.3.6 Soil Structure, Compaction and Erosion

There are many examples of the ways in which soil characteristics function towards ecosystem health and stability. Organic management strategies such as incorporating plant residues in soil maintain and improve soil structure of the soil in long term compared with conventional agriculture (Bailey and Lazarovits 2003). Gerhardt (1997) reported that an organic farm had a significantly ameliorated soil structure, with an increased A-horizon depth, organic matter content, porosity, earthworm abundance and activity and more developed aggregates than a conventional farm. Pulleman et al. (2003) found that organic management increased total organic matter content, earthworm activity, water-stable macro-aggregation and N mineralization, which are important indicators of soil quality. Improving other soil characteristics such as cation exchange capacity (CEC) in organically managed fields demonstrates a clear on-site sustainability advantage over the conventional systems (Wells et al. 2000). There are many reports that applying organic matter improves soil structure. Moreover, Forge et al. (2003) reported that the use of organic materials such as mulches can have profound effects on the structure of the soil food web, which is relevant to turnover of the microbial biomass and macronutrients. In organic agriculture application of green manures and catch crops are highly recommended. Green manure catch crops promote the sustainability of agricultural systems by reducing soil erodibility and by nutrient uptake and transfer to the following main crops. This effect efficiently reduces the risk of nitrate leaching. Biological nitrogen fixation by legume catch crops is an additional benefit, mainly in organic farming (Rinnofner et al. 2008). Depending on soil type and climate, farmers must be very cautious not to destroy the soil structure by tillage, vehicular traffic or grazing under wet conditions. Adverse soil structural conditions due to soil compaction or poor drainage greatly increase the chances of serious infection with many plant pathogens (Davies et al. 1997).

One of the costs that is rarely considered in evaluation of agricultural production efficiency, but could be significant, is productivity losses due to the soil and nutrient erosion in top soils, and loss of biodiversity, which are much higher in conventional than organic systems (Jordahl and Karlen 1993). Brown et al. (2000) reported that conventional farms showed the lowest values for aggregate stability and CEC while organic farms had the highest mean humic acid content and available water and air capacity. As the soil resource becomes degraded, the environment becomes less favourable for crop growth but better for plant pest and disease incidences: therefore, over the long-term productivity and profitability will be decreased (Wells et al. 2000).

4.3.7 Crop Protection

Many references suggest that an increase in weed, pest and disease pressure in agroecosystems is due to changes in agricultural practices and cropping systems especially rotation, fertilization and application of agrochemicals that contribute to greater intensification (Altieri and Nicholls 2003). Conventional farming tends to rely on synthetic chemicals and some genetically modified crop varieties for pest, disease and weed control, but these are explicitly avoided in organic farming systems, which utilize crop rotation, natural enemies, resistant crop varieties and limited biological intervention (Hani et al. 1998; Lampkin and Measures 1999). Combining these approaches in integrated management strategies aims to: increase crop and animal health and make conditions for pests, diseases and weeds less favourable; enhance the activities of the natural enemies of pests, diseases and weeds including other insects, fungal, bacterial and other living organisms as biological control agents (Lampkin 1999; Speiser et al. 2006). Agronomic practices and the use of organic fertilizers in which nutrient release is gradual, can reduce weed competition and possible damages. A study demonstrated that it should be possible to reduce weed competition by ensuring that the amount of nitrogen in soil before sowing is around 100 kg/ha (Valantin-Morison and Meynard 2008).

Poor soil aeration caused by poor soil structure, soil type or water logging was associated with the development of cavity spot (*Pythium* spp.) disease in carrot (Hiltunen and White 2002). The pea root rot complex (*Fusarium* spp.) is known to be affected by compaction, temperature and moisture of the soils. Chang (1994) showed that an increase in soil bulk density due to compaction significantly increased root rot incidence and disease severity, and drastically reduced the fresh weight of pea plants due to the disease. Tillage practices that reduce soil compaction, increase drainage and increase soil temperature have been shown to generally reduce the severity and damage caused by root rot pathogens to many vegetables such as beans (Abawi and Widmer 2000).

Soil microbial biomass may contribute to crop protection in general, and mycorrhizal organisms to the control of plant root pathogens in particular. Mycorrhizae act in a number of ways such as: improving nutrient acquisition by host plant; competitive exclusion of pathogens at infection sites and within the rhizosphere; inducing anatomical and structural changes in the root thereby creating physical barriers to pathogen entry; production of antagonistic substances against root pathogens and activation of plant defence mechanisms (Sullivan 2001). Agricultural practices can have major short- or long-term impacts on mycorrhizal fungi as well as on other soil micro-organisms. In an experiment examining the effectiveness of mycorrhizal spores from organically and conventionally managed soils in promoting the growth of leek and white clover cultivars, it was shown that white clover only benefited from mycorrhizal infection in a low-fertile organically managed soil. Furthermore, in this study inocula from organic soils were more effective in both achieving mycorrhizal infection and in allowing more efficient P uptake in both crops (Scullion et al. 1998). Intensive farming practices probably reduce the benefits of indigenous mycorrhizal fungi.

Biological control agents, especially plant-pathogenic fungi, offer possible alternatives to chemical pesticides (Ghorbani et al. 2005). By using biocontrol agents instead of chemical pesticides as Speiser et al. (2006) suggested, organic farming substitutes ‘agrochemicals’ such as pesticides or veterinary drugs with ‘organic inputs’ such as biocontrol agents. However, crop protection is particularly critical in the early stages of conversion from conventional to organic farming because natural enemies and biocontrol agents are not fully available and need time to reach equilibrium (Lampkin 1999). Biological control methods are accepted as practical, safe, environmentally beneficial management techniques applicable to agroecosystems (Charudatan 2001). Mechanisms by which endophytes can act as biocontrol agents include production of antibiotic agents (Lambert et al. 1987; Chen et al. 1993; Sturz et al. 1998, 2000), siderophore production (Kloepper et al. 1980), nutrient competition (Kloepper et al. 1980), niche exclusion (Cook and Baker 1983) and induction of systemic acquired host resistance (Chen et al. 1995).

Since early observations that biodiversity in agricultural systems tended to be associated with less incidence of plant disease and high ecological stability, it has been demonstrated by many scientists that a range of soil micro-organisms actively support plant health (Dehne 1982; Fitter and Garbaye 1994; Azcon-Aguilar and Barea 1996). Soil microbial biomass changes as a consequence of switching from conventional to organic management (Shannon et al. 2002), and therefore plant pathogens in the community will be changed and the absence of synthetic pesticides improves biodiversity and increases occurrence of beneficial organisms (Klingen et al. 2002).

Choice of crop in a rotation with plants less susceptible to specific pathogens causes a decline in population due to natural mortality and the antagonistic activities of co-existent root zone micro-organisms (Fry 1982). Crop rotation may also provide microbial benefits beyond those normally associated with pathogen host range and saprophytic survival (Peters et al. 2003). Rotation is most successful in limiting the impact of biotrophic pathogens that require living host tissues, or those pathogens with low saprophytic survival capability (Bailey and Duczek 1996). However, crop rotation is least successful in reducing diseases caused by pathogens with a wide host range or those that produce long-lived survival structures such as sclerotia or oospores (Umaerus et al. 1989). Legume plant age was also the parameter that most strongly influenced the quality of the legume residues, and consequently its N and P release dynamics, with potentially significant consequences for N and P uptake recovery and losses and, ultimately, cropping system sustainability (Vanlauwe et al. 2008). Seed quality is also a major issue for crop establishment especially in low-input farming systems, where varieties often grow under more stressful conditions than in conventional farming systems. In the absence of organic seeds from varieties bred specifically for organic systems, non-GMO crop genotypes selected for high seed quality in a conventional system will also have high seed quality when grown in a low-input, organic system (Yara et al. 2008).

There is growing interest in using organic amendments and compost extracts not only to improve biological, chemical and physical soil conditions, but also to provide direct and indirect control of crop pests and diseases in tropical, arid and temperate climates (Abbasi et al. 2002; Litterick et al. 2004). Organic farmers routinely use organic fertilizers, composts and additions of rock minerals for these purposes to help ensure acceptable yields of high-quality produce particularly in intensive vegetable production systems (Zhang et al., 1998; Diver et al. 1999; Montemurro et al. 2005; Barker and Bryson 2006; Toor et al. 2006). However, the effects of applications of plant residues and compost to the soil or aqueous extracts to soil and/or crop foliage are very much related to the degree of decomposition of the plant material or compost feedstock (Ghorbani et al 2008b). Matured composts are generally more suppressive although readily available carbon compounds found in low-quality, immature compost suppressed *Pythium* and *Rhizoctonia* (Nelson et al. 1994). Beneficial organisms may be used to inoculate composts: for example, strains of *Trichoderma* and *Flavobacterium*, added to suppress *Rhizoctonia solani* in potatoes. *Trichoderma harzianum* acts against a broad range of soil-borne fungal crop pathogens, including *R. solani*, by production of anti-fungal exudates (Sullivan 2001). Composts' contribution to nitrogen fertility must also be taken into account as nutrient status may influence the severity of pathogens. *Phytophthora* die-back of Rhodododendron, *Fusarium* wilt of cyclamen and fire blight are examples of diseases that increase in severity as a result of excessive nitrogen fertility introduced into container media with composted biosolids (Ceuster and Hoitink 1999). Direct changes in host susceptibility to infection in response to nitrogen supply have also been postulated but are still controversial (Savary et al. 1995). It is known, for example, that fertilization with large amounts of nitrogen increases the susceptibility of pear to fire blight (*Erwinia amylovora* (Burrill) Winslow), and of wheat to rust (*Puccinia graminis* Pers.) and powdery mildew (*Erysiphe graminis* DC. *f.* sp. *tritici* Marchal) (Agrios 1997). Sheath blight (*R. solani* Kuhn) in rice fields increases with increasing N level (Cu et al. 1996). Applications of urea increase the severity of *Rhizoctonia* blight (Colbach et al. 1996). Growth and disease responses to high levels of NH_4-N have been documented with a range of plants and pathogens (Sasseville and Mills 1979; Marti and Mills 1991). In contrast, reduced availability of nitrogen may increase the susceptibility of tomato to *Fusarium* wilt, of many solanaceous plants to *Alternaria solani* (Ell. & Mart.) Jones & Grout. early blight and *Pseudomonas solanacearum* (Smith) Smith wilt; of sugar beets to *Sclerotium rolfsii*, and of most seedlings to *Pythium* damping off (Agrios 1997). Similarly ammonium fertilizer can decrease disease levels and infection cycles of take-all (*Gaeumannomyces graminis* (Sacc) Arx & Olivier var. *tritici* Walker (Ggt) in wheat (Colbach et al. 1996). Thus, there is a real need to determine the effect of soil nutrient supply on disease development and biocontrol activities of biocontrol agents.

Application of organic matters and all treatments that increase the total microbial activity in the soil and increasing competition for nutrients might enhance general suppression of pathogens (Ghorbani et al 2008b), improve plant health and induce disease resistance in many plants (Sullivan 2001). Application of poultry manure showed lower disease incidence, as shown by 80% healthy tomato, compared with the chemical fertilizers (Ghorbani et al 2008a). As the active microbial biomass increases, the capacity to utilize carbon, nutrients and energy in the soil is increased and thus these resources will be very limited for the soil-borne pathogens. In this situation, substantial quantities of soil nutrients are tied up in soil microbial bodies, so that there will be very high competition for nutrients. Organic fertilizers and especially composts act as food sources and shelters for antagonists that compete with plant pathogens; organisms that prey on and parasitize pathogens and beneficial micro-organisms that produce antibiotics (Sullivan 2001). Anyway, as Ceuster and Hoitink (1999) suggested, many aspects of organic amendments must be controlled to obtain consistent results because of their variable nature. The composition of the organic matter from which the organic fertilizer is prepared, the processing method, the stability or maturity of the finished product, the quantity of available plant nutrients provided and time of application all must be carefully considered.

Organic farmers should know the C/N and N/P ratios in organic fertilizer before application of N–P–K in order to formulate an overall pest or disease management strategy. Most high C/N ratio composts (>70:1) immobilize nitrogen and plants grown in such products suffer from chronic nitrogen deficiency resulting in lack of growth and increased susceptibility to pathogens or insects (Ceuster and Hoitink 1999). High C/N ratio tree bark compost may suppress *Fusarium* wilts, but with lower C/N ratio composts, they may become more severe as a result of the excess nitrogen, which favours *Fusarium* (Hoitink et al. 1997). The moisture content following the peak heating stage of compost is critical to the range of organisms inhabiting the finished product. Compost with at least 40–50% moisture will be colonized by both bacteria and fungi and will be suppressive for *Pythium* disease (Hoitink et al. 1997).

Various alternative, non-chemosynthetic treatments have been developed for the direct control and management of plant pathogens, particularly for use in organic systems, but which are also applicable in conventional cropping. These include aqueous extracts of plant material or compost, mineral preparations and also specifically selected microbial populations applied to the soil and/or crop foliage, usually at low dose rates. They may have direct anti-disease effects and/or induce plant resistance or stimulate competitor micro-organisms or otherwise be antagonistic to target plant pathogens (Ghorbani et al. 2006). The components of composts responsible for induced activity may be biological or chemical in nature (Zhang et al. 1998) and nutrient supply may be involved with regard to effects of organic manures on plant pests.

4.4 Food Quality, Safety and Environmental Impacts

Food quality and safety in agricultural products is another important issue irrespective of the production system – organic or conventional. Food quality is the suitability of the particular foodstuff for its intended purpose and characterized by quantitative and qualitative characteristics that may differ between markets, e.g. fresh and processed, consumers and regions and influence the prices received by producers and paid by the customers. One aspect of food quality that is becoming more important is the way that the food has been produced in relation to techniques and inputs used, environmental impacts, energy demands and animal welfare standards. In this respect, consumers have choices, e.g. between food produced by conventional, low-input or organic production systems. Food safety on the other hand is defined as the assurance that food will not cause harm to the consumer when it is prepared and/or consumed according to its intended use (Brandt 2007). It is regulated by national and international legislations. There are ample examples that the methods used for food production do make a difference to food composition or other aspects of its quality, and that these differences are large enough to make a real difference for the consumer in terms of health. Food production methods probably affect food quality to the extent that they have a significant impact on health. There is now a good basis for designing studies that can elucidate which production factors are important in this regard, and that the next step is to define and test these factors (Brandt 2007). Hazards traditionally considered serious food safety issues responsible for food poisonings and with no indication of benefits are pathogens such as prions (BSE), allergens, mycotoxins, dioxins, GMOs, pesticide residues, growth hormones, food additives: colourants, preservatives, flavours, process aids, nitrite added to processed meat, salt, added sugar and saturated fat (Brandt 2008). The role of organic agriculture whether in farming, processing, distribution or consumption is to sustain and enhance the process of food safety and health at all stages and levels of the agroecosystem.

4.4.1 Food and Agrochemicals

The harmful short- and long-term effects of application of agrochemicals on human health have been proven. Several pesticides have been shown to produce complex chronic effects such as change in endocrine functions and immune systems (Woese et al. 1997; Soil Association Organic Standards 2001). Increased uterine weights, reduced pregnancy rates, decreased litter size, interference with development of the reproductive tract or related sexual behaviour are symptoms that are coupled with endocrine disruption (Lundegardh and Martensson 2003). In addition to the short-term direct effects of chemicals on the immune and the endocrine systems, application of several types of agrochemicals during the growing season, typical of conventional systems, will give accumulated and combined effects on living organisms in the ecosystems. Farmers and farm workers are at greatest risk, in particular in countries with less efficient enforcement of safety procedures. Prevention of serious exposure to pesticides represents an important step in avoiding chronic as well as acute disease (Reigart and Roberts 1999). Organic farming that avoids pesticide application helps to provide a ‘healthier’ agroecosystem by protecting non-target organisms against unintended exposure. In addition to farmers and other human users of the farmed landscape, these include beneficial insects, micro-organisms and insectivorous birds, mammals and reptiles.

4.4.2 Nutritional Quality

Approximately 40 micronutrients, minerals, fatty acids and vitamins cannot be produced by the human body and must be supplied via foods. Substances in food have recently been discovered that are not among those micronutrients but still exhibit beneficial effect on health (Harborne et al. 1999) when ingested in optimal amounts (Brandt et al. 2004). Many of these substances belong to the large group of secondary metabolites that are produced within the plants (Luckner 1990).

Evidence indicates that secondary plant metabolites play critical roles in human health and may be nutritionally important (Brandt and Mølgaard 2001). Some scientists believe that plant-based phenolic metabolites are very important due to their antioxidant activity (Rein et al. 2000; Asami et al. 2003), while others have found that other bioactive secondary metabolites, such as glucosinolates from broccoli, are more likely to account for the health-promoting effects of vegetables and fruits (Brandt et al. 2004). Secondary metabolites are common constituents of fruits and vegetables that function in the defence against disease, insect and animal herbivory (Stevenson et al. 1993). There is a growing concern that the levels of some secondary metabolites may be lower than optimal for human health in foods grown in conventional agricultural practices (Brandt and Mølgaard 2001). This concern arises because conventional agricultural practices utilize levels of plant nutrients that can result in a reduction of the natural production of secondary metabolites in the plant (Brandt and Mølgaard 2001; Nørbæk et al. 2003). Differences between the content of secondary metabolites in organically and conventionally produced fruits and vegetables is in line with the observation that organically grown plants are more resistant to diseases and pests than corresponding conventional plants (Evers 1989; Van-Bruggen 1995) and allows for the possibility that organically grown produce may be more beneficial for human health than corresponding conventionally grown produce (Brandt and Mølgaard 2001; Carbonaro et al. 2002; Asami et al. 2003).

In terms of levels of compounds indicated as positive for health, the composition of plants that obtain much of their nutrients from slowly released sources such as plant residues or compost, tend to differ from those provided large amounts of easily available mineral fertilizers. These include higher levels of ascorbic acid (vitamin C); lower levels of nitrate; lower levels of total N (often expressed as ‘protein’); higher proportion of essential amino acids in protein; higher zinc (Zn) to phytate ratios (on tropical soils); lower levels of β-carotene; and higher levels of dry matter and plant secondary metabolites (Brandt and Kidmose 2002). Organic foods generally have a lower content of nitrate than conventional foods (Woese et al. 1997; Soil Association Organic Standards 2001). Several reports show higher levels of flavonoids in organic vegetables than in conventional products (Ren et al. 2001; Carbonaro et al. 2002; Asami et al. 2003; Grinder-Pedersen et al. 2003), and correspondingly greater oxidation of proteins in humans, which may be related to the pro-oxidative effect of these compounds and is probably a positive biomarker, even though it contradicts the ‘traditional’ model for effects of phenolic antioxidants (Grinder-Pedersen et al. 2003). Products from animals fed a large proportion of grass or other relevant roughage have higher levels of β-carotene and other carotenoids, such as lutein; higher proportions of conjugated linoleic acids in the fat; proportions of polyunsaturated fatty acids in the fat; and higher levels of vitamin E, in particular the active, natural isomer (e.g. Dhiman et al. 1999; Nielsen et al. 2004).

Cobalt is an essential element for animals but not for plants, found in vitamin B12 and is utilized by micro-organisms. Vitamin B12, in common with a range of other organic substances can be taken up passively by plants. Plants products can therefore, contain considerable quantities of vitamin B12 although it is not essential for normal plant development (Mozafar 1994; Lundegardh and Martensson 2003).

Application of organic fertilizer in soil increases the supply of vitamin B12 in plants and Mozafar (1994) found that barley and spinach fertilized with organic materials had higher concentrations of vitamin B12, whereas sheep grazing cobalt-deficient forage were deficient in vitamin B12 (Ulvund and Pestalozzi 1990). However, human diets normally provide more than sufficient intake of B12, so deficiency is normally caused by impaired absorption due to medical conditions such as gastric atrophy (Cuskelly et al. 2007), which are common among the elderly. It is essential that patients with vitamin B12 deficiency are identified and treated with injection of the vitamin, since the condition cannot be alleviated through the diet, and B12 deficiency causes irreversible damage to the nervous system if not treated. The symptoms of vitamin B12 deficiency can be masked if the diet contains large amounts of folate, so folate fortification of foods can be a serious health risk for older people (Cuskelly et al. 2007). However, organic foods are exempt from fortification in countries where this takes place, providing an additional nutritional benefit for a large group of consumers.

Therefore, the type of farming system has implications on nutritional quality and safety of food and there is growing evidence that certain foods from organic production may have a number of advantages for consumers over food from conventional systems.

4.5 Conclusion

The challenge facing agriculture today is to increase the quantity and quality of food produced, with limited impact on sustainability and the environment. Organic agriculture is a very small, but expanding sector and could have an increased global significance in future by creating a sustainable agroecological system based on local resources. It is the clear from the studies reviewed in this paper that organic crop and soil management practices are generally beneficial for the environment, biodiversity and food quality. Organic farming also has potential for reducing greenhouse gases; however, additional research in energetic efficiency balance is necessary to determine the overall impact of organic agriculture and to compare it with other production methods. In addition, since greenhouse gas emissions originate from both biotic and abiotic processes, the complete emission inventory of a farm such as soils, livestock, animal wastes, consumption of fossil fuels and production of fertilizers have to be considered (Adger et al. 1997; Kramer et al. 1999).

Various cultural practices used in organic farming, such as applying organic manures and composts, mixed cropping, green manure, long-rotation, tillage systems and other strategies for enhancing soil quality all have effects on crop protection and production, environment and food quality. Several studies have provided interesting results to support the view that optimal long-term management of soil organic matter can lead to improved soil conditions, maintain biodiversity and improve plant resistance against pests and diseases. Several studies support the claim that consumption of organically produced food may be beneficial to human health because of increased content of health-related compounds, especially trace elements, vitamins and several secondary metabolites coupled with reductions of pesticides in the farmed environment (Lampkin 1999; Lampkin and Measures 1999). Indeed, public and governments' concerns about agrochemical use and environmental degradation are driving consumer demand for organic products, which should increase profitability of organic farming.

With predictions of world shortages of fossil oil energy and energy use-induced climate changes, organic farming should be considered as a measure to mitigate these problems, but both organic and conventional producers will have to modify their approaches, adopt new technology and varieties in order to face the challenges. However, the type and extent of conversion from conventional to low-input and organic production systems should be carefully evaluated and matched with other environmental and socio-economic consequences of such conversion. Analysing agricultural system efficiency is very complex. Account needs to be taken of the costs of productivity losses due to erosion and declining fertility; pesticide poisonings and associated chronic health problems, costs of developing new pesticides, antibiotics and medicines due to chemical resistance in plants, animals and micro-organisms; transportation of non-renewable fossil inputs and fuel; farm subsidies and implications for taxpayers, externalized costs for cleaning up air and water pollution from pesticides and mineral fertilizers and reducing greenhouse gases, and many social welfare costs, as well as productivity, if the real differences between organic and convention farming systems are to be determined. However, the major advantages of organic farming compared to conventional agriculture, summarized as higher biodiversity, more diverse landscape, soil conservation and maintenance of soil fertility, less pesticide exposure in the landscape, less utilization of non-renewable external inputs and energy, and less water pollution, support the view that its further expansion could provide a bigger part of the solution to global problems. The review of recent scientific progress and achievements, highlighted in the present article, clearly demonstrate that the type of production system has implications for environment, food quantity, nutritional quality and safety.

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Chapter 5
Sustainability of Energy Crop Cultivation in Central Europe

Volkhard Scholz, Monika Heiermann, and Peter Kaulfuss

Abstract Currently biomass contributes to 69 10^6 tons of oil equivalents (MtOE) or 4% of the total energy consumption in Europe. According to the European Union (EU) Biomass Action Plan biofuels shall contribute 150 MtOE to the total energy consumption in 2010. This share shall increase to 20% or 220 MtOE in 2020. Approximately half of it will be derived from arable land, i.e. 23 MtOE woody biomass (short rotation coppice [SRC]) and 88 MtOE herbaceous biomass. This would comprise 15% of the arable land and hence, the question arises whether this energy resource can be exploited sustainably or not. It is assumed that using energy crops as resource increases biodiversity and farmers sources of income. In this chapter sustainability will be assessed in relation to energy balance, greenhouse gas (GHG) reduction and emission of other air pollutants.

Energy crops from agriculture can be categorised into three types: oil plants, cellulose providing plants and starch-and sugar-containing crops. The utilisation of energy can also be distinguished into three categories: liquid, gaseous and solid biofuels. Biomass yields range from 2 to 15 t organic dry matter (ODM) ha^{-1} $year^{-1}$ depending mainly on the fraction appropriate for energy conversion, i.e. if only grains can be used the lower values are applicable, whereas in the case of whole crops 10 to 15 t ODM $ha^{-1}y^{-1}$ can be harvested.

The assessment of the sustainability of the cultivation of energy crops includes the input and recycling of nutrients, the application of pesticides, the water-use efficiency, the consumption of fossil fuels and the balance of soil carbon. The aim is to recycle the nutrients, which is simple in the case of anaerobic digestion by applying the digestate to the field. If crops are combusted many of the minerals can be returned via the ash. In the case of liquid biofuels, exported nutrients are lost and have to be replaced. The application of pesticides, mainly herbicides, can often be reduced in comparison to food production, but the energy yield per hectare might be reduced if the share of weeds exceeds certain thresholds. Water use efficiency,

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V. Scholz (✉), M. Heiermann and P. Kaulfuss
Leibniz Institute for Agricultural Engineering Potsdam-Bornim (ATB),
Max-Eyth-Allee 100, 14469, Potsdam-Bornim, Germany
e-mail: vscholz@atb-potsdam.de

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fossil fuel input and soil carbon losses and gains do not differ, in general from food crop cultivation. Although during cultivation, short rotation coppice sequesters considerable amounts, 0.4 – 1.6 t C ha^{-1} $year^{-1}$, of soil carbon.

Fertiliser levels of nitrogen, potassium, sulphur and chlorine and to a lesser extent phosphorous determine the contents of these elements in energy crops and hence the risk of releasing these into the atmosphere or of damaging the energy conversion installations. 150 kg N fertiliser input increase nitrogen concentrations in energy crops by absolute 0.1 to 0.3%. Potassium concentrations in energy crops are not only dependent on fertiliser application but on species as well. Herbaceous plants show potassium concentrations of > 0.7% whereas concentrations in woody species are <0.4%.

The uptake of heavy metals from soils is also determined by their contents in soil and by plant species. If these crops are used for anaerobic digestion one has to consider that there is a remarkable risk of an accumulation of heavy metals in soil. In the case of combustion, most heavy metals can be removed by filtering the ash and it can be used safely as fertiliser. Thus cultivation and combustion of short rotation coppice is a smart scheme of removing heavy metals from contaminated soils.

Nitrous oxide emissions are generally induced by fertiliser application. Emission strength varies with soil type, temperature and moisture and is substantially crop specific. There is a considerable difference between woody species and cereals. While the Intergovernmental Panel on Climate Change (IPCC) general N2O emission value is set to 1.25% of the nitrogen applied an average of 0.8 to 1.0% could be found from sandy soils.

The energy yield is mainly dependent on the biomass yield and on the conversion technology and hence on the fraction of crop used as energy source. Liquid biofuels have the lowest energy yield with approximately 30 to 130 GJ per ha, whereas the solid biofuels yield is 110 to 260 GJ per ha. Whole crops converted to biogas deliver energy yields in between these values. However, the net energy yield depends also on the input of energy for production and conversion of the crops. The cumulated energy demand (CED) of cultivation and harvest varies mostly between 4 and 14 GJ ha-1 for oil plants, between 7 and 21GJ ha-1 for sugar/starch plants and between 3 and 24 GJ ha-1 for lingo-cellulosic plants. The energy balance of biofuels can be improved by the appropriate use of by-products.

Most important greenhouse gases are carbon dioxide, methane and nitrous oxide, less important ones are fluorinated compounds, although their greenhouse warming potential ranges in the thousands of CO_2 equivalents. GHG emissions correspond, in general, with the energy balance of energy conversion paths, i.e. liquid biofuels have the lowest GHG reduction potential in comparison to mineral fuels, whereas solid fuels save most GHG emissions compared to fossil fuels. Greenhouse gas reduction ranges from zero to 15 t ha-1y-1 CO_2 equivalents. So, the cultivation of energy crops on 15% of total arable land would significantly contribute to the EU CO_2 reduction target.

Sustainability of energy crops is, in general, dependent on the crop species and the system boundaries considered. But the type of conversion and the use of by-products have also considerable effect on its sustainability. Nevertheless, it can be concluded that the utilisation of energy crops considerably increase sustainability of energy provision in the EU.

Keywords Carbon • Cultivation • Energy crops • Energy yield • Fertiliser • Greenhouse gases • Heavy metals • Nutrients • Sustainability • Yield

Abbreviations

BtL	Biomass-to-Liquid
CED	Cumulated energy demand
CF	Conversion factor
DM	Dry matter
DME	Dimethyl ether
ETBE	Ethyl *tert*-butyl ether
EU	European Union
FAME	Fatty acid methyl ester
GHG	Greenhouse gas
GtL	Gas-to-Liquid
GWP	Global warming potential
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
L	Lignocellulose
MeOH	Methanol
MTBE	Methyl *tert*-butyl ether
MtOE	10^6 t of oil equivalents
n	Number of measurements
NHV	Net heating value
NMHC	Non-methane hydrocarbons
O	Oil
ODM	Organic dry matter
PCDD/F	Polychlorinated dibenzodioxines and dibenzofuranes
RME	Rapeseed methyl ester
S	Sugar/starch
SRC	Short rotation coppice
SVO	Straight vegetable oil
VOCs	Volatile organic compounds
WUE	Water-use efficiency

5.1 Introduction

In view of the finiteness of fossil energy products, accompanied by growing environmental problems, it is necessary to establish new, sustainable and future-oriented concepts for energy generation. The goal of sustainable development inevitably involves the exploitation of renewable sources of energy. Therefore, the European Union (EU) aims to double the proportion of renewable energy from 6% to 12% by 2010. Currently, around 4% (69 MtOE = 69 × 10^6 t of oil equivalents) of the EU's total primary energy consumption is met from biomass. This makes biomass by far the most important renewable energy source, providing two thirds of the total energy produced from renewables (AEBIOM 2007). To fulfil its potential, the European Commission published a Biomass Action Plan (EC 2005) with an aim to increase biomass use to 150 MtOE in 2010, and look at the longer term to achieve an ~20% share of renewables in total energy consumption in 2020 (EP 2005). These goals are accompanied by measures to improve the supply of, and increase the demand for, biomass, as well as to overcome technical barriers, thus ensuring that existing targets will be met.

Biomass potentials are mainly determined by agricultural productivity and the amount of land accessible for energy crop production. The total area under energy crops in the EU was around 1.6 million hectares in 2004 (estimate for 2005: 2.5 million hectares), which represents nearly 3% of the total arable land. AEBIOM (2007) estimated a total biomass supply of 220 MtOE for the year 2020, while 23 MtOE are covered by wood-based bioenergy (direct from forests) and 88 MtOE by agriculture-based energy crops (by-products not considered). The Commission has estimated that about 15% of the EU's arable land (17.5 million hectares) would be used to reach the targets for 2020.

Increasing the use of bioenergy offers significant opportunities for Europe to reduce greenhouse gas (GHG) emissions and improve the security of its energy supply. However, besides food and feed production, the significant increase in the use of biomass from agriculture and forestry to provide energy carriers may put considerable environmental pressure on farmland or forest biodiversity as well as on soil and water resources. In general, energy crops should have characteristics such as high yields, low production inputs and high energy values to make the production of energy from biomass even more economically efficient and optimise the environmental benefits. Thus, in the scope of multifunctional agriculture, energy farming creates alternative sources of income besides food production and strengthens added value and employment, in particular in rural areas. The purpose of this review is to contribute to the debate on whether energy crops can be cultivated sustainably by providing a comprehensive picture of the status quo in energy crop cultivation in Europe.

5.2 Energy Crops

Energy crops belong to biomass. In general, the term "biomass" is applied to renewable energy sources, referring to organic materials that are viable as sources of energy or may be converted to biofuels, which may be used as energy sources. The majority of biomass resources fit into the broad categories of energy crops, residues (by-products of existing crops) and waste products produced directly or indirectly from the solar conversion process.

According to Bassam (1998) who provided a well-established definition, "energy crops" are "those annual and perennial plant species that can be cultivated to produce solid, liquid or gaseous energy feedstock. The organic residues and wastes from the most widely diverse types of plant production, also used for producing energy, do not fall under this term but nevertheless represent a large potential.” Silvicultural plants are mostly excluded too. Worldwide, approximately 300 plant species have been domesticated as crops for agriculture to supply food, feed and fibres. Of these, more than 60 species play an important role as feedstock for energy conversion processes (Fig. 5.1).

Energy crops can be divided into three principal groups: oil, cellulose and sugar/starch plant species. The first group is used for the production of liquid biofuels. Oil pressed or extracted from seeds (e.g. sunflower and rape) is mainly supplied as straight vegetable oil (SVO), or as ester (biodiesel, RME and fatty acid methyl ester [FAME]) for power generation, or as a fuel in the transport sector. The second group is represented by ligno-cellulosic plant species, mostly used as whole plants for biomass conversion processes (combustion, gasification and synthesis). Ligno-cellulosic feedstock (annual and perennial crops) is processed into solid, gaseous and liquid energy carriers for heat and/or power generation. The third group presently cultivated on a large scale for ethanol production comprises sugar and starch crops (e.g. cereals, maize, potato and sugar beet). The most frequent use of ethanol in Europe is, however, for conversion into derivates such as Ethyl *tert*-butyl ether (ETBE). Many crop species are multipurpose, i.e. they can be used to produce more than one type of energy carrier, for example, cereals (ethanol and solid biofuel). Hence, biomass (wet) rich in oil, sugar and starch is also suitable for

Fig. 5.1 Energy crop species on the experimental field of ATB Potsdam-Bornim (poplar, rye and triticale)

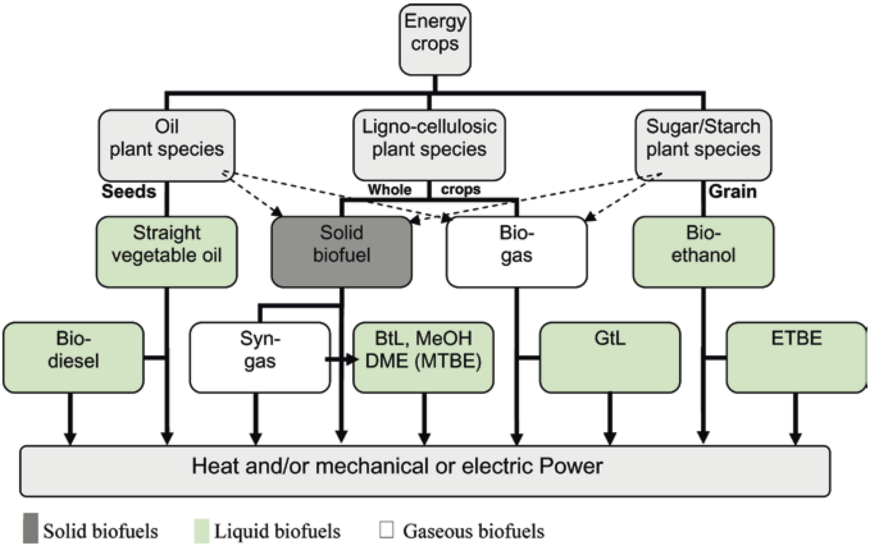

Fig. 5.2 The main crop-to-energy chains. BtL: Biomass-to-Liquid, GtL: Gas-to-Liquid, ETBE: Ethyl *tert*-butyl ether, MTBE: Methyl *tert*-butyl ether, MeOH: Methanol, DME: Dimethyl ether. Pyrolysis oil, HTU-Diesel (Hydro Thermal Upgrading), ethanol and hydrogen from ligno-cellulosic species are not considered here because of their minor practical relevance in the near future

biogas production by anaerobic digestion. In Germany, biogas produced is most frequently used for heat and power generation. However, upgraded compressed biogas can be used as an engine fuel (Gas-to-Liquid [GtL]), which currently represents a niche market (Fig. 5.2).

Aquatic species (e.g. algae) are not considered in this study, which relates strictly to terrestrial energy crops that are classified as woody or herbaceous. Woody crops are predominantly plantation trees, frequently grown in short rotation intervals of 1-20 years (short rotation coppice [SRC]). Cultivating practices in energy plantations (e.g. willow and poplar) have only been established in a few countries (Scholz 2004). In most cases production practices for herbaceous crops (annual and perennial) resemble those of agricultural crops, although in both woody and herbaceous crop production the end use of the biomass determines the management and cultivation inputs, as well as practices employed to optimise the production system (Heiermann et al. 2007). Actual and/or potential energy crops and forms of use are listed in Table 5.1 according to their current distribution and temperature requirements.

5.3 Sustainability

Many different definitions of "sustainability" have evolved over the past decades (Pretty 2007). Despite this ambiguity, Klauer (1999) for instance stated that "common ground of all definitions of sustainability is the preservation of a system

Table 5.1 Potential energy crops suitable for present and future European climate conditions, and forms of use as well as simple climate and elevation rules according to Bassam (1998), IIASA (2002), BioBase (2004), IENICA (2004) and Tuck et al. (2006)

Common name	Botanical name	Use	Elevation(m)		Temperature(°C)			Rainfall (mm year^{-1})	
			Min	Max	Months	Min	Max	Min	Max
Oilseed rape	*Brassica napus*	O	0	800	04–07	6	40	400	1,500
Linseed	*Linum usitatissimum*	O	0	900	03–09	4	32	250	1,300
Field mustard	*Sinapis alba*	O	0	950	04–08	7	27	600	1,200
Hemp	*Canabis sativa*	O/L	0	950	04–09	5	28	600	1,500
Sunflower	*Helianthus annuus*	O	0	950	04–09	15	39	350	1,500
Safflower	*Carthamus tinctorius*	O	0	900	04–09	20	45	400	1,300
Castor	*Ricinus communis*	O	100	1,800	04–08	17	38	500	2,000
Olive	*Olea europaea*	O	0	2,000	03–11	−7	42	200	1,300
Groundnut	*Arachis hypogaea*	O	0	1,500	04–08	19	45	450	2,000
Barley	*Hordeum vulgare*	S/L	0	900	05–09	8	35	250	2,000
Wheat	*Triticum aestivum*	S/L	0	950	05–09	11	32	400	1,600
Oats	*Avena sativa*	S/L	0	1,000	04–08	6	25	400	1,200
Rye	*Secale cereale*	S/L	0	950	05–09	11	32	400	1,600
Potato	*Solanum tuberosum*	S	0	1,000	04–09	5	25	500	1,500
Sugar beet	*Beta vulgaris*	S	0	1,000	04–09	5	25	500	1,500
Jerus. artichoke	*Helianthus tuberosus*	S	100	750	05–09	8	25	500	1,600
Sugarcane	*Saccharum officinarum*	S	0	1,200	03–09	16	41	1,000	–
Cardoon	*Cynara cardunulus*	L	0	500	11–08	−3	37	400	900
Sorghum	*Sorghum bicolor*	L/S	0	1,100	04–08	16	40	300	700
Kenaf	*Hibiscus cannabinus*	L	0	600	02–11	−2	33	500	1,100
Prickly pear	*Opuntia fiscus-indica*	L	0	1,500	12–02	6	–	350	1,500
Maize (whole)	*Zea mays*	L/S	0	950	05–09	9	40	450	1,500
Reed canary	*Phalaris arundinacea*	L	0	1,100	04–10	1	38	600	2,000
Miscanthus	*Miscanthus* spp.	L	0	950	04–09	11	40	600	1,500
SRC	*Salix* spp.	L	0	1,100	04–10	1	38	600	2,000
	Populus spp.		0	1,100	05–09	3	38	600	2,000
Eucalyptus ssp.	*Eucalyptus globulus*	L/O	0	1,500	10–03	−6	36	400	2,500
	E. camaldulensis		0	1,500	04	7	36	400	2,500
	E. grandis, E. terticonis		0	1,500	05–09	10	36	400	2,500

O: Oil; S: Sugar/Starch; L: Lignocellulose.

or certain characteristics of a system, e.g. the productive capacity of the social system or the life-supporting ecological system. Therefore, something should always be preserved for the well-being of future generations" [translated by the authors]. In a narrower sense "sustainability" refers mainly to the environment in the agricultural context. According to Tilmann et al. (2002), we define sustainable agriculture as practices that meet current and future societal needs for food, fibre, energy, ecosystem services, and healthy lives. This concept may be reached by maximizing the net benefit to society when all costs and benefits of the practices are considered. If society is to maximize the net benefits of agriculture, there must be a fuller accounting of both the costs and the benefits of alternative agricultural practices, and such an accounting must become the basis of policy, ethics and action. In addition, the development of sustainable agriculture must accompany advances in the sustainability of energy use, manufacturing, transportation and other economic sectors that also have significant environmental impacts. In this context, the assessment of the sustainability of the cultivation of energy crops includes the input and recycling of nutrients, the application of pesticides, the water-use efficiency (WUE), the utilisation of fossil fuels and the balance of soil carbon.

Developed environmental accounting and evaluation methods based on relevant parameters indicating potential impacts on the environment make it possible to describe and monitor processes, states and tendencies of the agricultural production systems at various levels (Hülsbergen 2003; Piorr 2003; Delbaere and Serradilla 2004; Zinck et al. 2004; Bergström et al. 2005; Meyer-Aurich 2005; Payraudeau and van der Werf 2005; Bockstaller et al. 2007).

On an international level, the norm DIN EN ISO 14040–14043 for life-cycle-assessment was established as a methodological guide and revised in 2006 (ISO/EN/DIN 14040 2006 and ISO/EN/DIN 14044 2006–2010). Policy decision makers need these tools to be able to provide appropriate agro-environmental policy measures (Pacini et al. 2000). However, assessing environmental impacts is not always straightforward because of widely varying parameters and complex system interactions. Table 5.2 presents an overview of relevant parameters indicating potential impacts on the environment caused by energy crop cultivation. Owing to the variety and complexity of environmental issues, the criteria should be applied to the major sustainability problems and opportunities currently encountered in the production of biomass or those anticipated for the future (Cramer et al. 2006; Lal 2008).

5.4 Biomass Yield

The yield is one of the most important ecological parameters, since all impacts on the environment have been related to it in order to characterise the energetic and "ecological" efficiency of an energy crop species (Scholz et al. 2006). The yields of the main products of conventional species such as cereals, oil and tuber crops are well known, whereas the yields of the whole plants are mostly not available in

Table 5.2 Relevant parameters indicating potential impacts on the environment caused by energy crop cultivation

Impact on environment	Parameter
Exhaustion of energy resources	Consumption of crude oil, natural gas, coal, uranium etc.
Exhaustion of other limited resources	Consumption of fertilisers, water (transpiration coefficient) etc.
Anthropogenic greenhouse effect	CO_2 equivalents (CO_2, CH_4, N_2O, VOCs, etc.)
Acidification	SO_2 equivalents (NO_x, NH_3, HCl, HF, H_2S, etc.)
Eutrophication	PO_4 equivalents (NO_x, NH_3, NH_4^+, PO_4^{3-}, NO_3^-)
Photosmog	C_2H_4 equivalents or NO_x corrected equivalent. (CH_4, NMHC, NO_x, ...)
Stratospheric degradation of ozone	N_2O
Human and ecological toxicity	Diverse selected individual substances, e.g. pesticides, heavy metals and particulates (PM10 equivalent)
Soil compaction	Soil morphology and structure
Soil erosion	Loss of topsoil
Change in soil quality	Organic matter content; carbon content
Change in water quality	Critical values for drinking water (e.g. nitrate, pesticides)
Nutrient leaching to groundwater and surface water	Volume and choice of fertilisers; rate, timing, methods of application; runoff or leaching potential
Change in biodiversity	Measures of impacts on flora and fauna, e.g. compatibility with native biomass, alteration of production and growth period and geographic distribution of populations and alterations in reproduction cycles of species
Change in land use	Landscape diversity (e.g. crop diversity, farmland diversity)
	Location of site (e.g. proximity to ecologically important areas)
	Scale of plantation (e.g. acreage)
Noise and odour	Diverse measures
Fire risk	Temperature, rainfall, wind, moisture, drought etc.

agricultural statistics and have to be calculated by means of the grain–straw or similar ratios. This may result in some errors because these ratios depend on various influencing factors and range over a wide span. Nevertheless, the method will do for a viable yield calculation (Table 5.3).

The yields of non-conventional crops such as *Miscanthus sinensis*, poplar and willow are little known. With the exception of willows in Sweden, these "new" energy crop species are mostly cultivated on small plots and are often at the research stage. Consequently, these yield data have to be examined critically. The published yields of *M. sinensis*, for instance, range between 8 and 22 t_{DM} ha^{-1} $year^{-1}$ and were mainly measured under special conditions (Frühwirth et al. 2006; Scholz et al. 2007; Stolzenburg 2008). The denoted average yields of poplar and willow are a result of an expert census in Germany (KTBL 2006).

Table 5.3 Mean biomass yield, moisture content and heating value of appropriated energy crop species in Germany according to Schmitz (2003), BMELV (2006), KTBL (2006), Frühwirth et al. (2006), Rosillo-Calle et al. (2007), BMELV (2007a) and own data

Use	Species	Product –	Yield (t_{DM} ha^{-1} y^{-1})	Moisture[a] (%)	NHV[b] (MJ kg_{DM}^{-1})
Oil use	Rape	Seeds	3.0[c]	12	26.5
	Sunflower	Seeds	2.2	12	–
Sugar/Starch use	Wheat	Grain	6. 4[c]	14	17.0
	Winter rye	Grain	4.6[c]	14	17.1
	Winter triticale	Grain	4.9[c]	14	16.9
	Maize	Grain	7.6[c]	14	17.0
	Potato	Tuber	8.9[c]	78	14.3
	Sugar beet	Tuber	13.5	77	–
Ligno-cellulose use	Wheat	Whole crop	14.0	16 or 65	17.1
	Winter rye	Whole crop	9.8	16 or 65	17.7
	Winter triticale	Whole crop	10.5	16 or 65	17.0
	Maize	Whole crop	17.5	65	17.9
	Perennial rye	Whole crop	8.5	16 or 65	17.7
	Grass	Whole crop	9.0	16 or 65	16.5
	Miscanthus	Whole crop	15.0[d]	16 or 65	17.6
	Poplar	Whole crop	10.0[d]	54	18.4
	Willow	Whole crop	7.0[d]	50	18.3

[a] Mean moisture content of harvested products, in the case of whole haulm-type crops in the form of dry bales or chips (16%) or in the form of silage (65%)

[b] Net heating value (NHV) of absolutely dry material

[c] Mean long-term yield (2000–2005)

[d] No statistically safe data

However, the statistical distribution of the poplar yield is very wide and ranges between <1.0 and >25 t_{DM} ha^{-1} $year^{-1}$ in Europe (Fig. 5.3). Nevertheless, the distribution of the poplar yields shows that some of these "new" energy crop species may have great potential if the right varieties are chosen for the right sites.

5.5 Need for Savings in Environmentally Relevant Resources

5.5.1 *Fertilisers*

Fertilisers are an essential prerequisite for obtaining acceptable biomass yields. The average contribution of fertilisers to yields ranges from 40% to 60% and tends to be higher in the tropics (Stewart et al. 2005). However, most fertilisers are produced on base of exhaustible raw materials and/or are sources of environmental

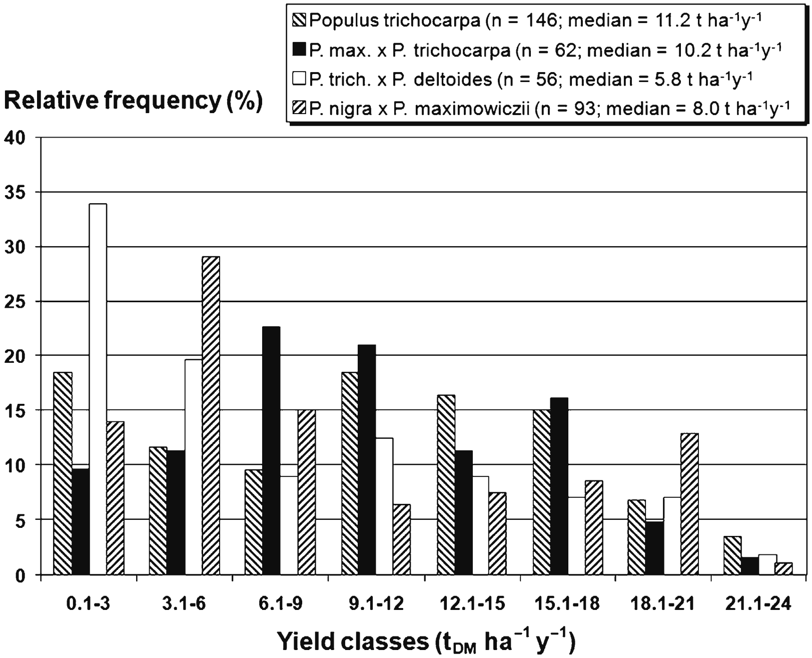

Fig. 5.3 Statistical distribution of measured poplar yields in Germany divided into subspecies. Result of a survey of a total of *n* = 357 yield data of various poplar stands of 2–18 years on 25 different sites in Germany. The high frequency of the lower yields is caused by the high share of young stands, as the yield of poplar grows up to an age of 5–10 years

pollution. Fertilisers cause not only eutrophication and an increase of environmentally harmful substances in biofuels but also emissions during their production as well as during the crop production. Thus, the demand for fertiliser is an evident indicator of the environmental sustainability of the crop production.

Of the relevant nutrient fertilisers (N, P_2O_5, K_2O, Ca, Mg, S), nitrogen (N), phosphate (P_2O_5) and potassium oxide (K_2O) have the highest efficiencies, i.e. 33%, 20% and 60%, respectively (Engelstad 1968; Raun and Johnson 1999). However, these nutrients cause various environmental problems (Scholz and Ellerbrock 2002). Nitrogen is the most problematic nutrient. Its production requires a great deal of energy (Patyk and Reinhardt 1997) and its utilisation results in relevant emissions into air and water (Kaltschmitt and Reinhardt 1997). Phosphate is a globally limited raw material (Pradt 2003), and potassium is often used in the form of potassium chloride (KCl), which contains harmful chlorine (Cl). Therefore, minimising the application of these fertilisers improves the environmental compatibility of biofuel production.

For conventional food crops there are several fertilising rate recommendations, based on soil type, intended yield and nutrient content in the harvested crops. The recommended mean application rates in Germany for N range in

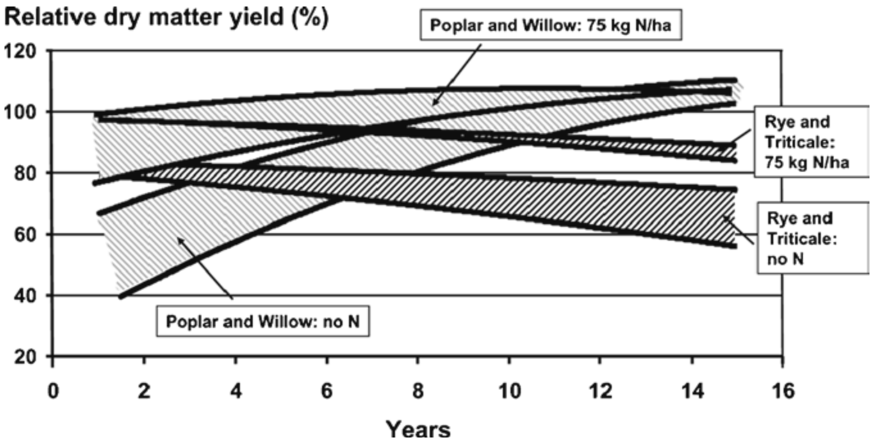

Fig. 5.4 Long-term impact of reduced nitrogen fertilisation on the yield of whole crop cereals and SRCs on a sandy soil in Germany (relative yield related to the yield of an application rate of 150 kg N ha^{-1}). The reduction of the N application rate by 50% results in a mean relative yield loss of ~10% after 15 years for rye and triticale. Non-fertilisation cause significantly higher losses. By contrast, the relative yields of poplar and willow on reduced and even non-fertilised stands do not decrease, but instead increase, although the absolute yields grow over time. One of the reasons for this phenomenon seems to be mycorrhica

general from 100 to 200 kg ha^{-1} $year^{-1}$, for P_2O_5 from 50 to 110 kg ha^{-1} $year^{-1}$, and for K_2O from 90 to 380 kg ha^{-1} $year^{-1}$ (KTBL 2005a). For energy crop species these recommendations are only partially correct, because (e.g. in the case of whole crop cereals) not only the grain (with a high N demand) but the whole plant is also used, because the energy efficiency of the cultivation may be higher with lower fertilising rates, and because some unconventional species such as SRCs need less or even no fertiliser (Fig. 5.4). Thus, the efficient use of fertilisers in energy crop production is an ongoing object of agricultural research.

Crop residues remaining on the field (straw, leaves and roots) as well as the recycling and refeeding of the residues and wastes of the crop products used for energy purposes such as ash and digested sludge contribute to minimising the demand for mineral fertiliser. Although the combustion and thermal gasification of biomass results in a major loss of nitrogen N (96%, …, 100%) and sulphur S (70%, …, 92%), the loss of P and K is lower and ranges between 30% and 100% (Hartmann and Strehler 1995; Heard et al. 2006). However, there are differences between the ash fractions (grate, fine and filter ash) concerning this matter. The grate ash used in practice is only 80–90% of the total ash content (percentage by weight) for cereals or grass and 60–90% for wood (Obernberger 1997), so that the actual nutrient recycling rate of solid biofuels is lower. Moreover, it must be considered that it is not the total percentages of these ash nutrients that are available to plants (Table 5.4).

Table 5.4 Selected nutrients in plant residues after combustion or digestion

Residue	Crop species	Percent by weight[a] (%DM)	Content of nutrients in residue[b] (% DM)		
			N	P_2O_5	K_2O
Grateash	Cereals[c]	4.0 ± 1.5	0, …, 2	7, …, 10	5, …, 18
	Grass	7.0 ± 2.5	0, …, 2	0.4, …, 1	11, …, 29
	Wood	1.5 ± 1.0	0, …, 2	1, …, 5	4, …, 12
Digested sludge	Grain	25 ± 5	5.4	3.1	2.5
	Cereals[c]	24 ± 5	3.2	2.0	5.0
	Grass	38 ± 5	3.9, …, 4.7	1.6, …, 2.6	7.2, …, 10.5
	Maize	30 ± 5	2.1, …, 3.1	1.4, …, 1.8	3.9, …, 7.2
	Beets	25 ± 5	2.8	1.2	3.4

[a] Ash content according to Obernberger (1997) and FNR (2005). Percentage of sludge, stoichiometrically calculated by Mähnert (2007) with moisture contents as shown in Table 5.3, a methane percentage of 55% and the biogas yields of Table 5.11

[b] According to Ruckenbauer et al. (1992), Vetter et al. (1995), Hasler and Nussbaumer (1996), Hartmann and Strehler (1995), Obernberger (1997), Frieß et al. (1998), KTBL (2005a,b), Holzner (2006), Heard et al. (2006) and Reinhold and Zorn (2007), converted by the mass equations $P_2O_5 = 2.29$ P and $K_2O = 1.20$ K

[c] Whole crops

During anaerobic digestion of energy crops in biogas reactors, the loss of N, P, K, S and other nutrient elements is theoretically zero, because only C, O and H in the form of methane (CH_4) and carbon dioxide (CO_2) are released. Trace gases, e.g. hydrosulphide (H_2S) and ammonia (NH_3), are insignificant in this connection and/or can be limited by technical means (Amon et al. 2002; FNR 2004). Although a calculation by means of the denoted weight percentages and nutrient contents results in other figures, there are some practical results which confirm the zero-loss hypothesis (Herrmann and Taube 2006). A special advantage of biogas residues (digested output) is the high share of the vegetable valuable nitrogen constituents (NH_4-N) and the high plant availability. Nearly 65% of the total N of maize sludge is NH_4-N, and 75% of this is available for plants (Wendland and Offenberger 2007).

The plant availability of some nutrients may be limited in both types of residues. Moreover, in certain cases the contents of some heavy metals (Cd, Pb, Cu, Zn, Ni, Cr and Hg) may exceed the legal thresholds (BioAbfV 2002). Nevertheless, the use of energy crop residues as fertiliser significantly reduces the need for mineral fertiliser.

5.5.2 *Pesticides*

Mainly comprised of plant protection products and biocidal products, pesticides are designed to influence fundamental processes in living organisms. They may have the potential to kill or control harmful organisms such as pests, but can also cause unwanted adverse effects on non-target organisms, human health and the environment (EC 2007). Both the hazards and benefits of pesticides are well documented in published literature and have been reviewed most recently by Cooper and Dobson (2007).

Focussing on pesticide life cycles, there is so far only little information available regarding, e.g. the temporary storage of pesticides at farm level, the management and calibration of application equipment, the protection of operators, the preparation of the spraying solution and the actual application (EC 2007). In order to find a connection between crop and pesticide inputs, a survey based on randomly selected farmers in different agricultural soil–climate regions was conducted in Germany. For the main field crops, detailed information on the real use of chemical plant protection agents in agricultural practice was collected and evaluated (Table 5.5).

Although the results presented only reflect agricultural practices of a single year, findings confirm that herbicides are the most widely used type of pesticide, as weeds are the major constraint that limit yield in many crops in conventional crop cultivation systems. According to CropLife (2004), herbicides represent around 50% of all crop protection chemicals used throughout the world, compared with insecticides and fungicides that each account for around 17%.

In view of the major influence of weeds on yield in conventional cultivation systems, Karpenstein-Machan (2000) investigated the effect of low-input energy crop rotations in cereals (rye, triticale and barley). Considering thermal conversion, grain yield and total biomass yield (crop and weeds) in non-pesticide variants were compared with conventional pesticide programmes. Total biomass yields increased no more than 5%, whereas grain yields showed approximately 16% higher values, rye being clearly the most competitive crop after herbicide application. Consequently, in arable energy crop systems, it is possible to reduce herbicide application, as weeds contribute to biomass as well.

These results may be transferable for SRC such as poplar and willow, but practical experience is still lacking. However, in short rotation plantations weed control is only indicated as an important factor during the establishment phase (Scholz et al. 2007; Walle et al. 2007).

Table 5.5 Application index of different pesticide groups and growth regulators used in Germany, calculated within the project Neptun 2000 (Roßberg et al. 2002)

Plant species	Number of farms	Total chemical plant protection measures	Pesticides			Growth regulators
			Fungicides	Herbicides	Insecticides	
Rape	644	3.41	0.68	1.18	1.44	0.12
Winter wheat	790	3.74	1.39	1.37	0.36	0.62
Winter rye	332	2.61	0.90	0.85	0.14	0.72
Triticale	319	2.26	0.46	0.96	0.09	0.74
Maize	489	1.24	0.00	1.22	0.03	0.00
Potato	130	8.56	6.08	1.55	0.94	0.00
Sugar beet	382	2.93	0.15	2.59	0.19	0.00

Application index: number of pesticides applied, related to the authorised application rate and the crop-specific cultivation area. For calculating the application index, each application of a pesticide is considered as a single application, irrespective of whether or not it is applied within a tank mixture.

The data collection is related to the vegetation period 1999/2000, containing all chemical plant protection measures including seed protection and growth regulator applications. The data set is based on voluntary cooperation of randomly selected farmers in the various agricultural soil–climate regions of Germany.

Up to now no negative effect of weeds has been observable as long as harvested biomass was regarded as feedstock for the thermal conversion process. Focusing on anaerobic digestion, first results reveal that biomass consisting of higher amounts of weeds leads to a reduction in methane yield (Heiermann et al. 2001, Hermann et al. 2007). For example, the methane yield of total biomass (crop and weeds) was reduced by up to 20% in comparison with pure crop (sorghum). Thus, to exploit the full methane formation potential, special attention must be paid to the impact of weeds in biogas crop cultivation.

5.5.3 Water

In recent years water availability has become an issue of global concern due to natural variability in water availability (rainfall) and changes in Europe's climate which indicate severe stresses on water resources. On average, 42% of the total water abstraction in Europe is used for agriculture. In south-western European countries, agriculture accounts for 50–70% of the total water abstraction (Freshwater Europe 2007). The role of irrigation differs between countries and regions due to climate conditions. While in Southern Europe irrigation is essential to secure agricultural production, in Central and Northern Europe irrigation is usually applied to maintain crop production in dry summers. Focusing on crop-specific irrigation, EEA (2005) reported that in Spain, Greece and France, grain maize is the most frequently irrigated crop, whereby in France 40% of the irrigated area is used for grain maize cultivation. Also a significant acreage of wheat, sunflowers and potatoes is irrigated in the southern parts of Europe (EEA 2007). Up to now, no data are available with respect to irrigated crops for bioenergy production. However, expansion in energy cropping associated with increasing water consumption will clearly stress water resources (Berndes 2002).

Under European conditions water requirements are typically in the range of 200–800 g water per gram dry matter (DM) produced (Table 5.6). Determined by genetic characteristics, water consumption of C_4 crops is less than that of C_3 crops, although a wide variation exists between the plant species due to certain photosynthetic mechanisms.

To assess the response of crops to irrigation, the reciprocal of the transpiration coefficient, the WUE, is applied indicating total biomass produced (above-ground DM) per unit mass of water taken up by the crop during the whole growth cycle (Manoliadis 2001; Nova et al. 2007). For conventionally cultivated crops, WUE values of harvested whole crops range between 1 and 9 g_{DM} kg^{-1} evapotranspiration water, increasing in the following order: oil crops (rape, sunflower), sugar/starch crops (wheat, rye as C_3 cereals) and potato, sugar beet, maize (C_4) and ligno-cellulosic crops such as *M. sinensis* (C_4) (EEA 2007). The WUE values for whole crop cereals are higher because usually the index is related to grain yield, which is approximately 40% of the whole plant biomass.

Table 5.6 Transpiration coefficients for energy crops under European conditions according to Geisler (1988), Schweiger and Oster (1991), Larcher (1994), Jacks-Sterrenberg (1995) and Hartmann (2001)

Crop species	Crop type	Transpiration coefficient (g H_2O g_{DM}^{-1})
Rape	C_3	600, …, 700
Sunflower[a]	C_3	500, …, 600
Wheat	C_3	250, …, 550
Rye	C_3	400, …, 500
Maize	C_4	300, …, 400
Potato	C_3	400, …, 500
Sugar beet	C_3	350, …, 450
Sorghum	C_4	200, …, 300
Miscanthus	C_4	250, …, 350
SRC (poplar, willow)	C_3	600, …, 800

[a] Up to the flowering stage

Owing to increasing water demand and a decline in water availability, irrigation of energy crops is a very critical resource issue. In Germany, the first research project has started to evaluate the efficiency of irrigation with special emphasis on suitability of selected energy crop species for local conditions.

5.5.4 Fossil Energy Sources

The consumption of energy is the main source of the GHG emissions. More than 60% of the global GHG emissions are caused by energy and 32% by agriculture and forestry (without energy) (EPA 2006). Since at present only 6% of the total primary energy consumption in Europe bases on renewable energy (BMU 2007), nearly all energy used in agriculture comes from fossil sources and has to be considered in the GHG balance.

There are several calculations and energy balances for biofuels in literature (Table 5.7). Most of them calculate the cumulated energy demand (CED), which takes all direct and indirect primary energy inputs into account (VDI 4600 1998), including final energy sources as well as the energy consumption for the production of agricultural machinery and fertilisers, for example. All processes from soil preparation to the harvest, which are part of the cultivation cycle of a crop, are integrated into this calculation.

The wide span of these values is caused not only by the various production technologies but also by the various methods and key figures of calculation. In some cases the published values of energy demand for the production of an energy crop vary across a span of ±25%, even if the agricultural technologies were arithmetically harmonised (Scholz and Hahn 1998).

Summarising the literature data it can be stated that most energy consumption in crop production is used on the field in the form of fertiliser and diesel. Only those energy-intensive processes such as drying or pelletising of haulm-type

Table 5.7 CED for the production of energy crops in Central Europe according to Reinhardt (1993), Kaltschmitt and Reinhardt (1997), Scholz et al. (1998), Scholz and Hahn (1998), Schmitz (2003) and BMELV (2007b)

				Energy (GJ ha^{-1} y^{-1})		
Species and utilised part of crop			Years	Cultivation	Harvest	Total[a]
Oil use	Rape	Seed	1	3, …, 9 (19)	2.5	4, …, 14 (22)
Sugar/Starch use	Wheat	Grain	1	6 … 12 (21)	-	14 (27)
	Winter rye	Grain	1	5 … 15.9	3.2	7 … 19
	Potato	Tuber	1	19	–	–
	Sugar beet	Tuber	1	7, …, 12 (30)	–	10, …, 21 (55)
Ligno-cellulose use	Wheat	Whole crop	1	13, …, 19.3	1.2, …, 3.4	15, …, 23
	Winter rye	Whole crop	1	12, …, 15.9	3.2, …, 6.2	14, …, 22
	Winter triticale	Whole crop	1	12	–	14
	Maize	Whole crop	1	–	–	10
	Grass	Whole crop	≤5	11, …, 14.1	–	13, …, 24
	Miscanthus	Whole crop	≥20	4.0, …, 8.3	1.6, …, 6.9	12, …, 32
	Poplar	Whole crop	≥20	0.5, …, 2.8	1.1, …, 6.7	3, …, 8
	Willow	Whole crop	≥20	0.5, …, 2.0	0.4, …, 6.7	3, …, 7

[a] Including various post-harvest processes and transport

Extreme figures are in brackets

crops may relevantly increase this part. Most of the crops need approximately 10–20 GJ ha^{-1} year^{-1} for cultivation, harvest and post-harvest processes, including transport of the storable crop product to the user. However, some oil and starch crop species, of which only seeds or grain are used, as well as SRCs have a lower energy demand.

5.5.5 *Soil Carbon*

The sequestration of carbon in soil has a considerable influence on the GHG balance of biofuels. Although the GHG balance of the production and utilisation of energy crops is approximately zero, except for some additional CO_2 equivalents mainly caused by the N fertilisation and the consumption of fossil energy (see Chapters 7 through 9), the storage or the release of carbon in soil may disturb this balance.

However, there are differences between the various soil and climate types, the ways of utilisation and the crop species (Freibauer et al. 2004; Smith 2008). Depending on the species, the cultivation of annual crops causes a loss of 280–1,300 kg C ha^{-1} year^{-1}, while grasslands and other conventional perennial crops do not cause a loss but a growth by 600–800 kg ha^{-1} year^{-1}, and SRCs by even 400–1,600 kg ha^{-1} year^{-1} because these fields are not tilled (Table 5.8).

In spite of the wide range of these data and the fact that the values for poplars and willows are based on only four trials, it can be stated that in contrast to

Table 5.8 Increase or decrease in the content of organic carbon in the soil depending on the crop species according to Hansen (1993), Matthews and Grogan (2001), Scheffer and Schachtschabel (2002), KTBL (2005a), Kahle and Boelcke (2004) and Strähle (2007)

Crop species	C (kg ha^{-1} y^{-1})	CO_2 (t ha^{-1} y^{-1})
Oil crops	−280, …, −400	−1.0, …, −1.5
Potato	−760, …, −1,000	−2.8, …, −3.7
Beets	−760, …, −1,300	−2.8, …, −4.8
Cereals	−280, …, −400	−1.0, …, −1.5
Grass	+600, …, +800	+2.2, …, +2.9
Poplar	+880, …, +1,600	+3.2, …, +5.9
Willow	+410, …, +1,300	+1.5, …, +4.8

annual crops, the perennial crops effect sequestration of carbon in the soil. So the cultivation of grass and SRCs saves about 1.5–5.9 t CO_2 ha^{-1} $year^{-1}$ (1 kg C → 3.67 kg CO_2), which is not negligible in the GHG balance of biofuels. Furthermore, in the case of SRC, the roots of the trees save an additional quantity of carbon (Hellebrand and Munack 1995), which is not considered in these ranges. However, up to now there are no reliable figures for C sequestration by poplar and willow roots.

The assessment of the sustainability of the cultivation of energy crops includes the input and recycling of nutrients, the application of pesticides, the WUE, the utilisation of fossil fuels and the balance of soil carbon. The aim is to recycle the nutrients, which is simple in the case of anaerobic digestion by applying the digestate to the field. If crops are combusted many of the minerals can be returned via the ash. In the case of liquid biofuels, exported nutrients are lost and have to be replaced. The application of pesticides, mainly herbicides, can often be reduced in comparison to food production, but the energy yield per hectare might be reduced if the share of weeds exceeds certain thresholds. WUE, fossil fuel input and soil carbon losses and gains do not differ, in general from food crop cultivation. Although during cultivation, SRC sequesters considerable amounts, 0.4–1.6 t C ha^{-1} $year^{-1}$, of soil carbon.

5.6 Content and Transfer of Environmentally Relevant Substances

5.6.1 Nutrients

Plant nutrients are interesting not only in connection with the yields and the fertilisation, but also with regard to environmental effects of energy conversion processes. Thus, they are regulated in various standards. Nitrogen (N), phosphorous (P) and potassium (K), as well as sulphur (S) and chlorine (Cl) are the most important environmentally relevant macronutrient and micronutrient elements.

The nitrogen content of the various crop species and their parts exhibits a wide range of variation from ~0.2– 4% (Table 5.9). It depends not only on the species and on the harvest time, but also on the fertilisation rate. This is known for conventional crops (Möllers 2000) and was confirmed for energy crops too (Scholz et al. 1999, 2004a). Depending on the species, the application of e.g. 150 kg N ha^{-1} causes an average absolute increase in the N content by 0.1–0.3%.

High N contents are not wanted in any type of biofuel, since they cause harmful emissions in boilers, gasifiers or engines, in particular emissions of nitrogen oxide (NO_x). If the connection between the N content in a fuel and the formation of NO_x during combustion is taken into account (Nussbaumer 1997; Obernberger 1997; Hartmann and Schmid 2001), the application of 150 kg N ha^{-1} causes an average increase of up to 100 mg m^{-3} of NO_x emissions related to non-fertilised crops. This increase is not insignificant given a legal limit of 250–400 mg m^{-3} (Scholz and Ellerbrock 2002). Furthermore, the N fertiliser is responsible for forming the GHG nitrous oxide (N_2O).

The content of phosphorus (P) in crops lies in the range of 0.02–0.87%. Oil seeds have the highest values with >0.6%, while SRC as well as potato and sugar beet have the lowest levels. In fuels made from vegetable oil, phosphorous is limited to <15 mg kg^{-1} (DIN 51506 2005), because it damages the engines. However, it does not exert any negative effects on the emissions during combustion, with the exception of phosphine (PH_3), which can be neglected in this context. Phosphorous increases the melting temperature of the ash, which may facilitate combustion. Nevertheless, this element contributes to eutrophication of water. Insofar, a lower P demand by the plants, which necessarily requires less fertiliser, is ecologically advantageous.

Like N, potassium (K) also shows a correlation between the contents in the crops and in the soil (Scholz et al. 2004a). Its content varies between 0.1% and 4.1% depending on the species and the part of the crop. All haulm-type crops have high mean contents >0.7%, while woody crops have <0.4%. During combustion, high potassium contents in the plants cause corrosion on overheated surfaces and lower ash melting temperatures (slag formation). Therefore, they are undesirable in crops intended for combustion and gasification.

The S content of the plants is also dependent upon the fertilisation and the atmospheric deposition, so the literature values show a wide span between 200 and 4,800 mg kg^{-1}. Oil seeds have high mean values of about 3,000 mg kg^{-1} (0.3%) and more, while SRC with <500 mg kg^{-1} has the lowest values. As known from fossil fuels, the sulphur contained in crops enters into the gaseous phase during thermal processes, forming sulphur oxides (SO_2 and SO_3). It is released into the atmosphere and thus contributes to the acidification of soils and waters. Moreover, it develops the corrosion in boilers, gasifiers and engines (Scholz and Ellerbrock 2002). Although the S content in all biofuels is much lower than in fossil coal (>0.3%), there are limiting values for pellets <(400, …, 2,000) mg kg^{-1} (DIN 51731 1996; prCEN/TS 14961 2004), and there are thresholds for biogas (H_2S < 0.15 Vol%) (FNR 2004) as well as for vegetable oil (S < 20 mg kg^{-1}) used in engines (DIN 51506 2005).

Table 5.9 Average and span of the content of environmentally relevant macronutrients and micronutrients in various energy crop species (From Hohmann (1994), Röhricht (1994), Vetter et al. (1995), Kasper (1997), Maier et al. (1997), Hartmann et al. (2000), Hartmann (2001), Röhricht et al. (2002), FNR (2002), Werner and Vetter (2003), Härdtlein et al. (2003), Scholz (2004), FNR (2004), KTBL (2005a), FNR (2005), KTBL (2006), Frühwirth (2006), Schweiger and Rasig (2006) and own results)

		Nitrogen (N) (%)		Phosphorus (P) (%)		Potassium (K) (%)		Sulphur (S) (mg kg^{-1})		Chlorine (Cl) (mg kg^{-1})	
Crop species	Used part	Mean	Min Max	Mean	Min Max	Mean	Min Max	Mean	Min Max	Mean	Min Max
Rape	Seeds	3.32	2.70	0.79	0.70	0.83	0.75	3,000	1,000	350	300
			3.94		0.87		0.91		5,000		400
Sunflower	Seeds	2.67	2.40	0.64	–	1.82	–	3,100	2,900	–	–
			2.94		–		–		3,300		–
Wheat	Grain	1.89	1.50	0.37	0.26	0.50	0.42	1,850	1,200	400	–
			2.28		0.48		0.58		2,500		–
Winter rye	Grain	1.66	1.40	0.38	0.26	0.54	0.42	1,800	1,100	1,600	–
			1.91		0.49		0.66		2,500		–
Maize	Grain	1.50	1.10	0.37	0.26	0.42	0.33	1,300	–	2,700	–
			2.00		0.48		0.50		–		–
Potato	Tuber	0.35	0.30	0.06	0.05	0.50	0.46	200	100	–	–
			0.40		0.07		0.54		300		–
Sugar beet	Tuber	0.20	0.15	0.08	0.03	0.21	0.17	3250	3,000	–	–
			0.26		0.05		0.25		3,500	–	–
Wheat	Whole crop	1.41	–	0.24	–	–	–	1,200	–	–	–
			–		–		–		–	–	–
Winter rye	Whole crop	1.19	0.62	0.20	0.02	0.76	0.18	1,456	700	1,523	640
			2.20		0.29		1.28		4,800		6,500

Winter triticale	Whole crop	1.14	0.40	0.21	0.02	0.89	0.61	1,322	170	1,388	160
			2.01		0.29		1.19		3,100		4,500
Maize	Whole crop	1.17	0.30	0.20	0.07	0.80	0.29	900	300	3,000	2,500
			2.00		0.30		1.30		1,400		3,400
Perennial rye	Whole crop	1.24	0.98	0.21	0.19	1.26	1.04	813	681	1,413	963
			1.50		0.23		1.35		966		1,702
Grass	Whole crop	1.64	0.80	0.25	0.09	1.71	0.50	1,938	190	2,704	400
			3.31		0.46		3.23		3,600		14,600
Miscanthus	Whole crop	0.96	0.21	0.22	0.05	1.48	0.30	1,700	400	2,650	2,300
			1.70		0.39		4.10		3,000		3,000
Poplar	Whole crop	0.64	0.32	0.11	0.06	0.33	0.10	440	200	143	20
			1.41		0.22		0.61		900		1,500
Willow	Whole crop	0.46	0.25	0.10	0.04	0.24	0.14	472	300	164	20
			1.04		0.18		0.56		900		2,000

Chlorine (Cl) forms chlorohydrocarbon (HCl) in thermal processes and so accelerates the corrosion. However, the forming of highly toxic polychlorinated dibenzodioxines and dibenzofuranes (PCDD/F) is more harmful (Daunderer 1991). Thus, Cl is strongly limited in fuel standards, e.g. for wood pellets <(200, …, 300) mg kg^{-1} (DIN 51731 1996; prCEN/TS 14961 2004). In energy crops, the Cl content ranges in the extremely wide span of 20–14,600 mg kg^{-1} and depends not only on the crop species, but also on fertiliser, site, weather, storage conditions, etc. Among all species, poplar and willow (SRC) have the lowest mean contents of less than 200 mg kg^{-1} (0.02%).

The content of environmentally harmful macronutrients and micronutrients in energy crops varies in a wide range and depends above all on the species. Therefore, the crop species with lower contents are, in general, more favourable. However, the fertilisation also has an influence. Fertiliser levels of nitrogen, potassium, sulphur and chlorine and to a lesser extent phosphorous determine the contents of these elements in energy crops and hence the risk of releasing these into the atmosphere or damaging the energy conversion installations.

5.6.2 Heavy Metals

The environmental relevance of heavy metals in energy crops results from both the use of energy crop residues as fertiliser and their influence on the conversion processes. Among the heavy metals analysed in plants, those especially relevant are the ones whose accumulation in soil and crops is caused by the energy-related input and/or the input from fertilisers (BioAbfV 2002; Düng MV 2003; Dünge V 2003) and/or whose emissions are legally limited, in particular cadmium (Cd < 0.2 mg m^{-3}), lead (Pb < 5.0 mg m^{-3}), copper (Cu < 5.0 mg m^{-3}) and zinc (Zn) (TA-Luft 2002).

Cadmium (Cd), which is produced during smelting and during combustion of fossil raw materials, and which is contained in some fertilisers as well as in some fractions of biomass ash, is phytotoxic and may cause functional kidney disorder and bone damage along with other detrimental effects (Daunderer 1991; Merian 1991). Moreover, it may disturb the fermentation processes in biogas production (FNR 2004). With mean contents of 0.75 and 1.15 mg kg^{-1} of DM, cadmium is preferably absorbed by poplars and willows. Potato, whole crop cereal and grain, such as wheat, rye and triticale, which are conventionally used as foods and feedstuffs, have significantly lower contents of 0.02– 0.20 mg kg_{DM}^{-1}. Grass and *M. sinensis* are situated in between them (Table 5.10).

Motor vehicle traffic is the main source of anthropogenic lead (Pb) emissions. In humans, toxication causes damage to the nervous system and the kidneys along with other harmful effects (Merian 1991). Lead is preferably absorbed by grass and rape seed. Its content reaches values of more than 5 mg kg^{-1}, while the average lead content of the other plant species is relevantly lower and in some cases below the detection limit.

Table 5.10 Average and span of the content of some environmentally relevant heavy metals in selected energy crop species (Ocker et al. (1984), von Steiger and Baccini (1990), KTBL (1990), Stadelmann and Frossard (1992), Wolfensberger and Dinkel (1997), Heinzer et al. (2000), Hartmann and Kaltschmitt (2002), Wittke (2002), Scholz (2004), FNR (2004), FNR (2005), KTBL (2006), Röhricht and Kiesewalter (2007), Stolzenburg (2008))

		Cadmium (Cd) (mg kg^{-1})		Lead (Pb) (mg kg^{-1})		Copper (Cu) (mg kg^{-1})		Zinc (Zn) (mg kg^{-1})	
			Min		Min		Min		Min
Crop species	Used part	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Rape	Seeds	0.07	0.04	5.25	–	8.80	2.60	41.5	35
			0.16		–		15.0		48
Sunflower	Seeds	0.37	0.22	–	–	21.5	18.0	46.0	36
			0.51		–		25.0		56
Wheat	Grain	0.10	0.05	0.13	0.10	4.20	3.50	38.8	18
			0.15		0.16		5.0		45
Winter rye	Grain	0.05	–	0.12	–	3.70	–	33.5	30
			–		–		–		35
Potato	Tuber	0.02	0.007	0.02	0.013	–	–	4.3	3.2
			0.028		0.024		–		5.4
Wheat	Whole crop	0.10	0.05	0.25	0.10	2.70	2.0	13.3	10
			0.20		0.60		3.9		20
Winter rye	Whole crop	0.04	0.03	<1.0	<1.0	4.42	3.8	23.7	32
			0.06		<1.0		4.7		25
Winter triticale	Whole crop	0.06	0.04	<1.6	<1.0	5,10	2.00	37.2	8
			0.08		2.60		6.80		66
Maize	Whole crop	0.20	–	2.00	–	4.80	4.50	45.0	35
			–		–		5.00		56
Grass	Whole crop	0.76	0.20	5.10	3.80	15.60	11.8	82.0	38
			1.57		5.80		22.6		135
Miscanthus sinensis	Whole crop	0.55	0.05	1.00	0.50	1.20	–	10.0	–
			1.00		4.50		–		–
Poplar	Whole crop	0.75	0.20	<1.0	<1.0	2.88	2.60	53.0	38
			1.35		<1.0		4.00		58
Willow	Whole crop	1.15	0.38	<1.0	<1.0	3.68	3.40	90.0	45
			2.18		<1.0		4.00		105

Like the previously mentioned metals, zinc (Zn) and copper (Cu) are released during smelting. Additionally, zinc can be found in abraded tyre material, engine oil and the smoke gas of coal combustion plants. Characteristic of both metals is that they are essential as well as toxic. However, an increased input does not constitute a severe health risk for humans (Merian 1991) but can, for example, restrain the biogas production (FNR 2004). The mean Zn content of the crops ranges between 4 mg kg$_{\text{DM}}^{-1}$ (potato) and 90 mg kg$_{\text{DM}}^{-1}$ (willow) and the Cu content varies between 1 mg kg$_{\text{DM}}^{-1}$ (miscanthus) and 22 mg kg$_{\text{DM}}^{-1}$ (sunflower). A general characteristic of both metals is that they belong to the micronutrients and that, despite relatively high values, in general their contents in the soil remain clearly below the tolerance threshold of ≤200 mg kg$_{\text{DM}}^{-1}$ for zinc and ≤60 mg kg$_{\text{DM}}^{-1}$ for copper (BioAbfV 2002).

Heavy metals may play an important role in using energy crop residues as fertiliser (see above). In connection with the use of biomass ashes, it is remarkable that during combustion of solid fuels the heavy metals are separated in different quantities in the ash fractions. For instance, 98% of the cadmium is concentrated in the filter ash, which generally has been decreed by law (Hasler and Nussbaumer 1996; Obernberger 1997). As a result, for example the grate ash is nearly free of Cd and can be used as a valuable basic fertiliser, if the law permits. Most of the pertinent laws and recommendations limit the yearly input of heavy metals into soil (Berg et al. 1991; Giller et al. 1998; Vance and Mitchell 2000; Perucci et al. 2006). In any case, there is no problem in the case of SRC, grass and miscanthus which have Cd contents >0.5 mg kg^{-1}. Even if the ash of such a crop is applied on the same field, the soil will be decontaminated of Cd in the long term (Scholz et al. 1999, 2004b). Thus, these energy crop species may be used for purifying polluted soils.

The uptake of heavy metals from soils is also determined by their contents in soil and by plant species. If these crops are used for anaerobic digestion one has to consider that there is a remarkable risk of an accumulation of heavy metals in the soil. In the case of combustion, many heavy metals can be removed by filtering the ash and it can be used safely as fertiliser. Thus, cultivation and combustion of SRC is a smart scheme of removing heavy metals from contaminated soils.

5.7 Emission of Nitrous Oxide

During cultivation of crops, i.e. during tillage, planting, fertilising and growth as well as during harvest and storage, various climate-effective gases emit from soil and plants. These so-called greenhouse gases, particularly the Kyoto gases CO_2, CH_4, SF_6, PFC, HFC and N_2O, impair the ecological benefit of energy crops. In addition to carbon dioxide (CO_2), the most harmful and most investigated gas of crop production is nitrous oxide (N_2O), also called laughing gas. Though it is only responsible for about 20% of the total GHG emissions from worldwide agriculture (EPA 2006), it may amount to 70% of the GHG emissions of energy crop production (Neubarth and Kaltschmitt 2000; Heinze 2001). On the field alone it emits nearly 50% of the CO_2 equivalents of all GHGs (Hartmann and Kaltschmitt 2002).

Nitrous oxide, a by-product of fixed nitrogen fertilisation, has a 100-year average global warming potential (GWP) about 300 times higher than an equal mass of CO_2. As a source of NO_x , i.e. NO and NO_2, N_2O also plays a major role in stratospheric ozone chemistry (Crutzen et al. 2007). In soil, N_2O is produced predominantly by two microbial processes, the oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) and the reduction of NO_3^- to gaseous forms NO, N_2O and N_2 (Firestone 1982). The rate of N_2O production depends on the availability of mineral N in the soil and the conversion factor (CF) depends on soil type and climate (e.g. Bouwman 1990, 1996; Granli and Bøckman 1994; Bouwman et al. 2002; Novoa and Tejeda 2006; Stehfest and Bouwman 2006).

Agronomic practices such as tillage and fertiliser applications can significantly affect the production and consumption of N_2O because of alterations in soil physical, chemical, and biochemical activities. Following N-fertiliser applications, an increase in N_2O flux rates has been observed in field and laboratory experiments (e.g. Mulvaney et al. 1997; Kaiser et al. 1998; Jackson et al. 2003). N_2O emission from croplands at site scales occurs essentially with great spatial and temporal variability (Veldkamp and Keller 1997; Dobbie and Smith 2003; Hellebrand et al. 2003, 2005). The annual pattern of temporal variation of N_2O emissions is determined in the temperate regions by the seasons and weather conditions, since soil N_2O emissions are regulated by temperature and soil moisture and so are likely to respond to climate changes (Frolking et al. 1998; Ruser et al. 2006).

Because of these influencing factors, the measuring results vary over a wide range. Moreover, there are several high emission periods with emission rates of more than 1,000 $\mu g\ N_2O\ m^{-2}\ h^{-1}$. These longer-lasting high N_2O emissions, called "hot spots" or "hotspots" (e.g. Christensen et al. 1990; Röver et al. 1990; Hellebrand et al. 2005; Wanga et al. 2006), were detected at fertilised blocks only. Thus, they can cause a local measured emission factor of more than 10%. The reason for these N_2O hot spot emissions is not clear up to now. High emissions after harvesting were observed several times and might be connected with soil distortions.

Reliable long-term measurements have been performed by Hellebrand et al. (2008). They measured the N_2O emissions on different fertilised energy crop plots on a sandy soil over a period of 9 years and found differences not only between the various fertilisation levels, but also between the crop species. In spite of the yearly spread it can be summarised that SRCs cause less N_2O than cereals and grass. So the N_2O emissions rate on non-fertilised poplar and willow fields is only 17–26% of the rate on conventionally fertilised cereal fields (Fig. 5.5).

In literature the absolute emission rates are scarcely discussed, but instead mainly the N_2O nitrogen CF. It is defined as N_2O-N emission caused by fertilisation in relation to the nitrogen fertiliser applied. The emission period considered is 1 year and the fertiliser-caused emissions are obtained by taking the difference between fertilised and non-fertilised fields (Bouwman 1996). The Intergovernmental Panel on Climate Change (IPCC) recommends an average factor of 1.25% (De Klein et al. 2006) and Hellebrand et al. (2005) measured an average value of 0.8% ± 0.1%. On the other hand, Crutzen et al. (2007) calculate a factor of 3–5% N_2O-N on the base of global N_2O emissions and Feehan and Petersen (2004) calculate even 10% N caused by further conversion processes of the N fertiliser. If they are right, the latter values had a considerable impact on the GHG balance of energy crops. However, these values are not verified and are widely discussed in the scientific community. There is thus a strong need for further research in this field.

Nitrous oxide emissions are generally induced by fertiliser application. Emission strength varies with soil type, temperature and moisture and is substantially crop-specific. There is a considerable difference between woody species and cereals. While the IPCC general N_2O emission value is set to 1.25% of the nitrogen applied, an average of 0.8–1.0% could be found from sandy soils.

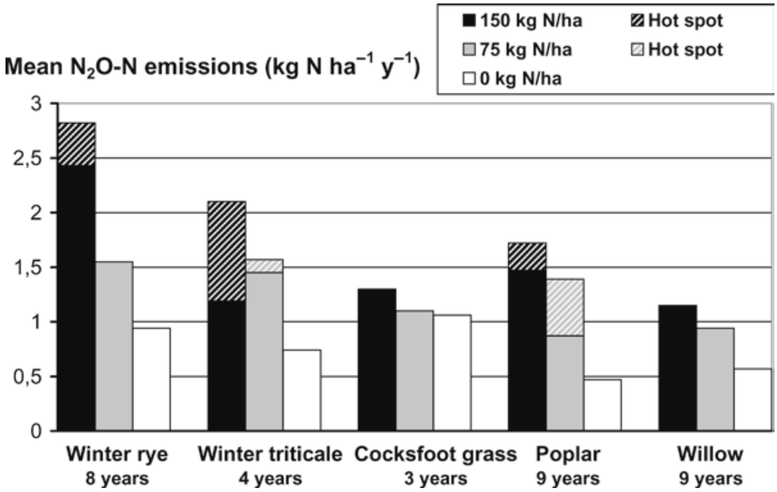

Fig. 5.5 Crop-specific N_2O-N emissions with and without hotspots for different N fertilising rates according to Hellebrand et al. (2008), continuously measured for up to 9 years on sandy soil in Germany. The additional N_2O emissions caused by the "hotspots" are not insignificant. However, the reason for these irregular increases is not yet clear

5.8 Energy Yield

One of the most important environmental criteria for the production of energy crops is the energy yield per hectare. The energy yield is mainly dependent on the biomass yield and on the conversion technology, and hence on the fraction of crop used as energy source (Table 5.11).

With approximately 170–230 GJ ha^{-1} year^{-1}, the highest energy yields in total are achieved by solid fuels (dry bales, chips, briquettes, pellets) produced from whole crop cereals such as wheat, rye and triticale. Only *M. sinensis* and maize have higher figures. However, the former bases on an uncertain biomass yield and the latter can be only wetly harvested and stored as silage (in central Europe). The energy yield of grass, poplar and willow is a little lower compared with cereals, which in the case of SRC is partly caused by the high moisture content of ≥50%.

Liquid fuels have the lowest figures. With less than 40 GJ ha^{-1} year^{-1}, the rape seed oil, which is similar to rapeseed methyl ester (RME, FAME), has lower figures than ethanol from several grain species. The highest energy yield of all liquid biofuels produced in Germany is obtained from sugar beets at more than 130 GJ ha^{-1} year^{-1}, which is even better than BtL fuels produced from whole crop cereals. However, the input of energy for the production (conversion) of the ethanol is also very high and ranges between 15 and 25 MJ L^{-1}, respectively 75–140 GJ ha^{-1} year^{-1} (Schmitz 2003; Quirin et al. 2004).

The energy yield of biogas produced from grains, beets or whole haulm-type crops lies mostly between the corresponding solid and liquid fuels, which predestines it for stationary (heat and) power generation (CHP).

Table 5.11 Average energy yields of different fuel types produced from energy crops

Crop species and used part			Biomass yield[a] (ton ha^{-1} y^{-1})	Solid fuels[b]	Liquid fuels[c]		Gaseous fuels[d]	
				Energy (GJ ha^{-1} $year^{-1}$)	CF[e] (l t_{DM}^{-1})	Energy (GJ ha^{-1} $year^{-1}$)	CF[f] (m^3 t_{DM}^{-1})	Energy (GJ ha^{-1} $year^{-1}$)
Oil use	Rape	Grain	3.0	–	380	39	–	–
	Sunflower	Grain	2.2	–	440	33	–	–
Sugar/starch use	Wheat	Grain	6.4	106	450	61	720	91
	Winter rye	Grain	4.6	77	480	48	720	65
	Winter triticale	Grain	4.9	81	460	47	720	69
	Maize	Grain	7.6	126	450	73	–	–
	Potato	Tuber	8.9	–	370	70	780	137
	Sugar beet	Tuber	13.5	–	470	134	760	202
Ligno-cellulose use	Wheat	Whole crop	14.0	233	220[g]	102[g]	600	165
	Winter rye	Whole crop	9.8	169	220[g]	72[g]	700	135
	Winter triticale	Whole crop	10.5	174	220[g]	77[g]	700	141
	Maize	Whole crop	17.5	–	220[g]	128[g]	620	214
	Perennial rye	Whole crop	8.5	146	220[g]	62[g]	700	117
	Grass	Whole crop	9.0	144	220[g]	66[g]	640	113
	Miscanthus	Whole crop	15.0[g]	258[g]	220[g]	111[g]	500[g]	147[g]
	Poplar	Whole crop	10.0[g]	155[g]	220[g]	74[g]	–	–
	Willow	Whole crop	7.0[g]	111[g]	220[g]	52[g]	–	–

[a] Mean yields in Germany according to Table 5.3

[b] Bales, chips, pellets, or grain with moisture contents and heating values as in Table 5.3 (CF = 1.0)

[c] Straight oils (37.2 MJ kg^{-1}, 0.91 kg l^{-1}), ethanol (26.8 MJ kg^{-1}, 0.79 kg l^{-1}) or BtL (43.9 MJ kg^{-1}, 0.76 kg l^{-1})

[d] Biogas (55% CH_4, 19.7 MJ m^{-3}, 1.28 g l^{-1})

[e] CF without losses according to Reinhardt (1993), Meierhofer (2006), Schmitz (2003) and Keppeler et al. (2004)

[f] Biogas yields according to recommended mean values of KTBL (2005b)

[g] No practically verified figures

However, the area-related energy yield is not the sole criteria for evaluating the energy efficiency of a crop species and/or a fuel type. The energy inputs (CED) of cultivation and conversion processes (see Table 5.7), the DM losses, the energetic use of by-products and the further ways of utilisation must also be considered.

5.9 Greenhouse Gas Balance

The most frequently used criterion for evaluating the impact of biofuels on the environment is the GHG balance. This balance represents the difference between the emissions of GHGs during production and utilisation of a biofuel and the saving of GHGs due to the substitution of a fossil fuel. Thus, the result of a balance, the reduction of GHG emissions, depends considerably on the substituted fuel and the technology used. Recent balances calculate not only CO_2 (1), but also CH_4 (18, …, 21) and N_2O (296, ..., 310) in CO_2 equivalents which are denoted here in brackets (e.g. Beer et al. 2001; ADEME 2002; Patyk and Reinhardt 2002; CONCAWE 2006). Some of them consider further gases such as HFC (140, …, 11,700), PFC (6, 500, …, 9,200) and SF_6 (23,900). Surveys and analyses of the results are given by Quirin et al. (2004), Arnold et al. (2006), Ramesohl et al. (2006), Nitsch (2007), Hill (2007), Fehrenbach et al. (2007) and others.

Most of the GHG emissions result from the energy input (CED) during production and conversion of the energy crops and from N_2O emissions on the field. Thus, highly fertilised crops such as rape, maize and sugar beets as well as energy-intensive conversion processes such as ethanol and BtL production have a priori unfavourable results. However, high energy yields and the consideration of CO_2 credits may improve them. Such credits result, for example, from the utilisation of by-products and/or residues as fertiliser or energy source. Moreover the carbon sequestration in soil may also influence the result. Depending on the detail of a balance, these shares are more or less completely considered in these calculations (Fig. 5.6).

In spite of the wide span of these calculation results, it can be summarised that oil seeds and grain converted to straight oil, biodiesel or bioethanol have the lowest CO_2 saving potential, less than 5 t CO_{2eq} ha^{-1} $year^{-1}$. Ethanol as gasoline substitute produced from sugar beets and potato shows a very wide range from −0.7 to 11 t CO_{2eq} ha^{-1} $year^{-1}$ which is caused by different conversion technologies, different credit assumptions and different calculation methods. This is also true for biomethanol from whole crop cereals. With approximately 10–14 t CO_{2eq} ha^{-1} $year^{-1}$ the best figures in total are achieved by ligno-cellulosic crop species such as whole crop cereals and SRCs which are used to generate heat or combined heat and power with a boiler or gasifier.

Hence assuming that appropriate energy crop species were cultivated on 17.5 million hectares (15% of arable land of EU) and used in appropriate energy technologies with an average saving potential of 10 t CO_{2eq} ha^{-1} $year^{-1}$, more than 20% of the CO_2 reduction target of the EU (843 Mt CO_{2eq} $year^{-1}$ respectively 20% from 1990 to 2020 according to AEBIOM 2007) could be fulfilled.

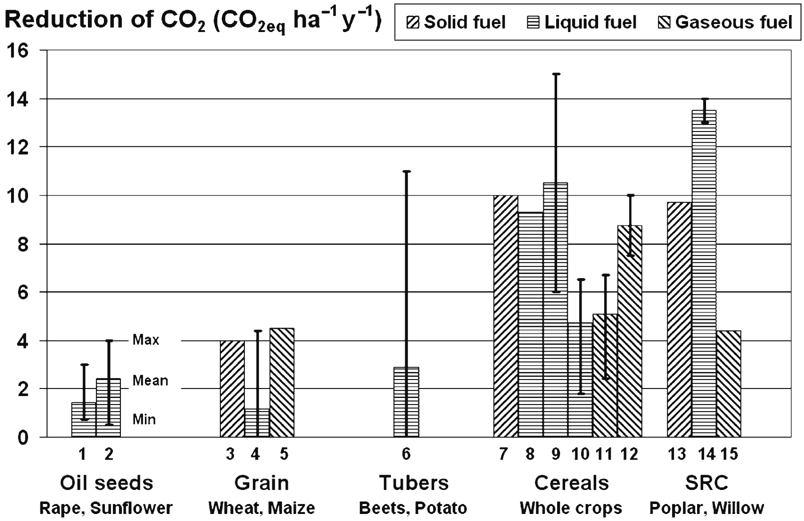

Fig. 5.6 CO_2-savings by use of biofuels made from energy crops according to Schmitz (2003), Quirin et al. (2004), CONCAWE (2006), Hill (2007) and BMELV (2007b). Conversion pathways: 1 Straight oil → Drive; 2 Biodiesel → Drive; 3 Grain → Heat; 4 Ethanol → Drive; 5 Ethanol → Heat & Power; 6 Ethanol → Drive; 7 Bales → Heat & Power; 8 BtL → Drive; 9 Methanol → Drive; 10 Ethanol → Drive; 11 Biogas → Drive; 12 Biogas → Heat & Power; 13 Chips → Heat; 14 Chips → Heat & Power; 15 BtL → Drive

Most important GHGs are carbon dioxide, methane and nitrous oxide, and the less important ones are fluorinated compounds, although their greenhouse warming potential ranges in the thousands of CO_2 equivalents. GHG emissions correspond, in general, with the energy balance of energy conversion paths, i.e. liquid biofuels have the lowest GHG reduction potential in comparison to mineral fuels, whereas solid fuels save most GHG emissions compared to fossil fuels. GHG reduction ranges from 0 to 14 t ha^{-1} $year^{-1}$ CO_2 equivalents. The cultivation of energy crops on 15% of total arable land would significantly contribute to the EU CO_2 reduction target.

5.10 Conclusion

The cultivation and supply of energy crops is, in general, sustainable, although there are differences between species. Ligno-cellulosic plants are more favourable in this context than oil seeds or grains. In addition to a great many usable species, which result in better biodiversity, the most important advantages of this species group consist of using the whole plant, releasing generally fewer environmentally harmful substances into the environment, as well as reducing the possibility of fertiliser and pesticide input without any loss in net energy gain. Ligno-cellulosic plants also include some promising perennial species such as poplar and willow, which need low inputs, cause low N_2O emissions, sequestrate carbon in soil and have a high potential for GHG reduction. However, broad practical experiences and validated yields are lacking so far.

In addition, the conversion pathways have a strong influence on the results of sustainability assessments. Here, it is favourable to apply technologies which use the whole crop rather than only parts of it. So combustion, gasification and anaerobic digestion are, in general, more favourable than producing liquid biofuels, although the production of ethanol from high-yielding species like sugar beet or the production of BtL from whole crops, i.e. using also the ligno-cellulosic plant parts, can substantially increase the sustainability of this pathway.

Hence, the assessment of sustainability of bioenergy has to integrate both the cultivation of the energy crops and the route of conversion and utilisation of the bioenergy carrier. Although there is already a broad range of publications on this issue, more integrating research is required for a sustainable development in order to reach the targets set by the EU.

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Chapter 6
Phosphorus, Plant Biodiversity and Climate Change

Nicole Wrage, Lydie Chapuis-Lardy, and Johannes Isselstein

Abstract Phosphorus (P) is a major plant nutrient. Its increasing use as a fertilizer has helped to raise crop and fodder production. However, the global reserves and resources of P are finite, demanding an efficient use of P. Under natural conditions, it is often in limited supply. Plants have developed adaptations to small soil P concentrations. Increased P levels can have unwanted side effects like eutrophication and algal blooms. Besides, P concentrations in the soil have often been found to be negatively correlated with plant diversity. For sustainable agriculture, it is essential to understand 1) adaptations of plants to small P concentrations in soils to maintain production with decreasing P reserves, 2) influences of P on phytodiversity to minimize unwanted effects, and 3) future developments of P and phytodiversity in relation to climate change to adjust agricultural practices.

P is essential for the energy and sugar metabolism of plants. As it moves in soils by diffusion only, the geometry of the root system is essential for its uptake. Plants have developed different adaptations for P uptake: e.g., localized or overall increases in the number of roots, the development of cluster roots that increase the root surface area by up to 140 times, exudation of different phosphatases and organic acids in reaction to specific forms of P, or symbiosis with mycorrhiza that may be responsible for up to 75% of the P acquired by plants. Gradual differences in these adaptations decrease interspecific competition and facilitate coexistence. Low P concentrations increase plant diversity by favoring stress-tolerant rather than ruderal species or by restricting the growth of competitive grasses more than that of forbs. According to the niche dimension hypothesis, more limiting resources lead to more coexisting species. Worldwide, P limitation is as relevant for plant production as nitrogen (N)

N. Wrage (✉) and J. Isselstein
Department of Crop Sciences, Institute of Grassland Science, Georg-August-University of Goettingen, von-Siebold-Str. 8, 37075, Goettingen, Germany
e-mail: nwrage@gwdg.de

L. Chapuis-Lardy
UMR Ecologie Fonctionnelle et Biogéochimie des Sols, Institut de Recherche pour le Développement, BP 434101, Antananarivo, Madagascar

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limitation. Thus, P could regulate the size of ecological niches by being the main growth-limiting factor or by being coupled to other limiting resources.

Global climate change influences soil P availability. Increasing temperatures tend to increase P mineralization of litter. Furthermore, temperature increases by 5 _ºC have been found to double the colonization of roots by mycorrhiza. Nitrogen mineralization was enhanced by on average 48% by temperature increases of between 0.3 and 6.0 _C. Larger amounts of N stimulate phosphatase exudation and plant P uptake. This could result in increased soil P availability, which is further enhanced by increased P mobilization due to human activities. Such a development would reduce phytodiversity and promote the growth of ruderal, fast-growing species. In the long run, this could cause mining of soil P, which would then again increase plant diversity. However, diversity needs a long time to recover from P additions. Therefore, in sustainable agriculture, increases in soil P relative to other factors limiting plant growth have to be prevented to guarantee large phytodiversity.

Keywords Climate change • Exudation • Niche • Phosphorus • Phytodiversity

6.1 Introduction

Phosphorus (P) is one of the major plant nutrients. Under natural conditions, it is often in limited supply and restricts plant growth. Since the middle of the nineteenth century, P has been used as a fertilizer. Its use as a fertilizer has increased globally from 4 Tg in 1950 to 15 Tg in 2000 (Zhang et al. 2008). Due to human activities, by the year 2000, P mobilization had tripled compared to natural flows (Smil 2000). While augmenting crop and fodder production, such increased P supply can have unwanted side effects on natural ecosystems. Thus, increased P levels have been identified as a main factor for eutrophication of surface waters that may lead to algal blooms (Schindler 1974; Schindler et al. 2008). Furthermore, in grasslands and natural systems, the availability of soil P has often been found to be negatively correlated with plant diversity (Janssens et al. 1998; Güsewell 2004; Hejcman et al. 2007a). Global P reserves and resources have been estimated to last between 100 and 470 years (Syers et al. 2008) or even less (Vance 2001) at current rates of exploitation with improving exploitation technology. Although such forecasts vary widely, it is certain that the P supply is finite (Syers et al. 2008) and that prices for P fertilizers will increase (Vance 2001).

How P is affecting plants and their growth is not only a function of P availability, but rather one of the relations between P availability and other factors limiting growth, e.g., other major plant nutrients, light and water. Verhoeven et al. (1996) found a ratio between nitrogen (N) and P of aboveground biomass of herbaceous mires at the end of the growing season of 15:1 that separated N from P limitation. Güsewell (2004) points out that in several studies of terrestrial plant systems, N/P ratios in the vegetation smaller than 10 or larger than 20 usually indicated N or P limitation, respectively. During successional vegetation stages, more N is becoming available, while soil P concentrations remain comparatively stable, leading to a shift from N to P limitation (Verhoeven et al. 1996). N deposition may also increase N availability, so that P becomes more limiting (Verhoeven et al. 1996; Turner et al. 2003). A meta-analysis of the recent literature has shown that P limitation is as crucial as N limitation for plant production in terrestrial systems, regardless of the latitude (Elser et al. 2007).

In soils, more than half of the extractable P has been found in the upper 30 cm in an analysis of global soil data sets averaged across climate zones and vegetation types (Jackson et al. 2000). According to this analysis, P has the shallowest distribution of the major plant nutrients (total nitrogen, extractable P, exchangeable potassium, calcium, magnesium, and sodium) in soils. This distribution is influenced by P input, vegetation uptake, and microbial activities, which are in turn affected by a range of variables, including climate, season, soil type, and management (e.g., Jackson et al. 2000; Styles and Coxon 2007).

In this article, we will first explore the influence of P on plant growth and the influence plants have on soil P availability. In competing for this essential and often limiting resource, plants have developed a range of adaptations like cluster roots and cooperation with mycorrhiza. Plants' different ability to cope with a range of soil P concentrations and to influence P availability also affects their coexistence and thus phytodiversity. Thus, increasing P mobilization due to human activities may threaten plant diversity. The relationship between P and plant diversity will be discussed in the second part of the paper. Climate change influences the mineralization and availability of P. This interaction and possible effects on phytodiversity will be explored in the last part. With the gained knowledge, it will be easier to understand how plants can maintain productivity despite low soil P concentrations, how P influences coexistence and how future changes might affect this. This should support the development of management practices improving the sustainability of agriculture with respect to both P resources and biodiversity.

6.2 Interactions of P Concentrations and Plants

6.2.1 Influence of Soil P Concentration on Plants

P is crucial for several aspects of plant metabolism, especially the energy and sugar metabolism, and several enzymatic reactions, including photosynthesis. Plants have therefore developed mechanisms for the uptake and efficient use of P. Maize plants recycled N quicker from old to young tissue when P is deficient, leading to earlier leaf senescence (Usuda 1995). P-deficient plants invest more resources into root development and therefore have an increased root-to-shoot biomass ratio compared to well-nourished plants. Furthermore, they accumulate more carbohydrates in leaves and allocate more carbon to the roots (Hermans et al. 2006).

Carbohydrates may influence gene expression in plants, thus helping to regulate enzymatic pathways in reaction to mineral deficiencies (Lloyd and Zakhleniuk 2004; Hermans et al. 2006). Müller et al. (2007) found that almost 150 genes in *Arabidopsis thaliana* were synergistically or antagonistically regulated by P and sugar. In white lupin, addition of sucrose, glucose, or fructose to the growth medium stimulated the accumulation of transcripts of genes essential for P uptake in seedlings grown in the dark with sufficient P (Liu et al. 2005). Interruption of phloem flow or growth in the dark of P-deficient plants reduced the accumulation of these transcripts compared with P-deficient control plants (Liu et al. 2005). Thus, it could be shown that the plant P metabolism is closely linked with and may be controlled by photosynthesis and sugar metabolism.

Plants can react to low P concentrations in their organs by adapting their root system and their exudative behavior. P does not move through the soil by bulk flow, but only by diffusion, which is very slow (10^{-12} to 10^{-15} m^2 s^{-1}, Schachtman et al. 1998). Thus, the geometry of the root system is crucial. He et al. (2003) described increases in total root length and root fineness of rice roots in soil zones with high P content. In split-root experiments, more roots were grown in the high-P compartment, especially when the other compartment was P deficient (He et al. 2003). The same was found for wheat when P was applied in a vertical strip in one of the compartments. In the first weeks of growth, root growth in this high-P strip was increased by plants supplied with 4 mg P kg^{-1} soil in the other compartment compared to that of plants supplied with 14 mg P kg^{-1} soil. After 8 weeks of growth, the plants showed similar root growth in the high-P strip (Ma and Rengel 2008). *A. thaliana* grew longer (Bates and Lynch 1996) and denser (Ma et al. 2001) root hairs in low-P environments.

Mycorrhiza have been shown to be very important for P uptake (Bolan 1991; van der Heijden et al. 2006). In wheat, the arbuscular mycorrhizal colonization decreased with increasing soil P. It was reduced from 60% of root length colonized at 10 mg P kg^{-1} soil to 10% at 27 mg P kg^{-1} soil (Covacevich et al. 2007). This was independent of shoot P contents.

An interesting adaptation of the root system to low P is the formation of cluster roots. As they are an adaptation, but not systematically different from other roots (Skene 2003), we will review the knowledge about the well-studied cluster roots in some detail as an example of root functioning.

Cluster roots have first been described for Proteaceae (Purnell 1960), where root clusters are widespread. Meanwhile, cluster roots have also been identified in several other families, including Betulaceae, Fabaceae, and Cucurbitaceae (Lamont 2003; Shane and Lambers 2005). Cluster roots are an aggregation of increased numbers of hairy branch roots at specific regions along the axis of growing roots (Lamont 2003; Shane and Lambers 2005). Opposite every protoxylem pole in the cluster root region, a rootlet develops (Skene 2003). This may lead to an increase of the surface area of 140 times and of the explored soil volume of 300 times per unit length of root as measured in *Leucadendron laureolum* (Lamont 1983, 2003).

From the cluster roots, carboxylates are exuded at high rates (Shane and Lambers 2005), leading to an increasing mobility and uptake of P and other nutrients (Gerke et al. 2000). A major factor leading to the formation of cluster roots seems to be the P concentration in the plant, not that in the soil (Shane and Lambers 2005). Furthermore, the P concentration in the shoots has been shown to be more influential than that in the roots of white lupin (Shane et al. 2003a) and *Hakea prostrata* (Shane et al. 2003b). Different P nutrition of the roots of white lupin in a split-root experiment did not lead to differences in root morphology or exudation in the differently treated halves of the root system (Shane et al. 2003a). However, Shane and Lambers (2005) reported results from split-root experiments with other species that did differ in their efforts on the low- and high-P side: *H. prostrata* and *H. trifurcata* developed more cluster roots on the low-P side, while *Lupinus pilosus* developed more on the high-P side. In the soil, cluster roots have generally been found in nutrient-rich layers, even to a depth of 5 m (Pate et al. 2001).

Next to the amount of P, the chemical form of this nutrient (Lambers et al. 2002; Shu et al. 2005; Shane et al. 2008) and the availability of other nutrients, especially nitrogen, potassium, and iron (Shane and Lambers 2005) affects the formation of cluster roots. It seems to be regulated by several plant hormones. Thus, application of auxin led to the production of cluster roots in white lupin at P concentrations that normally suppress cluster roots (Gilbert et al. 2000; Neumann et al. 2000). Cytokinines might also play a role, as kinetin applied to the growth medium of P-deficient white lupin inhibited the formation of cluster roots (Neumann et al. 2000).

A role of noninvasive microorganisms in cluster formation has been suggested, as the number of formed cluster roots in *H. prostrata* was increased from none to 160 g^{-1} root when grown on autoclaved sand with autoclaved or non-autoclaved soil extract, respectively (Lamont and McComb 1974). Auxin-producing bacteria have been found to be more frequent in juvenile and mature cluster roots than in senescent cluster roots (Weisskopf et al. 2005). As auxin induces cluster root formation, there might be an interaction between these bacteria and the roots. However, there were no significant differences in the frequency of auxin-producing bacteria between cluster roots and non-cluster roots (Weisskopf et al. 2005). The exudation of phenolics by root clusters has been suggested to inhibit microbial breakdown of the exuded carboxylates (Lambers et al. 2006; Weisskopf et al. 2006). Thus, while the role of bacteria in the formation of cluster roots is still being discussed, there are indications for reciprocal influences between rhizosphere bacteria and cluster roots.

To sum up, several mechanisms exist that allow plants to exploit scarce resources of P. Interestingly, some plant species are able to locally adapt their root system and exudation behavior when they encounter soil areas rich in P (Fransen et al. 1999; Shane and Lambers 2005). Mycorrhiza are also able to react to areas rich in P with increased production of hyphae (St. John et al. 1983; Cavagnaro et al. 2005). In contrast, other species seem to take their shoot P concentrations as a trigger for producing more or less roots, regardless of patchy soil concentrations of this nutrient, or they even produce more cluster roots in low-P areas. Figure 6.1 shows several strategic models for root development in environments with patchy P distribution. A general increase in root production as shown in Fig. 6.1b makes sense when the distribution of P is patchy, but nutrient availability is not severely limiting. This strategy ensures a high probability of accessing high-P areas. It could also allow the

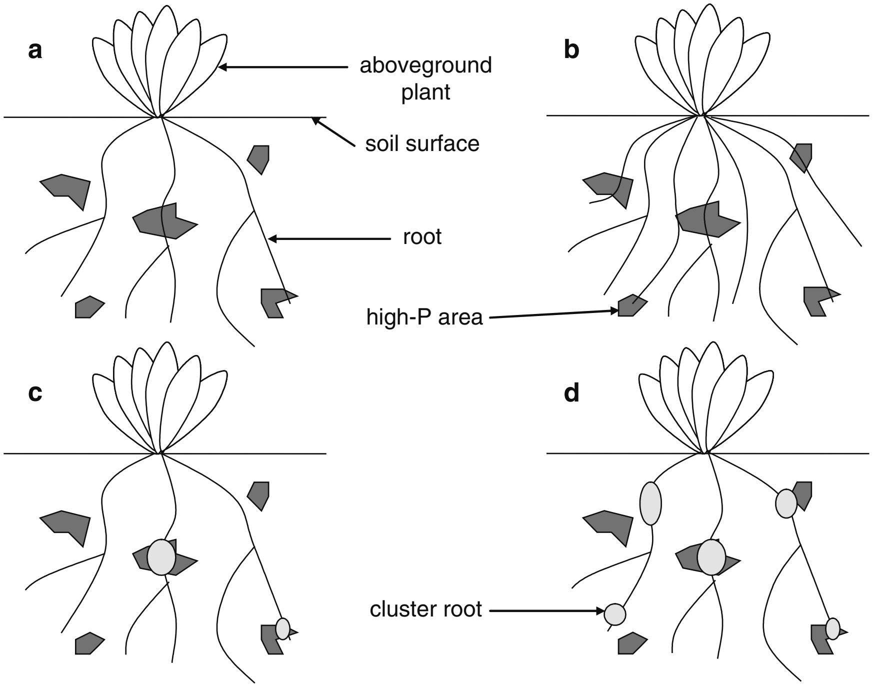

Fig. 6.1 Different plant strategies for dealing with patchy distribution of P in soil: (**a**) initial situation: random distribution of roots, (**b**) increased root production, (**c**) production of cluster roots in high-P environments, (**d**) production of cluster roots at random. For discussion, see text

exploitation of P in deep soil layers if more roots are developed in greater depths. However, it is very cost-intensive, as a lot of resources need to be used for building roots. Under limiting nutrient supply, plants have been found to use up to 35% of photosynthates for root growth, plus an extra 20% for exudation (Lambers et al. 1998). The strategy shown in Fig. 6.1c is more efficient: Cluster roots are developed in all accessed high-P areas. Soil high-P areas are missed more easily than in the case shown in Fig. 6.1b. Therefore, this P-reactive cluster root formation is the best strategy if high-P areas are encountered regularly, e.g., due to their homogeneous distribution throughout the soil or due to their large size. Figure 6.1d shows a strategy where root clusters are formed independently of the P concentration in the affected soil region, e.g., in reaction to low shoot-P concentrations. This would be advantageous if the distribution of P was relatively homogeneous or if the concentration of P outside of high-P areas would still be worthwhile extracting. It could also be an adaptation to seasonal variation, when the P concentration in the plant decreases just before new sources of P become available.

Although cluster roots form an interesting adaptation, species that do not form clusters generally have the same means of accessing nutrients, albeit not in such a condensed form: They use root growth and branching to access nutrient-rich areas, exudation to increase nutrient availability, and absorption for uptake (Skene 2003).

Thus, the outlined regulating factors and strategies also apply to species that do not form cluster roots. Furthermore, nutrient uplift, i.e., net displacement of nutrients from deep layers to the topsoil (Jobbágy and Jackson 2004), is used by plants to make P more accessible. This leads to the next section, where we discuss the influence of plants on soil P concentrations.

6.2.2 Influence of Plants on Soil P Concentration

McGill and Cole (1981) suggested that the concentration of available P in the soil depended on biochemical mineralization, i.e., mineralization by extracellular enzymes, which does not provide energy to organisms and depends on the amount of enzymes present. This is controlled by the need for P. Thus, organic P input into the soil only influences the size of the total pool, while plants, microbes, and mycorrhiza can make P available by releasing phosphatases and phosphohydrolases into the soil. Phosphatase excretion has been used as an indicator of the P status of plants (Johnson et al. 1999; Phoenix et al. 2004).

Exudation occurs in response to environmental constraints, especially P deficiency (e.g., Jones 1998; Hinsinger et al. 2003) and differs depending on the P-form (Lambers et al. 2002) and plant species (Nuruzzaman et al. 2006). *Banksia grandis* exuded citrate, malate, and trans-aconitate when supplied with aluminium-phosphate. It exuded less of these tricarboxylates and dicarboxylates, but instead lactate and acetate, when supplied with iron-phosphate (Lambers et al. 2002). Plant species differ in their abilities to use various P species (van Ray and van Diest 1979), which can be due to differences in their exudation behavior (Nuruzzaman et al. 2006) and acidification of the root zone (Haynes 1992). This can influence the interspecific competition and coexistence of species, as we will discuss later.

Exuded carboxylic acids may form complex metal cations binding phosphate and cause exchange of phosphate from the soil matrix; phenolics and mucilage may serve similar purposes (Lambers et al. 2006). Organic acids are also exuded by so-called phosphate-solubilizing microorganisms that may increase the availability of P to plants in sustainable agriculture (Khan et al. 2007). Exudation of organic acids has often been referred to as a possible source of rhizosphere acidification (e.g., Hoffland et al. 1989), and enhanced proton release may occur as a response to P shortage (Bertrand et al. 1999; Neumann and Römheld 1999; Hinsinger et al. 2003). Soil pH is one of the main parameters determining adsorption/desorption equilibria of phosphate in soils (Hinsinger 2001). Decreased pH mediated by plants was invoked as a possible mechanism for the increased dissolution of P-containing minerals and thus of increased P availability shown for example for the exotic invasive plants *Lepidium latifolium* (Blank and Young 2002) and *Solidago gigantea* (Herr et al. 2007).

Besides their influence on P availability, plants also influence the size of the total organic P pool, mainly through the rate and quality of organic input from aboveground litter and root turnover. The rate of organic P input with litter depends on the size and P status of the plants. P-deficient plants usually have less aboveground biomass and less P per unit biomass. Input into the soil from litter of P deficient plants may also be reduced because they may be more efficient in reallocating P during senescing of leaves (Güsewell 2004). This may also have an effect on leaf longevity, which is normally increased in reaction to nutrient limitation, but may be reduced when nutrient translocation to young tissue plays a relevant role (Lajtha and Harrison 1995). Root turnover may be a major input for the soil P pool. Aerts et al. (1992) calculated that root turnover contributed 67% to the total litter production of a stand of *Molinia caerulea*, and even 84% to total litter P loss, since no resorption of P from senescing roots was observed. The rates were about two or three times smaller for stands of *Deschampsia flexuosa* and *Calluna vulgaris*, respectively. Root turnover itself seems to be influenced by P availability: In Hawaiian montane forests, old, P-deficient sites had an increased turnover of roots when fertilized with P and differently fertile sites also showed a correlation between root turnover and P availability (Ostertag 2001). This can be caused by different rates of mineralization and immobilization of P, which are influenced by litter quality, e.g, its P content (McGrath et al. 2000).

Of course, plant symbionts also influence the P cycle. Ectomycorrhizal fungi have been described to contribute to rock weathering, i.e., solubilizing P from minerals that would otherwise be inaccessible for plants, even through tunnels to the inside of the minerals (Landeweert et al. 2001). Van Schöll et al. (2006) have shown that the fungus *Paxillus involutus* can increase weathering of muscovite, but not hornblende. Two further tested fungi did not increase weathering, indicating that this ability seems to depend on the species of ectomycorrhizal fungus. Van der Heijden et al. (2008) suggest that mycorrhizal fungi are responsible for up to 75% of P acquired by plants annually. The role of free-living bacteria for P acquisition by plants is still unknown (van der Heijden et al. 2008).

Invertases, the enzymes catalyzing irreversible hydrolysis of sucrose to fructose and glucose, were upregulated in mycorrhizal roots in response to colonization by arbuscular mycorrhiza, not to P nutrition (Garcia-Rodriguez et al. 2007). Since mycorrhizal colonization is negatively related with P availability (Covacevich et al. 2007) and fructose and glucose increase the transcription of genes essential for P uptake (Liu et al. 2005), this coupling may have developed in response to P nutrition, but might have a similar fate as in Pavlovian conditioning, where the original stimulus need not be present any more to evoke a reaction.

Another possibility for plants to influence the P cycle is the hydraulic redistribution of water. This is the redistribution of water from wet to dry soil areas via the roots, which has been suggested to have an impact on the availability of P due to better mobility of inorganic P in wet soil (Lambers et al. 2006). McCulley et al. (2004) found that the concentration of extractable P was greater at depth than in the top meter of the soil in several arid and semi-arid systems in the southwestern USA and that nutrients were uplifted from this depth. They proposed that hydraulic redistribution of water from the soil surface to depths up to 10 m by roots was the mechanism by which P and other nutrients were mobilized and could be taken up by plants.

Thus, plants have a range of possibilities to influence the total P pool and the availability of P directly or via symbionts. The influence of plant species on

P concentration can be seen clearly in cases of invasive species. These have in several studies been shown to affect P turnover rates. For example, *Centaurea maculosa*, an invasive forb in Montana grasslands, was more efficient in P uptake than native species, but also apparently increased P availability in invaded fields (Thorpe et al. 2006). The same was found for *S. gigantea* in Belgium: It increased the concentrations of labile soil P in summer, probably by enhancing mineralization (Chapuis-Lardy et al. 2006). An increased P concentration in belowground organs was found in plots invaded by *S. gigantea* in autumn. This could lead to easily mineralizable root debris in spring and may have caused the higher content of plant-available P in the invaded stands (Herr et al. 2007).

6.3 P and Phytodiversity

Highest plant diversity has often been found to be correlated with low P availability (Table 6.1). Different shapes of this relationship have been found, e.g., linear or hump-backed shapes. The form of these shapes seems to be independent of the overall amount of P in the soil. However, comparison between different studies is hindered by different methods of P extraction as well as different units. In the

Table 6.1 Literature overview of the relation between species richness and P concentration

Habitat	Relation species richness to P	P concentration	Reference
Old permanent grassland, Western and Central Europe	Negative (hump-backed, optimum at approx. 30 mg kg^{-1})	Soil extractable P (acetate-EDTA) 0–350 mg kg^{-1}	Janssens et al. (1998)
Alpine meadows, Italy	Negative (linear)	Soil extractable P (Olsen) 13–155 mg kg^{-1}	Marini et al. (2007)
Grassland or related vegetation in environmentally sensitive areas, GB	Negative (hump-backed, optimum at 4–15 mg P L^{-1})	Soil extractable P (Olsen) 1–85 mg L^{-1}	Critchley et al. (2002)
Arable field boundaries, Finland	Negative (linear)	Soil extractable P (acid-ammonium-acetate) 2.95–12.21 mg L^{-1}	Ma (2005)
Park Grass Experiment, England	Negative	Fertilization with or without 35 kg P ha^{-1} in combination with other nutrients since 1856	Crawley et al. (2005)
Low-productive grassland, Germany	Negative	Fertilization with or without 80 kg P annually in combination with other nutrients since 1941	Hejcman et al. (2007a)

(continued)

Table 6.1 (continued)

Habitat	Relation species richness to P	P concentration	Reference
Semi-natural and urban meadows, England	Negative	Log soil extractable P (Truog's) 0.15–1.35	McCrea et al. (2004)
Mesotrophic grassland, Netherlands	Negative (not significant)	Soil extractable P (ammonium lactate) 12.4–281 mg kg^{-1} (means), biomass N/P ratios: between 4.5 and 15.9 (means)	Aerts et al. (2003)
Open, grassy woodlands, Australia	Negative	Soil extractable P (Colwell) 10 – 45 mg kg^{-1} (means)	Dorrough et al. (2006)
Wet meadows and fens, The Netherlands, Belgium	Negative correlation with endangered species	Soil extractable P (ammonium acetic-acid lactic-acid) 1.3–4.1 g m^{-2} (means)	Olde Venterink et al. (2001)
Herbaceous terrestrial ecosystems across Eurasia	Sites with intermediate N/P ratios most species-rich (hump-backed), negative correlation with endangered species	Plant biomass N/P ratios: between 2 and 60	Wassen et al. (2005)
Degraded broad-leaf forest, China	Positive correlation for trees and shrubs, negative for forbs	Soil extractable P (ammonium carbonate) 9.85 – 13.33 ppm (means)	Fu et al. (2004)
Mediterranean dwarf-shrub community, Israel	No effect on total richness, but positive correlation with annual legumes	Fertilization with 0, 4.5 or 9 g P m^{-2} in 1988, measurements between 1989 and 1993	Henkin et al. (2006)
Fens and wet grasslands, Europe and USA	Plots with high N/P ratio more species-poor than those with low N/P ratios	Plant biomass N/P ratios: between 4 and 36, plant P concentrations 0.5–4 mg g^{-1}	Güsewell et al. (2005)
Grassland, New Zealand	No clear relation	Soil P (method not specified) 7–41 ppm	White et al. (2004)
Salt marsh, New England	Positive relation	Soil extractable P (acetic acid, ammonium hydroxide) 15–23 mg kg^{-1} soil (means)	Theodose and Roths (1999)

following, we will discuss the impact of P on phytodiversity compared to the influence of other nutrients.

According to the law of the minimum, P should only influence the growth and competitive strength of plants if it is the limiting factor. The niche dimension hypothesis predicts that a larger number of limiting resources in a habitat leads to a larger number of coexisting species. The prediction was consistent with experimental results and developments in the Park Grass Experiment (Harpole and Tilman 2007). For the often found importance of P limitation for phytodiversity, this could mean that (a) P limitation is often coupled to limitation of other resources. This was for example the case in the studies of a degraded broad-leaved forest in China (Fu et al. 2004), where P limitation was coupled to low potassium concentrations, and of continuously or rotationally grazed pastures in New Zealand (White et al. 2004), where the availability of all nutrients was generally correlated. However, it could also mean that (b) P is the main limiting resource in the examined habitats, so that it controls the dimension of the niche to a large extent. In many habitats, N deposition has reduced the former importance of N limitation. In a meta-analysis of recently published studies, Elser et al. (2007) have shown that N and P limitation are equally important in terrestrial systems, independent of the latitude. An increasing importance of P limitation could increase the correlation between P concentration and the total extent of the niche (Fig. 6.2). Furthermore, habitats with sufficient P but low N availability may promote the growth and N fixing of legumes, leading to higher N concentrations (Almeida et al. 2000; Saber et al. 2005).

Güsewell (2004) has pointed out that interspecific competition in P-limited habitats might be less than that in N-limited ones, so that species' coexistence could be favored under P limitation. For example, there are several forms of P in soils, so that different species can exploit distinct P pools (van Ray and van Diest 1979; Haynes 1992; Nuruzzaman et al. 2006). We have already seen that plant species

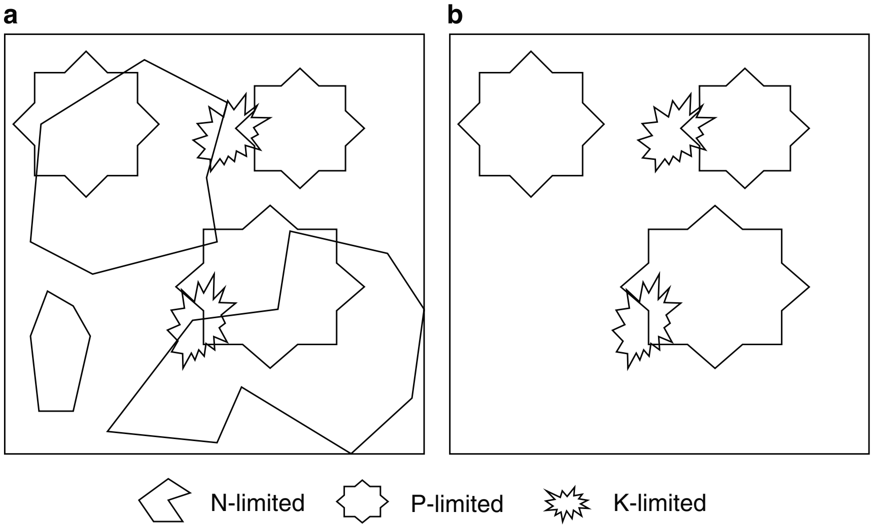

Fig. 6.2 (**a**) Niche dimension of a habitat that is co-limited by nitrogen (N), phosphorus (P), and potassium (K), and (**b**) niche dimension of the same habitat after N addition. The different shapes indicate soil areas that are limited by N, P, or K. If one nutrient is added, e.g., N by N deposition, the total soil area with limiting amounts of one or more nutrients for plant growth becomes smaller. The habitat becomes more uniform and may offer less niches for plants to coexist

have various adaptations to low-P environments. As they differ in their efficiency of P uptake, species with different adaptations will colonize distinct niches. In Western Australia, species with cluster roots are generally found on spots with lowest P concentrations and those with mycorrhiza on intermediately P-rich soils (Lambers et al. 2006). Klironomos et al. (2000) proposed a generalized niche model similar to the one by Tilman et al. (1997), with two resources limiting species abundance, but including mycorrhizal fungi. It became clear that mycorrhiza may be able to expand the range covered by plant species, since they can access more soil resources. That will affect the outcome of competition between plants as well as plant community diversity (van der Heijden et al. 1998a, b; Klironomos et al. 2000).

Coexistence of species may also be enabled by facilitated nutrient uptake of one species due to the presence of another species. Thus, in silvopastoral systems with combined over and understorey species, P availability for one species can be affected by the other (Scott and Condron 2003). Gillespie and Pope (1989) found that P uptake by black walnut (*Juglans nigra*) was larger when grown with alfalfa (*Medicago sativa*) than with other walnuts, black locust (*Robinia pseudoacacia*) or orchard grass (*Dactylis glomerata*). They attributed this to acidification of the root zone during N_2 fixation by alfalfa, which solubilized P. Different rooting depths can also help to reduce competition between species (Jackson et al. 2000). Although roots of the same species generally avoid contact, intertwining of different species has been observed, especially of legumes and nonlegumes (Gardner and Boundy 1983). Furthermore, transfer of N and P between coexisting plants has been observed (Høgh-Jensen and Schjoerring 2000). For P, it has been shown to occur via connecting mycorrhizal hyphae (Whittingham and Read 1982).

Different life history strategies of plants also interact with their reaction to and influence on P availability. The plant strategy types according to Grime (2001) have been suggested to differ in their requirements of P and N/P ratios (Güsewell 2004). Stress-tolerant (S) and competitive (C)/stress-tolerant species have low P and high N/P requirements, while ruderal (R) and mixed strategists (CSR) have high P and low N:P requirements. This is consistent with results by Hill et al. (2005) in extensive grazing systems. It also fits the finding that during succession, ecosystems are first N and later P limited (Verhoeven et al. 1996), as they would first be colonized by ruderals, which are later replaced by competitive and stress-tolerant species. Against this background, lower diversity in P-rich systems could be explained by the quick growth of R strategists, leading to competitive exclusion of other species. However, Hill et al. (2005) also pointed out that the relation between plant strategy types and nutrients did not hold in intensive grazing systems, where tolerance or avoidance of grazing became the most crucial plant traits for survival.

Halsted and Lynch (1996) examined the reaction of C_3 and C_4 species to P limitation. They could not find different reactions between C_3 and C_4 species, but concluded that monocots can better cope with P stress than dicots due to contrasting allocation of P and biomass. Combined with the finding that graminoids are favored by N applications more than dicots (Falkengren-Grerup 1998) and usually have a larger N/P ratio (Güsewell 2004), graminoids may grow better in P-limited conditions rich in N (Fig. 6.3). Systems both high in N and P are dominated by

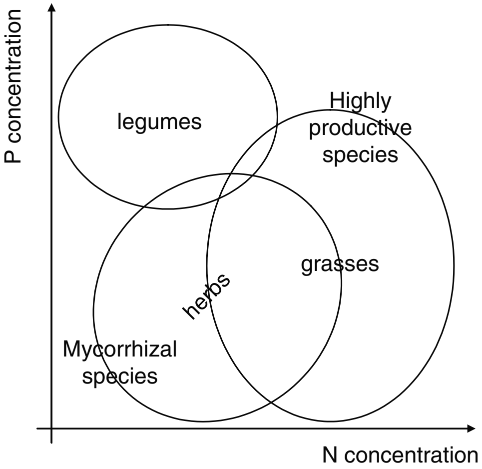

Fig. 6.3 Conceptual drawing of the distribution of different groups of herbaceous plants in relation to major plant nutrients. Cycles represent the distribution of grasses, herbs, and legumes. Species with mycorrhiza are able to exploit sites low in both nitrogen (N) and phosphorus (P). Highly productive species, such as ruderal plants, need conditions abundant in N and P.

fast-growing species that are very productive, usually grasses. Species-rich systems are often dominated by forbs (Willems and van Nieuwstadt 1996; Theodose and Roths 1999). As these prefer habitats with lower N/P ratios (Güsewell 2004), this could be another explanation for the often found relation between species richness and P availability.

To sum up, there are several possible explanations for interactions between P and phytodiversity:

1. P determines the size of the niche because
   (a) P is the main limiting resource in the system
   (b) P limitation is coupled to other limiting resources
   (c) P-rich systems favor growth of legumes, leading to an increase in N, another nutrient often determining the niche size
2. P-limited habitats have lower interspecific competition than N-limited ones due to:
   (a) A range of available P forms that may be exploited by different species
   (b) Favoring of stress-tolerant rather than ruderal species in low-P environments
   (c) Larger restriction of the growth of grasses than of forbs in habitats with low N/P ratios

Thus, P may not have a larger impact on phytodiversity than other nutrients per se, but can gain it due to its availability relative to other resources. This explains also why the relation between P and phytodiversity may be overruled easily by other factors, e.g., management factors like heavy grazing (Hill et al. 2005; Dorrough et al. 2006) or environmental factors like soil salinity (Theodose and Roths 1999).

6.4 Implications of Climate Change for Future Developments of Phytodiversity

One of the major future challenges affecting phytodiversity is climate change. In the following, we will discuss current knowledge concerning the influence of climate change on plant species richness via effects on nutrient availabilities and invasive species.

Table 6.2 shows an overview of recent studies on implications of the aspects of climate change on P cycling. It becomes obvious that increasing temperatures tend to increase the rate of P cycling, more precipitation seems to decrease P availability, and increased CO_2 concentration has no direct effect on P cycling. Simulated increased N deposition increased phosphatase activities and P uptake (Table 6.2). In a study of effects of warming, moisture, CO_2 concentration, and N deposition on P cycling, the effect of N deposition was found to have a larger impact than effects of the other tested factors (Menge and Field 2007). This is crucial with respect to global warming, since Rustad et al. (2001) have shown in a meta-analysis that increasing temperatures by 0.3– 6.0°C at 32 research sites (~35–79°N latitude, one at 45°S latitude) increased N mineralization by 46% on average. Turner et al. (2003) showed that soil with a long history of N deposition in northern England had low P concentrations and most P was in the form of relatively stable organic P.

Thus, with respect to global warming, where increases in temperature, the incidence of heat waves and heavy rainfall events are likely (IPCC 2007), and N mineralization is probably increased (Rustad et al. 2001), the availability of P may be increased by higher phosphatase activity and higher plant demand, but losses by leaching or erosion also become more probable. This could at first mean a higher P availability and quicker P cycling, but in the long run lead to mining of soil P, especially if the finding that increased temperatures decreased P in plant litter (Sardans et al. 2006) is valid widely.

The outlined nutrient developments due to global warming would mean that in most unfertilized soils, a development might take place first towards more nutrient-rich conditions (up and to the right on Fig. 6.3), but later towards more nutrient-limited conditions, i.e., down and maybe to the left in Fig. 6.3, depending on the ratio between increased N mineralization and N losses. Increasing nutrient availability would favor R strategists and highly-productive, quickly growing species. Later, decreasing P availability may potentially lead to increasing phytodiversity. If N availability also decreases, e.g., due to larger N losses, an increase in plant diversity could take place, if seed occurrence and other requirements are met. If N availability stays high, so that the N/P ratio increases, graminoids may be favored (Falkengren-Grerup 1998), which may lead to decreased diversity (Güsewell 2004). In a grassland experiment, 3 years of elevated temperatures increased forb production and abundance, but only insignificantly increased species numbers of grasses and forbs (Zavaleta et al. 2003). The soil N and P pools or phosphatase activities were unfortunately not measured.

Climate change leads to shifts of species' distribution ranges towards the poles (Parmesan and Yohe 2003) and influences the success of invasive species.

Table 6.2 Implications of different aspects of climate change for P cycling

Change of	Conditions	Implication for P cycle	Reference
Temperature	Mediterranean shrubland, Spain, +1°C over 6 years	Increased phosphatase activities and P concentration in *Erica multiflora*, decreased litter P, soil extractable P and total P in soil	Sardans et al. (2006)
	Annual grassland, central California, USA, +1°C, 3–5 years	No effect on phosphatase activities, plant P concentrations, or N/P ratios	Menge and Field (2007)
	Dry, P limited heathland, NL, incubation of litter at 5°C, 10°C, 15°C, 20°C for 48 days	Increased microbial P mineralization with higher temperature, no effect on microbial P immobilization	van Meeteren et al. (2007)
	Incubation experiment with soil from arable field in Denmark, peas and mycorrhizal inocula at 10°C or 15°C	Almost doubled colonization of roots with mycorrhiza	Gavito et al. (2003)
	Experimental Forest in New Hampshire, USA, removal of snow cover to promote soil freezing	Missing insulation increased leaching of N and P, possibly due to increased fine root mortality	Fitzhugh et al. (2001)
Water availability	Mediterranean shrubland, Spain, 20.6% decrease in water availability over 6 years	No effect on phosphatase activity or soil extractable P	Sardans et al. (2006)
	Annual grassland, central California, USA, 150% of ambient precipitation, 3–5 years	Decreased soil phosphatase activity and total P in aboveground plant biomass	Menge and Field (2007)
	Dry, P limited heathland, NL, incubation of litter at 50%, 100%, 200% moisture content for 48 days	Increased microbial P mineralization (approx. 0.8 mg P kg^{-1} day^{-1}) and immobilization (approx. 6 mg P kg^{-1} day^{-1}) with higher moisture content	van Meeteren et al. (2007)
Increasing CO_2 concentration	Annual grassland, central California, USA, 370 or 670 ppm CO_2, 3–5 years	No effect on soil phosphatase activities, plant P concentrations, or N/P ratios	Menge and Field (2007)
	Incubation experiment with soil from arable field in Denmark, peas and mycorrhizal inocula at 350 or 700 ppm CO_2	No effect on colonization of roots with mycorrhizae	Gavito et al. (2003)
	Rice/winter wheat rotation, China, FACE experiment with ambient or +200 ppm CO_2, fertilized (NPK)	Increased shoot P, decreased P use efficiency in plants	Yang et al. (2007)
N-deposition/ faster N cycling	Annual grassland, central California, USA, +7 g NO_3^--N m^{-2} a^{-1}, 3–5 years	Increased soil phosphatase activity, net plant primary production, total aboveground P	Menge and Field (2007)
	Calcareous and acid grassland, UK, 0, 3.5, or 14 g NH_4NO_3-N m^{-2} a^{-1}, up to 7 years	Increased phosphomonoesterase activities, increased soil and shoot P	Johnson et al. (1999), Phoenix et al. (2004)

As outlined above, invasive species also have an effect on the P cycle. This will not only affect their own competitive behavior, but also that of the species surrounding them. So far, no studies have investigated indirect effects of invasive species on surrounding vegetation via changes in P cycling. However, increased P availability following establishment of invasive species will favor fast-growing graminoid species and lead to a decrease of plant diversity on the short term.

Thus, the trends due to global changes all lead to a decreased diversity of plant communities in the near future. They also cause a mining of nutrients from the soil, leading to decreased fertility in the long run. This may then allow a recovery of plant diversity, provided that enough species are still present in the seed banks or can colonize from nearby sites. At the same time, decreased soil fertility also reduces productivity. As increased phytodiversity can be positively related with biomass production under experimental conditions at fixed nutrient availability (Hector et al. 1999; Bullock et al. 2001; van Ruijven and Berendse 2003; Dodd et al. 2004), it could become a management tool in the future, especially when resources for mineral fertilizers become limited. Prognoses suggest that the global P reserves would support the current rate of application for about 100 – 470 years (Smil 2000; Syers et al. 2008).

To sum up, changes in N and P availability due to climate change may first lead to decreasing phytodiversity (with increasing productivity). Later, the trend may reverse due to mining of soil P resources. However, long-term studies have shown that biodiversity takes a long time to recover from nutrient additions, especially from P additions (Hejcman et al. 2007b). Thus, measures should be taken to prevent increased P availability in soils of unfertilized systems in relation to other factors influencing plant growth and competitive strength as far as possible.

6.5 Conclusion

To increase sustainability of agriculture, plants' adaptations to low P concentrations in soils should be taken better advantage of. With rising prices for P fertilizers, the use of P-solubilizing microorganisms and mycorrhiza and the breeding of cultivars with adapted root systems or exudation strategies are possible tools in maintaining or increasing productivity.

Past and present large inputs of P in agricultural systems lead to problems such as eutrophication and loss of biodiversity. P is probably not per se more significant for plant diversity than other nutrients. However, as a relevant limiting nutrient, it often (co-) determines the niches enabling species to grow. When P availability increases, plant diversity therefore often decreases. With global warming, P and N mineralization are stimulated. As both temperature and the amount of N have positive direct and indirect effects on soil P availability, global warming threatens phytodiversity via enhanced P availability. The effects of global warming on soil nutrients might lead to better conditions for fast-growing competitive and ruderal species, but in the longer run also to P mining. This could allow plant diversity to improve again.

However, long-term studies show that recovery of plant diversity may take a long time, especially after P addition, so that prevention of diversity loss due to increased P concentrations in the soil is preferable to later restoration measures.

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Chapter 7
Co-evolution and Migration of Bean and Rhizobia in Europe

Paula A. Rodiño, Marta Santalla, Antonio M. De Ron, and Jean-Jacques Drevon

Abstract The legumes crop common bean is one of the most important crops for the human nutrition common bean is the protein basis from developing countries. Common bean presents many limitations such as the deficiencies or toxicities of minerals in soils. These limitations in common bean production regions occur throughout the world. To overcome mineral deficiencies and toxicities, common bean growers must use corrective soil amendments. Symbiotic nitrogen fixation (SNF) is important as a source of N for agriculture, because the use of nitrogenous fertilizers has resulted in unacceptable levels of water and atmosphere pollution and by nitrate and N_2O emissions, contributing to the increase of greenhouse effect. The common bean grown in Europe, and other continents, is the result of a process of domestication and evolution, from wild forms found exclusively in the Americas, and it is possible to distinguish two major domestication centres, Andean and Mesoamerican centers. Most of the European germplasm is from Andean locations since the type T phaseolin pattern is found in their seeds. It is thought that Mesoamerican lines were less popular because of their lower adaptability to winter cold and to short duration summers. Subsequently, new cultivars may have evolved within and between the two gene pools in Spain and Portugal making the Southern Europe a secondary center of diversity for the common bean. The microorganisms associated with the common bean plant for its symbiotic nitrogen fixation may exhibit a similar arrangement of genetic diversity in Mesoamerica and Andean gene pools. R. etli bv. phaseoli is the dominant microsymbiont in both the Mesoamerican

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P.A. Rodiño (✉), M. Santalla, and A.M. De Ron
Legumes Breeding Group, Plant Genetic Resources Department, Misión Biológica de Galicia,
P.O. Box 2836080, Pontevedra, Spain
e-mail: aprodino@mbg.cesga.es
e-mail: msantalla@mbg.cesga.es
e-mail: amderon@mbg.cesga.es.

J.-J. Drevon
INRA-Montpellier-SupAgro, UMR1222, Rhizosphère et Symbiose, 2 Place Viala, 34060,
Montpellier, France
e-mail: drevonjj@supagro.inra.fr.

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and Andean centers of origin. Many other species have been found in bean nodules in region where they have been introduced. In Europe, rhizobia strains that nodulate common bean have a narrow genetic diversity that was correlative to beans being an introduced crop. In this respect, the large number of rhizobia species capable of nodulating bean supports the premise that bean is a promiscuous host and a diversity of bean-rhizobia interactions exists. Since there seems to be a large variation in the capacity of bean genotypes to nodulate with a large range of host-or non-host specific strains, this knowledge could be used to enhance the symbiosis and possibly to enhance nitrogen fixation.

Keywords Common bean • Diversity • Domestication • Evolution • Origin • Rhizobia

7.1 Introduction

Deficiencies or toxicities of minerals in soils in common bean production regions occur throughout the world. To overcome mineral deficiencies and toxicities, common bean growers must use corrective soil amendments such as lime (Fageria et al. 1995), manure or composted manure (Tarkalson et al. 1998), and fertilizers rich in macronutrients and micronutrients such as N, P, B, Fe, and/or Zn (Henson and Bliss 1991). Symbiotic nitrogen fixation (SNF) is important as a source of N for agriculture, because the use of nitrogenous fertilizers has resulted in unacceptable levels of water pollution and the eutrophication of lakes and rivers. However, international emphasis on environmentally sustainable development with the use of renewable resources is likely to focus attention on the potential role of SNF in supplying N for agriculture.

Common bean (*Phaseolus vulgaris* L.), domesticated in Mesoamerica and Andean South America, was introduced into Spain after the colonization of the Americas (Gepts et al. 1986). Currently common bean is the world's most important grain legume for direct human consumption and are staple crops serving as the primary source of protein nitrogen in the diet for developing pays. In Europe, the importance of the common bean is due to a change in nutritional habits and a greater demand for healthy and functional products. Large germplasm collections are maintained in different countries. New cultivars are displacing landraces but farmers still grow landraces for personal consumption and sale in farmer's markets. Genetic variability found for seed colour, size, shape, and other characteristics is very high among genotypes grown by farmers. The Legumes Breeding Group at the Mision Biologica de Galicia – Spanish Council for Scientific Research (MBG-CSIC) has an Iberian common bean germplasm collection and oversees the task of further collecting, evaluating, and maintaining the landraces (De Ron et al. 1997). Knowledge of patterns of genetic diversity among landraces and their relationships with new cultivars helps broaden the genetic base and maximizes use of available germplasm. In spite of increasing use of the DNA-based markers for studying genetic diversity, study of phenotypic variation in a germplasm collection is crucial for determining adaptation, agronomic potential, and breeding value of landraces.

The Leguminous as common bean, have formed an important part of crop cultivation systems performing relevant roles in sustainable agricultural practice, effective management of fertilizer, improving soil health, and protection of surface and ground water from contamination. Among these crops, common bean can satisfy a great proportion of their nitrogen requirement by means of SNF. Nitrogen availability is often a limiting factor for crop productivity, particularly in developing countries. Moreover, the use of chemical N must be limited for the preservation of the environment, particularly in Europe where rates of N fertilization have increased steadily, in addition to manure recycling and significant N deposition from the atmosphere (Fink et al. 1990; Goulding et al. 1998; Graham and Vance 2000). Rhizobia are soil bacteria studied for their ability to establish nitrogen fixing symbiosis (Fig. 7.1). The SNF still provides more nitrogen to the agricultural ecosystems worldwide than the total amount of N fertilizer applied. This system could constitute an ecologically acceptable alternative to the high application of N fertilizers, particularly in Europe, and an economic alternative to the limited access of developing countries to N fertilizers. Thus, this review aims at summarizing the most recent information regarding the evolution and the diversity of common bean accessions and the soil bacteria as rhizobia that can be associated with them. The main topics will be: (i) origin, domestication, and dispersal routes of common bean, (ii) phaseolin is an important evolutionary marker, (iii) diversity of rhizobia, and (iv) conclusions and perspectives.

Fig. 7.1 Association of common bean with rhizobia. This association provides the development of nitrogen fixing organs, called nodules, in the roots of plant-host

7.2 Migration of Common Bean and Their Rhizobia Strains

7.2.1 *Origin, Domestication and Dispersal Routes of Common Bean*

Over a period of at least 7,000 years, the common bean has evolved from a wild-growing into a major leguminous food crop. During this period, which encompasses the initial domestication phase and the subsequent evolution under cultivation, evolutionary forces (mutation, selection, migration, and genetic drift) have acted on the raw material provided by wild-growing populations in Middle America and Andean South America. It is only since the late twentieth century that scientist have accepted a New World origin for the common bean and this was contrary to the belief in an Asian origin, which had been held for several centuries (Gepts and Bliss 1988; Gepts and Debouck 1991). Several common bean remains have been uncovered, not only in the Andes but also in Mesoamerica and North America consisting of seeds (Kaplan et al. 1973), pod fragments (Kaplan 1981) and even whole plants (Kaplan and MacNeish 1960) which date from 8,000 to 10,000 BP in the Andes and 6,000 BP in Mesoamerica. Dating methods have been recently the subject of much discussion among archaeologists for new world crops. The oldest records for common bean 4,300 years BP, revised using Accelerator Mass Spectrometry direct dating (Kaplan and Lynch 1999) is from Ancash, Peru, and 2,200 years BP for Puebla, Mexico, although much earlier dates have been repeatedly presented using radiocarbon indirect dating (Debouck 2000). These archaeological findings are phenotypically similar to current cultivars grown in the same area. Also, there are the historical and linguistic data as the sixteenth century Spanish texts mention the presence of the common bean in the Americas and the vocabulary (e.g., purputo) of several native Indian languages includes a specific word designating the common bean.

Thus, the common bean is a species of American origin derived from wild ancestors distributed from northern Mexico to northwestern Argentina (Gepts et al. 1986; Koenig et al. 1990; Toro et al. 1990; Payró de la Cruz et al. 2005) and was domesticated in two distinct regions of the New World, one in Mesoamerica and another along the eastern slope of the Andes in the South America (Gepts and Bliss 1985; Gepts et al. 1986; Gepts and Debouck 1991; Tohme et al. 1995; Chacón et al. 2005) (Fig. 7.2). The cultivated gene pools of common bean can be distinguished by their morphology and agronomical traits (Singh et al. 1991a), phaseolin seed protein electrophoretic type (Koenig et al. 1990); isozymes (Koenig and Gepts 1989; Singh et al. 1991b), molecular markers (Becerra-Velásquez and Gepts 1994; Haley et al. 1994; Freyre et al. 1996; Galvan et al. 2003; Chacón et al. 2005; González et al. 2005; Zizumbo et al. 2005; Blair et al. 2007; Lasry et al. 2007), and adaptation traits (Singh 1989; Voysest and Dessert 1991). Most cultivars from either the Middle American or the Andean region contain characteristics that are found in wild accessions from the same area, but not in wild accessions from the other gene pool (Koenig and Gepts 1989). Cultivars from Mesoamerica usually have small

Fig. 7.2 Distribution of the major gene pools of wild *P. vulgaris* L. in Latin America (Gepts et al. 1986), indicating two major domestications, in Mexico and in the Andes which led the two groups of cultivars with contrasting agronomic characteristics

(<25 g/100 seed weight) or medium-seeded (25–40 g/100 seed weight) and have a S and B phaseolin that differ from those of their South American counterparts, with large seeds (>40 g/100 seed weight) and T, C, H, and A phaseolin types (Gepts et al. 1986; Singh et al. 1991b). Six races (Singh et al. 1991c) have been proposed both for common bean from Mesoamerica (Mesoamerica, Durango, and Jalisco races) and from the Andean region in South America (Chile, Peru, and Nueva Granada races). In addition to these two major gene pools, recently discovered wild populations constitute a third gene pool ancestral in the evolution of wild common bean located in Ecuador and northern Peru (Debouck et al. 1993; Kami et al. 1995). These ancestral populations were not involved in domestication as shown by their phaseolin type, which is absent from the domesticated gene pool. Chloroplast DNA polymorphism data agree with other studies in supporting independent domestications in two regions and in demonstrating a founder effect associated with domestication. Andean landraces have been classified into three racial groups, but all share the same chloroplast haplotype. This suggests that common bean was domesticated once only in South America and that the races diverged post-domestication. Mesoamerican landraces have been classified into four racial groups (Beebe et al. 2000). The samples of races Jalisco and Guatemala differ from the races Mesoamerica and Durango in types and/or frequencies of haplotypes. Independent domestications of at least some of the races in Mesoamerica and/or conversion of some locally adapted wild beans to cultigens by hybridization with introduced domesticated beans, followed by introgression of the "domestication syndrome" seen the most plausible explanations of the chloroplast and other molecular data (Chacón et al. 2005).

During the evolution of common bean, some morphological, physiological, and genetically marked changes have occurred such as gigantism (seed, pod, stem, and leaves), suppression of seed dispersal mechanism, changed growth habit form (from climbing to dwarf plants), loss of seed dormancy, and photoperiodic sensitivity (Smartt 1988; Gepts and Debouck 1991). The divergence between the Andean and Middle American gene pools has implications for bean breeding that have not yet been fully explored (Blair et al. 2007). Despite their partial reproductive isolation (Singh and Gutiérrez 1984; Gepts and Bliss 1985; Koinange and Gepts 1992), the two gene pools still belong to the same biological species (Papa and Gepts 2003). Viable and fertile progeny obtained, and therefore, favorable genes alleles have been transferred between the two pools, although the transfer of quantitative traits such as seed yield appears to be problematic. Attempts to recombine desirable traits between both gene pools, such as the large seed size of the Andean gene pool with the yield potential of the Mesoamerican gene pool, have generally failed (Nienhuis and Singh 1986; Welsh et al. 1995).

Some limited bean germplasm exchange has taken place in pre-Columbian times between Mesoamerica and South America, but much more extensive seed movement occurred after the 1500s (Sonnante et al. 1994; Kaplan and Lynch 1999; Blair et al. 2007). Thus, outside the American centers of primary diversity one can identify several secondary centers which bean collectors should consider in search of diversity. The different genotypes found in these secondary zones were introduced from the Americas, either soon after the Spanish conquest or more recently. As secondary centers, one can tentatively suggest East Africa and Europe, since the *Phaseolus* beans were introduced in those regions by the Spaniards and the Portuguese in the sixteenth and the seventeenth centuries. Concerning the origin of the European beans, McClean et al. (1993) suggested that the germplasm dispersed to Europe was probably domesticated in the South American Andes since the Mesoamerican cultivars are not currently very popular in Europe. This suggests that, during crop expansion in Europe, sampling or selection favored the large-seeded races within the Mesoamerican S gene pool or possibly, introgression from Andean germplasm did occur. The domestication process may have excluded valuable genetic variability in the relation to adaptive characteristics, such as resistance to insects during storage and *Rhizobium* strain specificity (Acosta-Gallegos et al. 1998; Payró de la Cruz et al. 2005; Zizumbo et al. 2005). Gepts and Bliss (1988) suggested that the bean grown on the Iberian Peninsula was introduced from a different area (Chile) compared to those of the rest of Europe. Nevertheless, the introduction of beans in Europe is unclear and currently under discussion (Ocampo et al. 2005; Martins et al. 2006; Rodiño et al. 2006; Svetleva et al. 2006; Logozzo et al. 2007; Marotti et al. 2007).

Seed exchanges with Europe must have happened since the first visits of Europeans to the Americas. Sailors and traders, 500 years ago, could have brought the nicely coloured, easily transportable bean seeds with them as a curiosity, only for fun, as is often observed in the present day with children at home and school in the Andean region. Within Europe there was likely a quick distribution of seeds as curiosities (Zeven 1997). It is possible that the initial common bean accessions introduced in Europe (into Iberian Peninsula), were mainly from Mesoamerica around 1506 (Ortwin-Sauer 1966). There is evidence that common bean reached France in 1508, probably as an ornamental plant without value for human consumption in that time (Zeven 1997). Thus, because Columbus arrived in Central America, in reality in Cuba, in 1492 and Cortés reached Mexico in 1518, Castiñeiras et al. (1991) and Hammer et al. (1992) proposed the introduction of seeds from Cuba since 1492. In 1528, Pizarro explored Peru, opening the possibility to introduce common bean accessions from the Andes (Berglund-Brücher and Brücher 1976; Debouck and Smartt 1995). It was distributed widely in all part of Europe and the Mediterranean area where many landraces and varieties evolved that were grown to provide dry seeds or fresh pods. Zeven (1997) has found some descriptions of common bean as early as 1542 which indicate, in fact, the wide distribution of this species in Europe, starting obviously by means of its introduction in Spain by C. Columbus. No records of common bean earlier than 1543 have been found in NW European herbaria, suggesting that the common bean was distributed in NW Europe after 1540 and in 1669 it was cultivated on a large scale (Zeven 1997). Due to adaptation to new ecological and man-made conditions, a large diversity evolved in European germplasm that is of particular interest for plant breeding. There are evidences of seed exchange among farmers and gardeners in many countries of Europe for testing some new material or for avoiding the degeneration of cultivars sown year after year (Zeven 1999). Europeans still collect common beans from neighboring and faraway regions. Therefore, the species has undergone an adaptive evolutionary process in those regions for about 400 years, resulting in today's very important additional variation (Debouck 1988; Hidalgo 1988; Ocampo et al. 2005; Martins et al. 2006; Svetleva et al. 2006; Marotti et al. 2007).

In the sixteenth century there were harbors maintaining active commerce with the New World in the Northwest of Spain (Galicia). The introduction of some crops such as bean and maize and the distribution to other areas could have occurred in this area. The traditional cropping systems for the bean crop similar to those used in many areas of the Americas (Santalla et al. 1994) are strong arguments to support this hypothesis. The sensitivity to long day and low temperature during the growing season could have been a limiting factor for cultivated bean in many European latitudes in the early times. In fact, it is possible to grow primitive Andean landraces and wild populations in the North of Spain (Pontevedra, 42°N) but only under greenhouse conditions during the fall–winter–spring period (De Ron et al. 1999). Thus, subsequently new cultivars may have evolved within and between the two gene pools in Southern Europe (mainly Spain and Portugal) making this region a secondary center of diversity for the common bean (Santalla et al. 2002; Rodiño et al. 2006). The consequential adaptation, occasional out crossing, cropping systems and strong selection for consumer preferences of seed types, might have played a significant role in arising of the new variation in the common bean of the Iberian Peninsula (Rodiño et al. 2006). The introduction routes of African common bean cultivars are more difficult to ascertain. Whereas a majority of the cultivars ultimately originated in the Andes, it is not known by which route they were introduced. They could have been introduced directly from the Andes, indirectly through the Iberian Peninsula or through Western Europe during the colonial period. Because historical and linguistic information provide little evidence regarding the origin and dissemination of common bean in Europe and Africa, phaseolin protein pattern, an evolutionary marker (Gepts et al. 1986), was used to complement morphological and agronomic data. This phaseolin protein analysis was useful to identify gene pools and the origin of accessions to the Mesoamerican or Andean domestication centers.

7.2.2 *Phaseolin, a Major Evolutionary Marker*

Phaseolin is the major seed storage protein of common bean and it can be used to trace the evolutionary origin of common bean genotypes. The electrophoretic variability of phaseolin of wild-growing common beans from Mesoamerica and the Andes was compared with landraces of the same region. The wild common bean accessions of different geographic origin could be distinguished by their phaseolin type (Fig. 7.3). In Mesoamerica, the wild forms showed both the S type as well as M types. The Colombian wild common bean exhibited the CH and B types, whereas in the southern Andes, wild forms showed only the T type (Brown et al. 1981). There was a correspondence in the geographic distribution of phaseolin types between wild and cultivated common bean. The cultivars with S and T phaseolin patterns predominated in Mesoamerica and in the southern Andes, respectively. The B phaseolin type was present only in wild and cultivated common bean from Colombia. On the other hand, the C, H, and A phaseolin types were found not only among landraces of the Andes, but also among wild forms (Koenig et al. 1990). Therefore, multiple domestications are thought to be the primary cause for parallel geographical phaseolin variation between wild and cultivated common bean forms. Secondarily, occasional outcrosses between wild and cultivated common beans may have also contributed to this parallel distribution of phaseolin types. Given the low frequency of B phaseolin cultivars, Colombia might, however, only be a minor or more recent domestication region (Gepts et al. 1986)

A relationship was observed between phaseolin pattern and seed type. Cultivars with T, C, H, and A phaseolin types on the average have larger seeds than cultivars

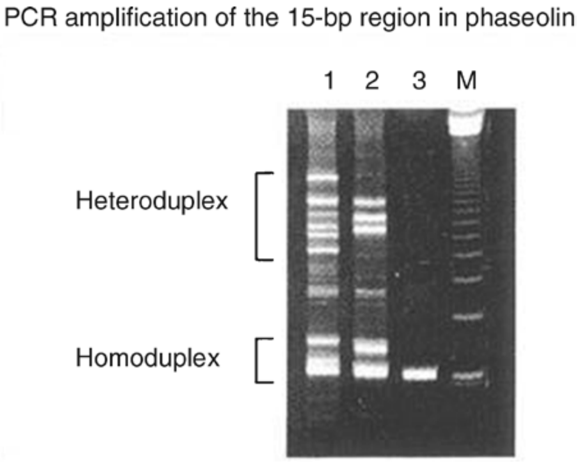

Fig. 7.3 Polymerase chain reaction amplification of part of the phaseolin genes surrounding the 15 repeat. 1: **T** phaseolin (Andean); 2: **S** phaseolin (Mesoamerican); 3: **I** phaseolin (Ecuador and northern Peru) (Kami et al. 1995)

with S and B phaseolin types (Gepts et al. 1986). This relation provides evidence for exchange of germplasm between Mesoamerica and the Andes. It makes it possible to follow the world–wide dispersal of common bean cultivars. Mesoamerican cultivars were introduced into North-eastern USA, the Iberian Peninsula, Western Europe, and Africa. In these regions, they formed, however, only a minor component compared to the cultivars of Andean origin. The latter may have had a competitive advantage over genotypes of other origins because of a more adequate photoperiodic adaptation due to similar latitudes. The Mesoamerican and Andean gene pools were introduced in Europe at different times (Zeven 1997; Santalla et al. 2002) but the amount and distribution of the two gene pools in Europe is not well-known (Papa et al. 2005).

Previous studies have indicated that most of the Iberian cultivars may have been introduced from Chile due to a high frequency of the C phaseolin pattern (Gepts and Bliss 1988; Gil and De Ron 1992). However, most recent studies (Escribano et al. 1998; Rodiño et al. 2003) indicated a high frequency of the T phaseolin pattern among Iberian cultivars. The T phaseolin type was also observed in Western Europe (Gepts and Bliss 1988). Subsequently, the Iberian Peninsula landraces could have been introduced in other parts of Europe such as Greece, Cyprus, and Italy, as indicated by the high proportions of T and C types in these areas (Lioi 1989; Limongelli et al. 1996; Santalla et al. 2002; Logozzo et al. 2007). These studies have provided evidence for the existence in the Iberian Peninsula of the two major gene pools, Andean and Mesoamerican. A much lower diversity of European common bean, due to a strong founder effect during the introduction into Europe, was suggested. However, recent studies show that the reduction of a genetic diversity was not as strong as expected and gene flow between the two American gene pools has been suggested (Santalla et al. 2002; Papa et al. 2005; Sicard et al. 2005) and the new genetic variation in the common bean was showed (Rodiño et al. 2006). The variation in bean-growing environments, cropping systems, and consumer preferences for seed types in this area might have played a significant role in the common bean crop diversity and could give rise to the preservation of a large variation in the characteristics of domesticated common beans. Different distribution of the C type compared to the T types was observed. While T type are more frequent in most of the European countries the C type are prevalent in Italy and Spain where the common bean first reached Europe (Logozzo et al. 2007).

7.2.3 Diversity of Rhizobia

Rhizobia is a gram-negative Proteobacteria with the capacity to fix atmospheric nitrogen when it is associated with the legume's roots. It is possible that the microorganisms associated with the common bean plant for its SNF may exhibit a similar arrangement of genetic diversity in Mesoamerican and Andean gene pools. While common bean is highly promiscuous in its relationship with rhizobia, *R. etli* bv. *phaseoli* has been found as the predominant nodule occupants in both the Mesoamerican and Andean centers of origin (Martinez-Romero 2003; Aguilar et al. 2004; Grange et al. 2007). This is not always the case in other areas where the crop is grown. Isolates belonging to *R. etli* bv. *phaseoli*, are predominant in soils of Mesoamerican countries (Eardly et al. 1995; Martinez-Romero and Caballero-Mellado 1996) and in Argentinean soils (Aguilar et al. 1998). A large genetic diversity has been documented for *R. etli* bv. *phaseoli* from the domestication centers and may be carried on bean-seed testa, possibly the means by which the species was distributed worldwide (Fig. 7.4). Differences in symbiotic effectiveness exist within *R. etli* bv. *phaseoli* isolates and these may be related to the large genetic differences observed in these bacteria and also the coadaptation of cultivar and bacteria. Occasionally, bacteria other than *R. etli* bv. *phaseoli* have been encountered in bean nodules in Mexico and they correspond to *R. gallicum* bv. *phaseoli* (Silva et al. 2003), whereas Andean cultivars form large number of nodules with *R. tropici* strains (Nodari et al. 1993). Thus, *R. tropici* is indigenous to South America and the reference strain was isolated in Colombia, likely a third center of the host common bean. *R. tropici* seems clearly dominant under field conditions, even when cultivars of Mesoamerican group are used as trap hosts (Mostasso et al. 2002; Hungria et al. 2003). Mesoamerican beans with high capacities to fix nitrogen nodulated poorly with *R. tropici* strains and in these beans *R. tropici* blocked *R. etli* bv. *phaseoli* nodulation when both strains were tested together (Martinez-Romero et al. 1998). Bean nodule isolates from Ecuador and Peru proved to be very diverse and could be divided into clusters distinct from the Mexican isolates. Ecuatorian and Mexican beans selected different *R. etli* bv. *phaseoli* strains both from Ecuatorian and Mexican soils (Bernal and Graham 2001) and efficiency in nodulation and nitrogen fixation was higher when both partners were from the same region. May it be that domestication and other human selections of beans indirectly affected host range?

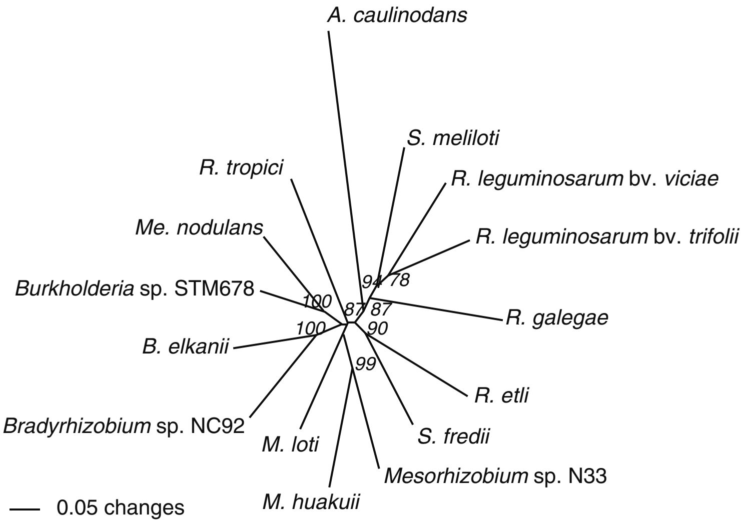

Fig. 7.4 The tree is based on full-length sequences, and constructed by using the neighbor-joining method. Bootstrap values (% from 1,000 replications) are indicated. NodA sequences of published rhizobia are available in GenBank. A, Azorhizobium, B, Bradyrhizobium. M, Mesorhizobium. Me, Methylobacterium. R, Rhizobium. S, Sinorhizobium (Moullin et al. 2001)

What would be the consequence, in terms of N_2 fixation, of inoculating a Mesoamerican cultivar with Mesoamerica *versus* Andean rhizobia strain?

In Europe, rhizobia strains have a narrow genetic diversity that was correlative to beans being an introduced crop (Laguerre et al. 1993). Segovia et al. (1993) proposed that when seeds containing *R. etli* bv. *phaseoli* were introduced into Europe, the symbiotic plasmid could have been transferred to *R. leguminosarum*. Later, the same process may have occurred from *R. leguminosarum* to *R. gallicum* and *R. giardinii* (Amarguer et al. 1997). It seems that in some sites of introduction bean is nodulated by other species in addition to diverse *R. etli* bv. *phaseoli* and the co-occurrence of several species is common. *R. tropici* is well adapted to acid soils and high temperatures and was also isolated in Europe and in Africa. It was demonstrated that pH can limit the presence of microorganism in soils and can be a barrier to diversity (Giongo et al. 2008). In Portugal, the molecular analysis of strains isolated from various soils revealed a novel species named *R. lusitanum* (Valverde et al. 2006). Remarkably, in a single soil in Spain five rhizobial species (*R. etli* bv. *phaseoli, R. leguminosarum, R. gallicum, R. giardinii,* and *S. fredii*) were found to nodulate *P. vulgaris L.* (Herrera-Cervera et al. 1999). The existence of one of the most genetically diverse collections of *Rhizobium* isolates recovered from root nodules of *P. vulgaris* L. from Spain was revealed (Martinez-Romero and Caballero-Mellado 1996). The most abundant species appeared to be *R. etli* bv. *phaseoli* presumably because they were brought into Spain from the Americas after introduction of beans about four centuries ago. It is also important to remember that, after 1492, a trade barrier was established in South America by the domains of Spain and Portugal, and isolation might have prevented the spread of other genotypes of *R. etli.* Thus, *R. etli* strains from Europe may have different origins. The results of Herrera-Cervera et al. (1999) indicate that extensive interspecific symbiotic gene exchange has taken place in this site and presumably, *R. etli* bv. *phaseoli* strains could have been the original gene donors. The other species, which have also been found at different locations in Europe, probably represent bacteria that preexisted in European soils when beans were first introduced and have received genetic material from the introduced *R. etli* bv. *phaseoli*. Thus, the Spanish soil studied represents a unique case where a donor and the putative DNA recipient coexist and probably compete for the same ecological niche. In a recent study, phenotypic features of 90 French rhizobia isolates from *Phaseolus* spp. nodules that were previously assigned to one of the three previously named species of rhizobia that nodulate beans (*R. leguminosarum, R. tropici,* and *R. etli* bv. *phaseoli*), were compared to the phenotypic features of reference rhizobial strains by numerical taxonomy. As a result of the present and previous studies, Amarguer et al. (1997) proposed that two new *Rhizobium* species should be created, *R. gallicum* and *R. giardinii*.

7.3 Major Advances

The high N_2 fixing potential found in a recent study reveals a genotypic variability for traits associated with N_2 fixation in common bean of the European germplasm collection of Mision Biologica de Galicia – CSIC, which has diversified in the Iberian Peninsula (Rodiño et al. 2005; Rodiño et al. 2006; Rodiño et al. in review). This study confirms the large nodulation potential of the studied germplasm. It is particularly important for low N_2-fixing legumes such as common bean, for which there appears to be large variability in nodulation and in the efficiency of the tested rhizobia, with regard to the native rhizobia strains, adapted to local environmental conditions and (Buttery et al. 1997) considered to present a real opportunity for improving N_2-fixation in the common bean through plant breeding. The low intrinsic number of native rhizobia were not due to the lack of previous legume crops, but were, most likely, the consequence of their susceptibility to local environmental conditions and their subsequent inefficiency. The selection of bean genotypes capable of being nodulated with indigenous rhizobia is a recent practice, and the distribution and cultivation of these genotypes by farmers has not been widespread (Thies et al. 1995; Abaidoo et al. 2007). The results also indicate that the potential exists for bean breeding to identify locations devoid of rhizobia strains but containing effective strains of rhizobia that can serve as local sources of elite strains for inoculum production and use in bean growing areas where the rhizobia populations are ineffective or inadequate. Therefore, researchers, extension workers, and policy markers should think of SNF as being a key process, with long-term benefits, essential for sustainable agriculture, improving productivity, ensuring food security, and maintaining environmental quality.

7.4 Conclusion

The morphological, physiological, and genetic characteristics of present common bean cultivars are the result of the evolutionary history of the species before, during, and after domestication. A better knowledge of this evolutionary history gives us a deeper understanding of the current characteristics of the cultivated gene pool of the common bean, which in turn, should lead to better management of common bean genetic resources and breeding programs. Thus, it is important to continue the exploration and collection of landraces of common bean, both from Europe and Africa to clarify the dispersal routes in these countries.

The diversity of rhizobia nodulating *P. vulgaris* has been widely studied, but because of its promiscuous nature, novel endosymbionts of this legume should be expected as more ecological niches are studied. This diversity of rhizobia, providing valuable ecological information by defining host preferences and predominance of strains, the dynamics of exchange of genetic material, and the basis for the proposal of evolutionary trends. The diversity studies also reveal that there is no unique *Rhizobium* strain highly adaptable and efficient for all soils, environmental conditions, and bean genotypes. Each of the major genetic pools of *P. vulgaris* and rhizobia coevolved independently of the others after geographic separation. Information concerning the structure of the indigenous rhizobial populations and the coevolution with the host plant could greatly contribute to understand the frequent reports of nodulation failure. The sensitiveness and promiscuity of common bean symbiosis may represent an interesting model for the examination of effects of different soil management systems on rhizobial diversity. A better understanding of the wild gene pool could lead to the establishment of improvement programs that would increase the yield of domesticates, improve their tolerance to pathogens, diseases, and environmental stress, and exploit the role of beneficial microorganism, thereby facilitating the establishment of sustainable productive systems through methods of conservation in situ and ex situ. The improvement of bean nitrogen fixation is an important goal; biological nitrogen fixation not only lowers production costs but is also environmentally sound. Researchers, extension workers, and policy markers should think of SNF as being a key process, with long-term benefits, essential for sustainable agriculture, improving productivity, ensuring food security, and maintaining environmental quality.

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Chapter 8
Non-isotopic and ^{13}C Isotopic Approaches to Calculate Soil Organic Carbon Maintenance Requirement

Francisco Mamani Pati, David E. Clay, Gregg Carlson, and Sharon A. Clay

Abstract To meet long-term food, energy, and fiber security requirements, production systems must be sustainable. A critical component in sustainable agricultural systems is the maintenance of soil organic carbon. Soil organic carbon (SOC) maintenance requires, over time, the amount of carbon added to soil to be equal to the amount of relic carbon mineralized. Obtaining the information required for maintenance calculations is difficult and therefore, many projects assume that: 1) above- and below-ground biomass have similar impacts on SOC turnover; 2) root to shoot ratios can be used to estimate below-ground biomass; and 3) ^{13}C enrichment during SOC mineralization is insignificant. This chapter reviews non-isotopic and ^{13}C isotopic approaches used to develop carbon budgets, and investigates the implications of simplifying assumptions on SOC turnover calculations. Sensitivity analysis of carbon-budget equations showed that: 1) if the root to shoot ratio is underestimated, then the above-ground biomass needed for maintenance is overestimated, whereas the reverse is true if the root to shoot ratio is overestimated; and 2) in systems where C_4 residue is applied to soil derived from C_4 and C_3 plants, the calculated half-life was higher when ^{13}C fractionation during relic carbon mineralization was considered. For C_3 plants, the reverse was true. For ^{13}C natural abundance calculation these errors can be minimized by testing the assumptions that ^{13}C isotopic discrimination during mineralization of relic carbon and fresh biomass does not occur. Correction values for ^{13}C isotopic discrimination of relic carbon can be calculated from data collected from control areas where plant growth is prevented. Temporal changes in relic SOC ^{13}C isotopic discrimination can be measured in this zone. A mathematical approach for using ^{13}C isotopic discrimination during relic carbon mineralization in SOC budget calculations is provided.

F.M. Pati, D.E. Clay (✉), G. Carlson, and S.A. Clay
South Dakota State University, Brookings, South Dakota, 57007, USA
e-mail: david.clay@sdstate.edu

F.M. Pati
Bolivian Catholic University, UAC-Carmen Pampa, Coroico, La Paz-Bolivia

E. Lichtfouse (ed.), *Sociology, Organic Farming, Climate Change and Soil Science*,
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Abbreviations

SOC	Soil organic carbon
NHC	Non-harvested crop residues
NHC_a	Amount of non-harvested carbon applied
NHC_m	Non-harvested carbon maintenance requirement
$SOC_{initial}$	Soil organic carbon at the beginning of the experiment
SOC_{final}	Soil organic carbon contained in soil at the end of the Experiment
SOC_e	Amount of SOC at equilibrium
MRT	Mean residence time
RPC	Plant-derived-respired
DPM	Decomposable plant material
RPM	Resistant plant material
$\delta^{13}C_{plant+soil\ CO_2}$	$\delta^{13}C$ value of the CO_2 containing both soil and plant carbon
$\delta^{13}C_{plant}$	$\delta^{13}C$ value of plant
$\delta^{13}C_{soil\ CO_2}$	$\delta^{13}C$ value of CO_2 in an area not containing plants
$CO_{2\ plant+soil}$	Total amount of CO_2 trapped in the soil plus plant system
$\delta^{13}C_{soil\ final}$	$\delta^{13}C$ value of SOC when the experiment was completed
PCR_{incorp}	New plant carbon incorporated into SOC
$\delta^{13}C_{PCR}$	$\delta^{13}C$ value of the plant material retained in the soil after mineralization
$SOC_{retained}$	Amount of relic carbon ($SOC_{initial}$) retained in the soil at the end of the study
$\delta^{13}C_{SOC\ retained}$	Associated $\delta^{13}C$ value
SOC_{lost}	Amount of organic carbon lost
ε_{SOC}	Rayleigh fractionation constant of the SOC
^{s}SOC	Soil organic carbon derived from corn stover
SOC_r	Total corn-derived carbon in the residue returned treatment
SOC_h	Corn derived from unharvested material in the stover harvested treatment

8.1 Soil Organic Carbon Maintenance

Declining amounts of arable land, increasing world populations, and increasing costs of fertilizer and food and energy needs will make it increasingly difficult to maintain our soil resources. A key component for sustaining soil productivity is the maintenance of soil organic carbon (SOC). SOC maintenance requires the amount of carbon added to the system to equal the amount of relic carbon mineralized

(Ortega et al. 2002; Prakash et al. 2002). The carbon cycle is driven by photosynthesis which produces organic biomass that is respired by microorganisms. Biomass mineralization rates are influenced by many factors including water, temperature, stability of the carbon, and management (Lloyd and Taylor 1994; Mikha et al. 2006). SOC content has been directly linked to productivity, temperature, cation exchange capacity, plant available water, bulk density, available nutrients, erosion, management, and native vegetation (Morachan et al. 1972). Several excellent reviews on soil organic matter turnover are available (Kuzyakov and Domanski 2000; West and Post 2002; Wilhelm et al. 2004; Amos and Walters 2006; Causarano et al. 2006; Johnson et al. 2006). These and other papers identified the need to develop complete carbon budgets when estimating SOC maintenance requirements (Arrouays and Pelissier 1994; Collins et al. 1999; Zach et al. 2006; Huggins et al. 2007).

Even though only a small proportion of the non-harvested biomass returned to soil ends up in soil humus, SOC is needed to improve water infiltration rates and reduce erosion. SOC contents can be increased by adding more non-harvested biomass to soil or by slowing the mineralization rate of fresh biomass.

To calculate carbon sequestration potentials, accurate measures of carbon inputs and outputs are needed. Long-term management studies may provide information needed in SOC maintenance calculations (VandenBygaart et al. 2003; McVay et al. 2006; Richter et al. 2007). One of the oldest management studies conducted in the world is the Rothamsted long-term study. Information on this study is available at http://www.rothamsted.bbsrc.ac.uk/resources/LongTermExperiments.html. Links to other long-term studies are available at http://ltse.env.duke.edu/resources/links.

Most historical studies do not contain the detailed information needed to develop carbon budgets. They are also confounded by erosional losses, changes in the chemical methods to measure SOC, management-induced differences in bulk density, and different methods to calculate turnover kinetics. The consequences of these problems are that it is difficult to compare studies and calculate carbon turnover rates. To overcome these problems simplifying assumptions are often used (Clay et al. 2006; Johnson et al. 2006; Bolinder et al. 2007). Assumptions can reduce the usefulness of the findings. This chapter reviews non-isotopic and ^{13}C isotopic approaches for determining SOC maintenance and implications of simplifying assumptions on SOC turnover calculations.

8.2 Carbon Budget

8.2.1 Maintenance Requirements from Incomplete Budgets

In a carbon constrained economy, the ability to accurately predict the impact of agricultural management, climate, and landscape variability on soil carbon rate constants is needed. A number of different approaches have been used to define rate constant. Some approaches define SOC as a single pool while other approaches separate SOC into multiple pools (Coleman and Jenkinson 1996; Clay et al. 2006). Unless a common approach for defining the rate constants is used they cannot be directly compared. Once the rate constants are defined, the impact of a management change can be calculated directly from the data set.

Defining SOC and non-harvested carbon (NHC) mineralization rate constants requires accurate measures of organic carbon inputs, outputs, and a clear mechanistic understanding of the C turnover processes. Obtaining good measures of above-ground biomass is relatively easy and is typically accomplished by weighting the amount of biomass returned or estimating the value from the harvest index. However, obtaining accurate measures of below-ground biomass is very difficult (Kuzyakov and Domanski 2000; Amos and Walters 2006). In the past, nearly all efforts have underestimated below-ground biomass because they do a poor job at measuring small roots, root exudates, and below-ground-biomass-derived CO_2. The ability to predict the consequences of agricultural intensification on long-term soil sustainability is limited by the quality of available data. To maintain SOC it has been estimated that between 2,500 kg biomass C ha^{-1} in Iowa (Larson et al. 1972) and 5,600 kg C ha^{-1} in Minnesota are required (Huggins et al. 1998). These differences may be real or artifacts from the approaches used to estimate the maintenance requirements.

One of the most difficult input values to measure is below-ground biomass. Below-ground biomass consists of the carbon contained in the root biomass, exudated carbon, and respired CO_2 by soil microorganism. Several recent reviews of below-ground biomass are available (Ehleringer et al. 2000; Amos and Walters 2006; Bolinder et al. 2007). These reviews show that extreme variability in root to shoot ratios exists and that all sources of carbon should be included in budget calculations. Different efforts have calculated below-ground biomass differently. For example, Larson et al. (1972) did not include below-ground residues (roots) in their non-harvested biomass calculations, while Huggins et al. (1998) considered below-ground biomass in their calculation. The amounts of roots included in the calculated value impact the maintenance value and the resulting removal estimate.

Field maintenance rate calculations (the NHC level required to maintain SOC levels) are further complicated by above- and below-ground biomass that often have different mineralization rates. Gale and Cambardella (2000) reported that in no-tillage, 75% of the new C incorporated into SOC was root-derived, while a large percentage of surface residue was released as CO_2. Barber and Martin (1976) had similar results and reported that 50% of the root-derived C was retained in SOC while only 13% of shoot-derived C was retained in SOC. Increased retention of root C could be attributed to a variety of factors including: (i) greater biochemical recalcitrance of root biomass; (ii) physical protection of root biomass within aggregates from degradation; (iii) large but unknown amount of exudates and fine roots providing carbon into below-ground systems; (iv) individual carbon sources that may interact to influence net carbon mineralization (Puget and Drinkwater 2001); and (v) lower O_2 concentrations with increasing soil depth that can result in reduced root decomposition. It has been hypothesized that the mineralization of exudates and fine roots may slow down the mineralization of relic SOC and larger roots. Puget and Drinkwater (2001) concluded that shoot residues are broken down quickly, whereas the slow decomposition of root litter is responsible for short-term structural improvements resulting from green manure crops. To predict the consequences of management on SOC, the mineralization kinetics and total amounts of C contained in the different C sources must be known.

8.2.2 Mineralization Kinetics

Once the carbon inputs are known or estimated, several different methods can be used to determine carbon turnover. SOC turnover can be described using zero and first-order kinetics (Paul and Clark 1989). For zero-order kinetics, the temporal change in the substrate concentration ($\delta SOC/\delta t$) is defined by the equation

$$\frac{dSOC}{dt} = -k$$

where k is the rate constant. After integration the equation is written as

$$SOC_t = \mathrm{SOC}_{\mathrm{initial}} - kt$$

where SOC_t is the amount of SOC at time t and $\mathrm{SOC}_{\mathrm{initial}}$ is the amount of SOC at the beginning of the experiment. For zero-order equations, the mean residence time (*MRT*) and half-life ($T_{1/2}$) residence are $MRT = SOC_{\mathrm{initial}}/\mathrm{k}$ and $T_{1/2} = \mathrm{SOC}_{\mathrm{initial}}/(2\mathrm{k})$.

For systems where the mineralization rate is dependent on the substrate concentration, first-order kinetics can be used to describe carbon turnover (Paul and Clark 1989; Six and Jastrow 2002). The first-order rate equation is

$$\frac{dSOC}{dt} = -k \quad SOC$$

which, when integrated, results in the equation

$$SOC_t = SOC_{\mathrm{initial}} e^{-kt}$$

For first-order rate equations, the MRT ($MRT = \frac{1}{k}$) and half-lives can be calculated ($t_{1/2} = \frac{0.696}{k}$). However, these relatively simple equations may not explain the complexity observed in natural systems (Baisden et al. 2002). To solve this problem the CENTURY model (http://www.nrel.colostate.edu/projects/century5/) divides SOC into active, slow, and passive soil carbon pools. The active pool represents microbial biomass with a turnover time of days to years. The slow pool represents more recalcitrant material with turnover times in years to decades. The passive pool is humified carbon stabilized on mineral surfaces with turnover times of hundreds to thousands of years. Each pool has different rate constants and, therefore, different MRT. As rate constants decrease, there is a concomitant increase in MRT. For example, if a pool has an annual rate constant (*k*) of 0.66 g (g year)$^{-1}$, the MRT would be 1.5 years, whereas a pool with *k* of 0.04 g (g year)$^{-1}$ would have an MRT of

25 years. This CENTURY model has been used to assess carbon turnover in a wide range of environments (Parton et al. 1993; Gilmanov et al. 1997).

The Rothamsted Carbon Model (RothC) uses a five pool structure, decomposable plant material (DPM), resistant plant materials (RPM), microbial biomass, humified organic matter, and inert organic matter to assess carbon turnover (Coleman and Jenkinson 1996; Guo et al. 2007). The first four pools decompose by first-order kinetics. The decay rate constants are modified by temperature, soil moisture, and indirectly by clay content. RothC does not include a plant growth sub-module, and therefore NHC inputs must be known, estimated, or calculated by inverse modeling. Skjemstad et al. (2004) tested an approach for populating the different pools based on measured values.

Many scientists have investigated chemical methods to define these pools (Wolf et al. 1994; Olk 2006; Olk and Gregorich 2006; Zimmermann et al. 2007). Zimmermann et al. (2007) reported that there is a good correspondence between extracted soil fractions and the carbon pools used in the RothC model. Olk and Gregorich (2006) stated that “each procedure has its strengths and weaknesses; each is capable to some degree of distinguishing labile SOM fractions from nonlabile fractions for studying soil processes, such as the cycling of a specific soil nutrient or anthropogenic compound, and each is based on an agent for SOM stabilization. Physical fractionations capture the effects on SOM dynamics of the spatial arrangement of primary and secondary organomineral particles in soil, but they do not consider chemical agents for SOM stabilization. They appear better suited for C cycling than N cycling. Chemical fractionations cannot consider the spatial arrangement, but their purely organic fractions that are suitable for advanced chemical characterization and can be used to elucidate molecular-level interactions between SOM and nutrients or other organic compounds. During all fractionations, the potential exists for sample alteration or mixing of material among fractions.” The general conclusion of many studies is that low-density soluble SOC turns over faster (i.e., has a higher k value) than high-density mineral-associated SOC, and hydrolyzable SOC turns over faster than non-hydrolyzable SOC (Martel and Paul 1974; Six and Jastrow 2002).

8.2.3 Non-isotope Approaches for Measuring SOC Maintenance

Many field experiments have relied on non-isotopic techniques for creating carbon budgets. In these experiments, carbon inputs are modified and the temporal changes in SOC are measured (Larson et al. 1972). Based on these changes, SOC maintenance rates are calculated. Maintenance calculations are based on the relational diagram shown in Fig. 8.1. In this diagram, non-harvested crop residues (NHC) represent the annual additions of organic carbon added to soil. A portion of NHC is converted into SOC. The rate constants (k_{NHC} and k_{SOC}) represent the rate that carbon is transformed from NHC into SOC or SOC to CO_2. The relational diagram is used to define several equations. The first equation is $\delta\mathrm{SOC}/\delta t = 0$ at the equilibrium point. For this equation to be true at equilibrium, the amount of NHC

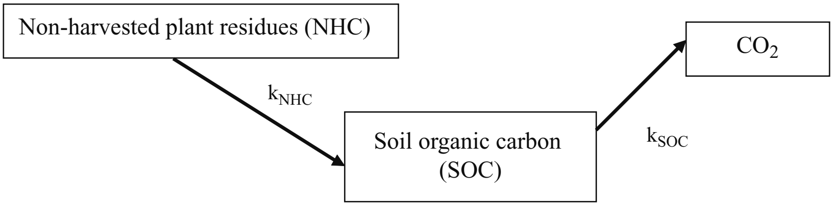

Fig. 8.1 A relational diagram showing the relationship between three carbon pools and the associated rate constants

transformed into SOC is equal to the amount of SOC transformed into CO_2. Mathematically this is expressed as,

$$k_{SOC}\ SOC_e = k_{NHC}\ NHC_m, \tag{8.1}$$

where SOC_e is the amount of SOC at equilibrium, NHC_m is the non-harvested C maintenance requirement (the amount of crop residues that must be returned to maintain current SOC levels), and k_{SOC} and k_{NHC} are first-order rate constants.

If the temporal change in SOC is small (near equilibrium), then the relationship can be defined as

$$\frac{dSOC}{dt} = k_{NHC}\left[NHC_a - NHC_m\right], \tag{8.2}$$

where NHC_a is the amount of non-harvested C applied.

This equation can be rearranged into the form

$$\frac{dSOC}{dt} = k_{NHC}NHC_a - k_{NHC}NHC_m. \tag{8.3}$$

This equation can be converted to a linear equation, $y = mX - b$, by defining dSOC/dt as y, NHC_a as x, and k_{NHC} as m (Fig. 8.2). This derivation provides the theoretical basis for the maintenance requirements reported by Johnson et al. (2006). An important consideration of this derivation is that the y-intercept is the product of the NHC first-order mineralization rate constant (k_{NHC}) and the NHC maintenance (NHC_m) requirement, whereas the slope is the NHC rate constant (k_{NHC}).

Clay et al. (2006) proposed an alternative maintenance calculation approach. This approach was also based on the flow chart shown in Fig. 8.1. The derivation of this approach is as follows. As already defined, the k_{NHC} and k_{SOC} represent the first-order rate constants for the transfer of fresh NHC to SOC and SOC to CO_2, respectively. Based on the flow chart (Fig. 8.1), three equations were identified. The first two equations were described above. The third equation, $NHC_a = NHC_m + (NHC_a - NHC_m)$, is the equality which is used to create the new SOC maintenance equation. The new equation,

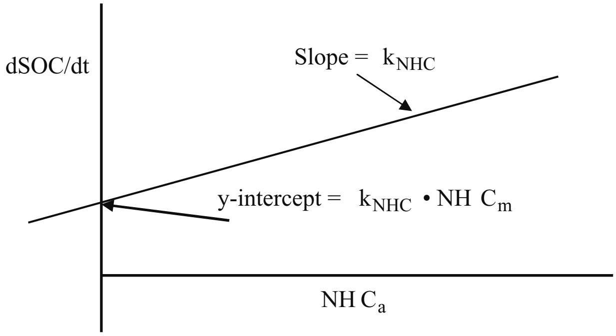

Fig. 8.2 Graphical representation showing the relationship between the change in SOC with time (dSOC/dt) and amount of NHC returned to soil

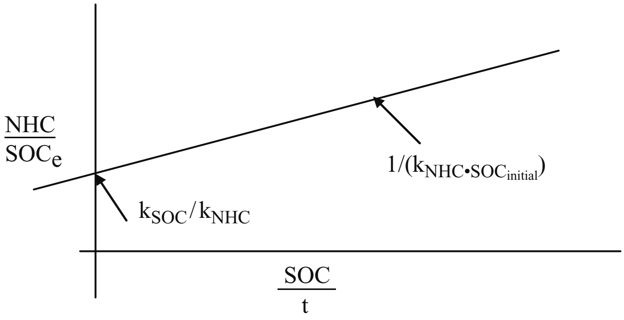

Fig. 8.3 A graphical representation of the maintenance calculations used derived by Clay et al. (2006)

$$\frac{NHC_a}{SOC_e} = \frac{k_{SOC}}{k_{NHC}}\ \frac{SOC_e}{SOC_e} + \left[\frac{dSOC}{dt}\ \frac{1}{k_{NHC}\ SOC_e}\right] \tag{8.4}$$

was developed by replacing (NHC_a – NHC_m) with $\frac{d\mathrm{SOC}}{dt}\ \frac{1}{k_{NHC}}$ and NHC_m with $\frac{k_{soc}}{k_{NHC}}\ SOC_e\cdot$ After dividing both sides by SOC_e and cancelling units, the equation

$$\frac{NHC_a}{SOC_e} = \frac{k_{SOC}}{k_{NHC}} + \frac{dSOC}{dt} + \left[\frac{1}{k_{NHC}\ SOC_e}\right] \tag{8.5}$$

was derived. This equation was solved by defining $SOC_{initial}$ as SOC_e, $\frac{NHC_a}{SOC_{initial}}$ as y, and $\frac{d\mathrm{SOC}}{dt}$ as x (Fig. 8.3). SOC_e was replaced with SOC_i because as time approaches infinity, $SOC_{initial}$ approaches SOC_e. The resulting *y*-intercept is $\frac{k_{SOC}}{k_{NHC}}$ and the slope is $\frac{1}{k_{NHC}\ \ SOC_{initial}}$. Based on these values, maintenance requirement and first order rate constants are determined with the equations,

$$NHC_m = b\ \ SOC_{initial} \tag{8.6}$$

$$k_{NHC} = 1/\left(m\ \ SOC_{initial}\right) \tag{8.7}$$

$$k_{SOC} = b/\left(m\ \ SOC_{initial}\right) \tag{8.8}$$

The advantages of the Clay et al. (2006) approach are that site-specific rate constants are calculated which can be used to calculate the impact of management on carbon turnover (Fig. 8.3). For example, based on Eq. 8.1, if $k_{SOC} = 0.011$, $k_{NHC} = 0.13$, and NHC = 4,000 kg C (ha year)$^{-1}$, then SOC_e is 47,300 kg C ha^{-1} [47,300 = (0.13/0.011)(4,000)]. If NHC is reduced to 2,000 kg C (ha year)$^{-1}$ then SOC will decrease to 23,600 kg ha^{-1}. The disadvantages with the Larson et al. (1972) and Clay et al. (2006) approaches are that they assume that: (1) above- and below-ground biomass make equal contributions to SOC, (2) the amount of below-ground biomass is known; (3) SOC is near the equilibrium point; and (4) the rate constants are constant. Numerous studies have shown that above- and below-ground biomass have different mineralization rate constants (Barber and Martin 1976; Huggins et al. 1998). If below-ground biomass mineralization rate constants are less than above-ground values, then the importance of above-ground values will be overestimated. In addition, accurate measurements of each pool contributing to the total amount of non-harvested biomass are needed. In almost all situations, the amount of below-ground biomass is unknown.

8.2.4 Sensitivity Analysis of the Non-isotopic Approach, Root to Shoot Ratio

Sensitivity analysis of the non-isotopic calculation approaches indicates that the rate constants and maintenance calculations are sensitive to NHC and soil depth (Clay et al. 2005, 2008; Fig. 8.4). The NHC value is the sum of above- and below-C pools. Above-ground biomass is easily measured. However, obtaining "good" measures of below-ground biomass is very difficult (Kuzyakov and Domanski 2000; Amos and Walters 2006). In the past, nearly all efforts have underestimated this value because destructive soil sampling techniques (soil sampling, rinsing, and weighing) do not measure small roots and root exudates. Molina et al. (2001) predicted that 24% of the plant's net fixed carbon was released from the corn plants during the growing

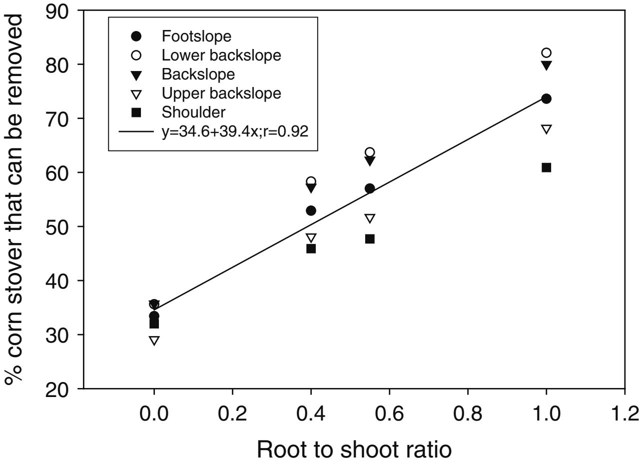

Fig. 8.4 Relationship between root to shoot ratio and the amount of above-ground biomass that can be harvested and still maintain the SOC level at the current level

season. Kuzyakov (2001) reported that about 1/3 of the below-ground carbon was either respired or exudated. Root exudation may actually reduce the mineralization of other carbon sources (Torbert et al. 2000). Efforts to measure root respiration and the impact of root exudates on soil respiration have relied on the measurement of CO_2 released in areas with and without plants. Kuzyakov and Domanski (2000) suggest that approximately half of the below-ground C is incorporated into root tissue, one third is respired by roots and rhizosphere microorganisms, with the remaining one sixth of the carbon incorporated into the soil and microorganisms.

Below-ground biomass is typically estimated from the root to shoot ratio (Johnson et al. 2006; Bolinder et al. 2007). Extreme care must be used when using published root to shoot ratios because different scientists define root to shoot ratios differently. For example, Johnson et al. (2006) defined root to shoot ratios for corn (*Zea mays*) as the ratio between root biomass and total above-ground biomass (grain, stover, and cob), whereas Amos and Walters (2006) defined this value as the ratio between root biomass and corn stover. In addition, a standardized root to shoot ratio has not been used in maintenance calculations. For example, Barber (1978) used a value of 0.17 for corn, Huggins et al. (1998) used a value of 0.53, and Larson et al. (1972) did not consider roots.

Sensitivity analysis showed that the amount of corn stover that could be harvested increased with root to shoot ratio (Fig. 8.4). If roots were not considered in the NHC value, then the estimated amount of above-ground biomass that could be safely harvested was about 35%, whereas if the root to shoot ratio was 1.00 then 70% of the above-ground biomass could be harvested. These findings are attributed to a relative increase in importance of the below-ground biomass. Based on these calculations, underestimating the root to shoot ratio will result in underestimating corn stover removal rates, which, while having a positive influence on future organic matter content of the soil, may cost producers valuable income if above-ground biomass is sold as a commodity.

In addition to highly variable root to shoot ratios (0.01–1.22) the use of these values is complicated by: (1) ratios that are hybrid, variety, and species-specific; and (2) below-ground allocations that are impacted by stress (Hérbert et al. 2001; Bradford et al. 2005; Amos and Walters 2006; Johnson et al. 2006). For example, Johnson et al. (2006) used root to shoot ratios of 0.82, 0.55, and 0.62 for wheat (*Triticum aestivum*), corn, and soybean (*Glycine max*), respectively; whereas Amos and Walters (2006) reported that root to shoot ratios increased with N and P deficiencies and decreased with increasing water stress, population, shade, and soil compaction.

8.2.5 Impact of Initial SOC

Rate constants and turnover calculations are sensitive to the initial data. For example, sensitivity analysis showed that mixing the NHC into a larger amount of soil impacts the calculated rate constants. For example, if only the SOC in the 0–15 cm zone was considered (SOC = 26,750 kg C ha^{-1}) for data from Larson et al. (1972), then k_{NHC} was 0.14 g (g SOC year)$^{-1}$. However, if the 0–30 cm soil zone was considered (SOC = 53,500 kg C ha^{-1}), then k_{NHC} was 0.28 g C (g SOC year)$^{-1}$. In these calculations, increasing the soil depth did not impact k_{SOC}.

Drainage class, tile drainage, soil characteristics, and initial SOC levels can also impact SOC maintenance requirements (Arrouays and Pelissier 1994; Zach et al. 2006; Clay et al. 2007). If the SOC maintenance requirement is related to the SOC level, then the range of values reported by Barber (1978), Wilts et al. (2004), Larson et al. (1972), and Frye and Blevins (1997) may be related to these differences. To assess the impact of SOC level on maintenance requirements, data from Barber (1978), Wilts et al. (2004), Larson et al. (1972), and Frye and Blevins (1997) were analyzed using the Clay et al. (2006) approach (Table 8.1). For these calculations, a common soil depth (0–15 cm) and root to shoot ratios suggested by Johnson et al. (2006) were used. Across the sites, located in the central USA, the analysis suggested that in plowed fields, 15.5% of the SOC contained in the surface 15 cm must be returned annually (Fig. 8.5). The 0–15 cm soil zone was selected because soil data from this zone are available in many studies.

In conservation tillage systems (chisel plow, strip tilled, or no-tillage fields), analysis indicates that the maintenance requirements are less compared with plowed fields (Table 8.1). Differences in C maintenance between the plowed and conservation tillage systems were attributed to the degree of soil disturbance. In Minnesota, the only disturbance was from the planter, whereas in South Dakota, soil disturbance resulted during planting and strip tillage. Differences between the maintenance requirements in the two tillage systems can be used to calculate the impact of tillage on carbon sequestration. For example, based on Eq. 8.1, if NHC is 4,000 kg (ha year)$^{-1}$, k_{NHC} is 0.20 and k_{SOC} in a tilled and no-tilled system are 0.015 and 0.010 g SOC-C (g SOC year)$^{-1}$, respectively; then, SOC$_{\mathrm{e}}$ will be 53,300 and 80,000 kg C ha^{-1}

Table 8.1 The calculated percentages of SOC, using the non-isotopic approach, that must be returned annually to maintain SOC. Root to shoot ratios for corn, soybean, and wheat were identical to the values reported in Johnson et al. (2006). SOC was from the 0–15 cm soil depth

			Landscape		Percentage of	
Location		Tillage	Position/soil	$SOC_{initial}$ (kg SOC ha^{-1})	SOC returned	Reference and notes
Rosemont, MN		No-till		55,600	5.35	Allmaras et al. (2004)
		Chisel			9.41	
		Plow			23.31	
Lafayette	Indiana	Plow		34,900	18.3	Barber (1978)
Morris, MN		Plow		48,400	15.9	Wilts et al. (2004)
Iowa		Plow		26,750	16	Larson et al. (1972)
Kentucky		Plow		28,270	17.7	Frye and Blevins (1997)
Moody, SD		Strip till	Footslope	47,100	9.9	Clay et al. (2005)
			Lower backslope	46,700	9.9	
			Backslope	44,000	9.9	
			Upper backslope	43,600	9.9	
			Shoulder/summit	46,700	9.9	
Colorado	Sterling	No-tillage	Footslope	14,210	8.72	Peterson and Westfall (1997)
			Backslope	12,980	8.26	
			Summit	18,530	8.54	SOC_i estimated from the 0–15 cm depth were calculated by multiplying the 0–5 depth by 2
			Backslope	14,500	9.26	
			Summit	13,570	9.66	
			Footslope	6,180	8.54	
			Summit	16,810	8.04	
Brazil	Southern Brazil	No-tillage/ plowed	Oxisol	40,180	5.4	Sisti et al. (2004)

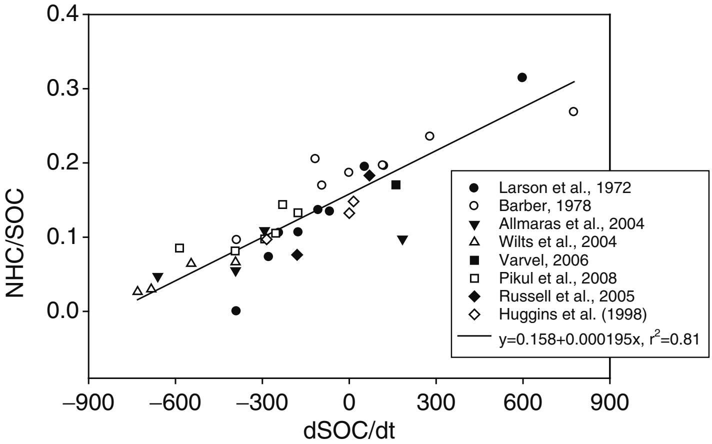

Fig. 8.5 A comparison of data collected from multiple sites analyzed using Clay et al. (2005). Tillage was conducted at all sites. In this plot NHC was non-harvested biomass, SOC was soil organic C, and dSOC/dt was the annual change in soil organic matter resulting from the imposed treatments. Root to shoot ratios was assumed to be 0.55 and the soil depth considered was the 0–15 cm zone

in a tilled and no-tilled system, respectively. The difference in SOC between the tilled and no-tilled SOC values (26,700 kg C ha^{-1}) represents the amount of sequestered carbon in the surface soil by adopting no-tillage. When making these comparisons it is important to consider the assumptions associated with the calculations.

This analysis is conceptually in agreement with reports from numerous tillage experiments (Rochette et al. 1999). West and Post (2002) reported that: (1) changing from conventional to no-tillage sequestered an additional 570 (±140) kg C (ha year)$^{-1}$; and (2) enhancing the rotational complexity, excluding a change in rotation from continuous corn to corn/soybean (*Glycine max*), can also increase carbon sequestration on average 200 (±120) kg C (ha·year)$^{-1}$. Campbell et al. (2005) reported that in unfertilized Great Plains systems, SOC gains were increased with N fertilizer. They also reported that SOC gains were lowest in toe slope areas even though these areas had the highest production. Larson et al. (1972) reported that carbon source (corn versus alfalfa [*Medicago sativa*]) had a minimal impact on SOC accumulation. Causarano et al. (2006) reported that in southeastern USA, no-tillage with cover crops sequestered 670 kg C (ha year)$^{-1}$ (±630) while no-tillage without cover crops sequestered 340 kg (ha·year)$^{-1}$ (±470). Data from an Oxisol soils located in southern Brazil did not show tillage differences (Sisti et al. 2004). In this 13-year study, SOC maintenance rates were approximately 5% or 2,170 kg C ha^{-1} of the 40,180 kg C ha^{-1} contained in the surface 15 cm of soil. This low maintenance requirement was attributed to the SOC content in the oxisol being highly stable.

The amount of carbon stored or sequestered in the soil is also influenced by the soil carbon content (Fig. 8.6). Sensitivity analysis showed that: (1) the carbon sequestration potential is higher in low than high carbon soils; and (2) the net carbon

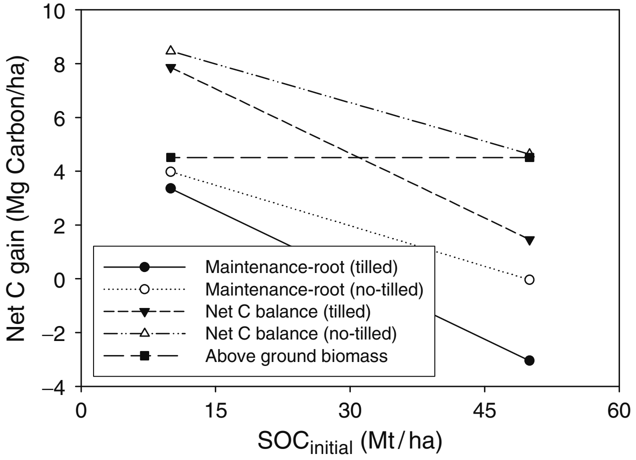

Fig. 8.6 The relationship between initial SOC and the net C balance (stover + roots – maintenance requirement), and relative amount of carbon supplied by the roots (maintenance requirement – root biomass carbon) tilled and no-tilled system. Calculations were based on tilled and no-tilled systems with maintenance requirements of 16% and 10% of the SOC, a 11,270 kg grain ha^{-1} (180 bu $acre^{-1}$), a harvest index of 0.5, a root to shoot ratio of 0.55, and that non-harvested corn stover contained 0.4 g carbon(g $plant)^{-1}$

gain for the maintenance – below-ground biomass value indicates that the amount of non-harvested biomass that can be removed – is influenced by tillage and initial SOC level. At high SOC contents, removing any non-harvested biomass can result in a negative carbon gain (carbon loss).

8.2.6 Tracer Experimental Approaches

Three general isotopic approaches, pulse labeling, continuous labeling, and the ^{13}C natural abundance have been used to assess carbon budgets and below-ground biomass. Techniques using ^{14}C and pulse and continuous labeling techniques are beyond the scope of this chapter and can be found in Goh and Molloy (1979), Goy (1991), Paul et al. (1997), and Kuzyakov and Domanski (2000). The major advantage of isotopic approaches over non-isotopic approaches is that source tracking of individual pools can be conducted and the number of assumptions associated with the maintenance calculations can be reduced.

Of the three approaches, the ^{13}C natural abundance approach is a technique that has been widely used to carbon turnover in production fields. The ^{13}C isotopic approach is based on soil, C_4, and C_3 plants having different $\delta^{13}C$ signatures. The relative amount of below-ground biomass is calculated by multiplying the total amount of SOC at the end of the season times a weighting factor (Balesdent and Mariotti 1996). Kuzyakov and Domanski (2000) concluded that the ^{13}C approach only provided a rough estimate of rhizodeposition because variability of $\delta^{13}C$ in soil and plants is between 1‰ and 2‰. However, successful utilization of the ^{13}C natural abundance by Kuzyakov and Cheng (2001) and Rochette and Flanagan (1997) dispute this claim. It is likely that the ability to use the ^{13}C approach is site-specific. For example, if 2,000 kg C ha^{-1} with a δ^{13}C value of −11.2‰ are added to a soil containing 80,000 kg of carbon with a δ^{13}C value of −17 ‰, then the resulting δ^{13}C value of the soil will be −16.86‰. Some mass spectrometers and experimental techniques do not have the accuracy to measure this small difference (0.14‰). However, if the initial SOC level is 40,000 kg C ha^{-1}, then the difference between treated and untreated soil will be much larger (0.28‰).

8.2.6.1 Root and Soil Respiration

Two general approaches, component integration and whole system analysis have been used for to assess soil and root respiration (Anderson 1982; Hanson et al. 2000; Böstrom et al. 2007). In component integration the net respiration is determined by summing the respiration rates of the individual components (roots, plant residues, and soil). The disadvantage of this approach is the physical separation of these materials and that interactions between components cannot be evaluated.

In whole system analysis, isotopic techniques are used to separate CO_2 into CO_2 derived from the plants or soil (Kuzyakov and Cheng 2001; Kuzyakov and Larionova 2005). When the natural abundance ^{13}C approach is used, soil- and root-derived CO_2 is trapped in a known amount in sodium hydroxide (NaOH). Total soil CO_2 from areas containing plants and non-plant control areas are determined by titration where $SrCl_2$ is used to precipitate the HCO_3^- and CO_3^{-2} as $SrCO_3$. The $SrCO_3$ precipitate is then washed with deionized water, dried, mixed with V_2O_5 (catalyst) and analyzed for δ^{13}C (Kuzyakov and Cheng 2001). To separate CO_2 into CO_2 derived from the soil and plant, reference values for the plant (δ^{13}C value of the most recently expanded) leaf and soil (δ^{13}C value of the no-plant control area) are needed. Using this approach, plant-derived-respired CO_2 (RPC) is calculated with the equation

$$\mathrm{RPC} = \mathrm{f}\left(\text{total CO}_{2\,\text{Plant + soil}}\right) \tag{8.9}$$

where total $CO_{2\ \text{Plant+soil}}$ is the total amount of CO_2 trapped in the soil plus plant system, and f is the percentage of respired carbon from the plant. The fraction f is calculated with the equation

$$f = \left[\frac{d\,^{13}\mathrm{C}_{\text{Plant + Soil CO}_2} - d\,^{13}\mathrm{C}_{\text{soil CO}_2}}{d\,^{13}\mathrm{C}_{\text{plant}} - d\,^{13}\mathrm{C}_{\text{soil CO}_2}}\right] \tag{8.10}$$

where $\delta^{13}\mathrm{C}_{\text{plant+soil CO2}}$ is the δ^{13}C value of the CO_2 containing both soil and plant carbon, $\delta^{13}\mathrm{C}_{\text{plant}}$ is the δ^{13}C value of the plant, and $\delta^{13}\mathrm{C}_{\text{soil CO2}}$ is the δ^{13}C value of CO_2

in an area not containing plants. Several recent reviews of rhizodeposition are available (Kuzyakov and Larionova 2005, 2006; Wichern et al. 2008). Rochette and Flanagan (1997) reported that the ^{13}C natural abundance approach can be used to quantify rhizosphere respiration. Kuzyakov and Cheng (2001) reported that the ^{13}C natural abundance and ^{14}C pulse labeling under controlled laboratory conditions produced similar estimates of root-derived CO_2 over a 7-day period. Based on their measurements, respired root-derived C was 17.3% and 20.6% of the total assimilated C for non-shaded and shaded plants, respectively. Kuzyakov and Larionova (2006) suggested that 40% of the rhizosphere CO_2 efflux is due to root respiration and about 60% of this efflux is due to decomposing root exudates.

Several alternative approaches for separating CO_2 into different components are available in Cheng et al. (2005) and Böstrom et al. (2007). These approaches often include collecting soil samples from fields and separating them into different depth increments and analyzing the resulting CO_2 directly on a GC/MS (Böstrom et al. 2007) or using buried root chambers (Cheng et al. 2005).

The kinetics and timing of rhizodeposition are largely unknown. Melnitchouck et al. (2005) used a pyrolysis-field ionization mass spectrometer tool to show that day and night rhizodeposits of C, N, and S concentrations were 3–9.7 times larger than samples from non-cropped soil. They concluded that the diurnal dynamics in the molecular-chemical composition between day- and night-rhizodeposits resulted from the exudation of carbohydrates and amino acids during the photosynthetic period, the deposition of other root-derived compounds such as lipids, suberin, and fatty acids, and microbial metabolism of all available organic compounds in the rhizosphere.

8.2.7 ^{13}C Isotopic Natural Abundance Techniques, Plant Carbon in Soil

The ^{13}C isotopic natural abundance C-budget approach can be used to determine the amount of NHC remaining in soil, SOC half-lives, and SOC turnover because relic SOC and new plant material additions have different isotopic values. When making these calculations, it is important to consider that above-ground and below-ground carbon inputs may have different isotopic signatures. For example, plant roots are often ^{13}C-enriched compared to plant leaves (Badeck et al. 2005; Bowling et al. 2008). Furthermore, mycorrhizal fungi are frequently ^{13}C-enriched compared to host plant leaves, probably because mycorrhizal fungi receive ^{13}C-enriched carbon from host plant (Böstrom et al. 2008).

An important benefit of the isotopic approach is that below-ground biomass values are not required. The ^{13}C natural abundance isotopic carbon budget approach is based on C_3 plants having lower δ^{13}C value than C_4 plants (Ehleringer 1991; Clay et al. 2006) and that the signatures can be tracked by placing C_3 plant residue into a soil derived from C_4 plants or vice versa. In these calculations, several definitions are needed. These definitions include

$$R = {}^{13}\mathrm{C} / {}^{12}\mathrm{C} \tag{8.11}$$

$$\delta^{13}\mathrm{C} = [\mathrm{R(sample)/R(standard)-1}] \times 1000\% \tag{8.12}$$

where ^{13}C and ^{12}C are the amounts of ^{13}C and ^{12}C contained in the sample and standard. By international convention, δ^{13}C is always expressed relative to PDB $CaCO_3$ standard. This standard was a limestone fossil of *Belamnitella Americana* for the Cretaceous Pee Dee formation in South Carolina. It has been assigned the δ^{13}C value of 0‰ and has been reported to have an *R* value of 0.0112372 (Craig 1957). Using mass balance relationships, the δ^{13}C values in a soil sample and total carbon in soil can be defined by the equations,

$$\delta^{13}C_{soil\ final} = \frac{\left[PCR_{incorp}\left(\delta^{13}C_{PCR}\right) + SOC_{retained}\left(\delta^{13}C_{SOC\ retained}\right)\right]}{\left(PCR_{incorp} + SOC_{retained}\right)} \tag{8.13}$$

$$\mathrm{SOC_{final}} = \mathrm{PCR_{incorp}} + \mathrm{SOC_{retained}}, \text{ and} \tag{8.14}$$

$$\mathrm{SOC_{initial}} = \mathrm{SOC_{retained}} + \mathrm{SOC_{lost}} \tag{8.15}$$

In these equations $SOC_{initial}$ is the SOC in the soil at the beginning of the experiment, SOC_{final} is SOC at the end of the study, $\delta^{13}C_{soil\ final}$ is the δ^{13}C value of SOC when the experiment was completed, PCR_{incorp} is the new plant carbon incorporated into SOC, $\delta^{13}C_{PCR}$ is the δ^{13}C value of the plant material retained in the soil after mineralization, $SOC_{retained}$ is the amount of relic C ($SOC_{initial}$) retained in the soil at the end of the study, and $\delta^{13}C_{SOC\ retained}$ is the associated δ^{13}C value. By simultaneously solving Eqs. 8.13 and 8.14 the equations

$$SOC_{retained} = \frac{\left[SOC_{final}\left(\delta^{13}C_{soil\ final} - \delta^{13}C_{PCR}\right)\right]}{\left(\delta^{13}C_{SOC\ retained} - \delta^{13}C_{PCR}\right)}, \text{ and} \tag{8.16}$$

$$PCR_{incorp} = \frac{SOC_{final}\left(\delta^{13}C_{soil\ final} - \delta^{13}C_{SOC\ retained}\right)}{\left(\delta^{13}C_{PCR} - \delta^{13}C_{SOC\ retained}\right)} \tag{8.17}$$

are derived. If it is assumed that ^{13}C fractionation during SOC and PCR mineralization is minimal, i.e., $\delta^{13}C_{SOC\ retained} = \delta^{13}C_{soil\ initial}$ and $\delta^{13}C_{PCR} = \delta^{13}C_{plant}$, then the PCR_{incorp} equation can be simplified into the expression

$$PCR_{incorp} = \frac{SOC_{final}\left(\delta^{13}C_{soil\ final} - \delta^{13}C_{soil\ initial}\right)}{\left(\delta^{13}C_{plant} - \delta^{13}C_{soil\ initial}\right)} \tag{8.18}$$

This equation can be solved if soil and plant material collected at time zero ($\delta^{13}C_{\text{soil initial}}$ and $\delta^{13}C_{\text{plant}}$) and soil collected at the end of the experiment are analyzed for total C and $\delta^{13}C$ (SOC_{final} and $\delta^{13}C_{\text{soil final}}$). The PCR_{incorp} equation can be reorganized into the equation

$$\frac{PCR_{incorp}}{SOC_{final}} = \frac{\left(\delta^{13}C_{soil\,final} - \delta^{13}C_{soil\,initial}\right)}{\left(\delta^{13}C_{plant} - \delta^{13}C_{soil\,initial}\right)} \tag{8.19}$$

where the ratio between PCR_{incorp} and SOC_{final} was the relative proportion (p) of new C incorporated in SOC ($p = PCR_{\text{incorp}}/SOC_{\text{final}}$). By replacing $\delta^{13}C_{\text{soil initial}}$ with δ_{c3}, $\delta^{13}C_{\text{plant}}$ with δ_{c4}, and $\delta^{13}C_{\text{soil final}}$ with δ the equations

$$p = \frac{\delta - \delta_{c3}}{\delta_{c4} - \delta_{c3}} \tag{8.20}$$

$$\delta = p\,\delta_{c4} - (1\text{-}p)\delta_{c3} \tag{8.21}$$

reported in Wolf et al. (1994) were derived. The p and δ equations are based on the assumption that ^{13}C discrimination during SOC and non-harvested biomass mineralization is minimal. This equation is similar to Eq. 8.10 reported above. Equation 8.20 has been used in numerous papers to calculate the percentage of C derived from C_3 and C_4 plants (Balesdent et al. 1988; Follett et al. 1997; Huggins et al. 1998; Collins et al. 1999; Clapp et al. 2000; Allmaras et al. 2004; Clay et al. 2005; Zach et al. 2006). However, extreme care must be used when applying these equations because the assumption that ^{13}C fractionation during SOC and PCR mineralization is insignificant may not be valid for many soils (Stout et al. 1981; Ehleringer et al. 2000; Clay et al. 2007).

Clay et al. (2007) tested the assumption that ^{13}C enrichment during SOC and fresh biomass mineralization did not impact calculated carbon turnover. They showed that ^{13}C enrichment during SOC mineralization occurred during mineralization but did not occur during fresh biomass mineralization. In this analysis, SOC contained in the surface 30 cm of fallowed soil at a Minnesota site decreased from 90.8 to 73.2 Mg ha^{-1} over a 22-year period. Associated with this decrease was a 0.72‰ increase in the soil $\delta^{13}C$ value (from −18.97 to −18.25‰). At the South Dakota site, SOC decreased 10% (2.8 ± 1.8 g kg^{-1}) and $\delta^{13}C$ increased 3.2% (0.548 ± 0.332 ‰) over a 5-year period. Nadelhoffer and Fry (1988) had similar results and reported that $\delta^{13}C$ value of bulk soil organic matter from forest mineral soils increased up to 0.5‰ over a 600-day period. Balesdent and Mariotti (1996) reported that over a 60-year period in an experiment initiated in 1928 at Versailles, France, relic SOC decreased 60% and $\delta^{13}C$ increased 1.6‰ at sites kept free of vegetation. The vegetation change from the C_3 plant wheat to the C_4 plant maize has added naturally ^{13}C-enriched material to the soil (Gleixner et al. 1999, 2002). Ueda et al. (2005) reported that $\delta\ ^{13}C$ of SOM values increased with depth in forest tropical soils. The enrichment of relic C with depth and time has been attributed to respired CO_2 from soil microorganisms being depleted in ^{13}C (DeNiro and Epstein 1978; Ågren et al. 1996; Šantrůčková et al. 2000; Ekblad et al. 2002; Böstrom et al. 2007; Bowling et al. 2008). Furthermore, mycorrhizal fungi were ^{13}C-enriched compared with plant materials (Böstrom et al. 2008).

Different results have been observed for fresh biomass. Clay et al. (2007) reported that the δ^{13}C values of corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) residues remained unchanged after 4 months. Balesdent and Mariotti (1996) had similar results and reported that the δ^{13}C value of the initial corn biomass did not change after 85% of the biomass had been mineralized. Cleveland et al. (2004) reported that the δ^{13}C signatures of dissolved organic matter (DOM) did not change during decomposition. Griebler et al. (2004) reported that ^{13}C fractionation of trichlorobenzene during mineralization was not observed under aerobic conditions but was observed under anaerobic conditions. Boutton (1996) in a review of isotopic ratios of SOC as indicators of change stated that "direct measurements indicate that the $\delta^{13}C_{PDB}$ of plant tissue remains relatively constant during the early stages of decomposition (1–7 years)." Fernandez and Cadisch (2003) reported that, over time, fractionation may even out, with microbes discriminating against ^{13}C (relative to the initial label) during early stages followed by a period of time when microbes discriminate against ^{12}C (relative to the initial label).

The apparent lack of ^{13}C enrichment during the early stages of non-harvested biomass mineralization may result from two independent processes cancelling each other out. The first factor is that many SOC consumers tend to accumulate ^{13}C. The second factor is that materials that are resistant to microbial degradation (waxes and lignin) tend to be depleted in ^{13}C (Lichtfouse et al. 1995; Boutton 1996; Huang et al. 1999; Conte et al. 2003). These data suggest that ^{13}C fractionation during SOC mineralization occurs and therefore this assumption should not be accepted without testing. In systems where C_4 residue is applied to soil derived from C_4 and C_3 plants, Clay et al. (2007) showed that the half-life increased when ^{13}C fractionation during relic carbon mineralization was considered. For C_3 plants, the reverse was true.

Clay et al. (2006) proposed an approach to account for isotopic discrimination that occurs during relic carbon mineralization. This approach is based on the equation

$$\delta^{13}C_{\text{SOCretained}} = \delta^{13}C_{\text{soil initial}} + \varepsilon_{\text{SOC}} \ln\left(\text{SOC}_{\text{retained}} / \text{SOC}_{\text{initial}}\right) \tag{8.22}$$

where ε was the Rayleigh fractionation constant. If fractionation occurs during fresh biomass mineralization, a similar equation can be used. The Rayleigh fractionation constant of the SOC (ε_{SOC}) is calculated from plots where plant growth is prevented. The Rayleigh equation has been used to explain isotopic fractionation in a variety of biological systems (Balesdent and Mariotti 1996; Accoe et al. 2002; Fukada et al. 2003; Spence et al. 2005; Wynn et al. 2005). The amount of ^{13}C fractionation and the selection of the model to predict fraction (Eq. 8.22) that occurs may be a function of soil texture. Wynn et al. (2005) reported that different models describing ^{13}C accumulation may be needed in coarse- and fine-textured soils. Once the fractionation is identified, carbon budgets are determined using appropriate equations. In Clay et al. (2006) the equations were

$$\delta^{13}C_{\text{SOC retained}} = \delta^{13}C_{\text{soil initial}} + \varepsilon_{\text{SOC}} \ln\left(\text{SOC}_{\text{retained}} / \text{SOC}_{\text{initial}}\right) \tag{8.23}$$

$$\text{SOC}_{\text{initial}} = \text{SOC}_{\text{retained}} + \text{SOC}_{\text{lost}} \tag{8.24}$$

$$SOC_{retained} = \frac{\left[SOC_{final}\left(\delta^{13}C_{soil\ final} - \delta^{13}C_{PCR}\right)\right]}{\left(\delta^{13}C_{SOC\ retained} - \delta^{13}C_{PCR}\right)} \tag{8.25}$$

After the pool sizes are determined, the first-order rate constant (*k*), half-life, and MRT can be determined using the equations

$$k = -\frac{ln\left(SOC_{remaining} / SOC_{initial}\right)}{number\ of\ years} \tag{8.26}$$

$$t_{half-life} = -\frac{\ln(0.5)}{k} \tag{8.27}$$

$$\text{Mean residence time} = \frac{1}{k} \tag{8.28}$$

This approach was used to recalculate the half-lives for a field study. These calculations showed that considering ^{13}C enrichment during SOC mineralization almost doubled the calculated half-lives of SOC when C_4 material was added to a soil derived from C_3 grasses. An alternative solution to direct measurement of ^{13}C isotopic fractionation is to use a simulation model, such as CENTURY to estimate ^{13}C fractionation. The CENTURY model was calibrated to give a slight increase in the delta ^{13}C value for the total soil organic matter relative to the vegetation (http://www.nrel.colostate.edu/projects/century5/).

The stable isotopic approach can be used to develop carbon budgets for individual sampling points in fields and can be used to develop contour maps (Fig. 8.7). These contour maps visualize the relationships between landscape position and potential carbon storage. In this budget, less new carbon was incorporated into summit shoulder

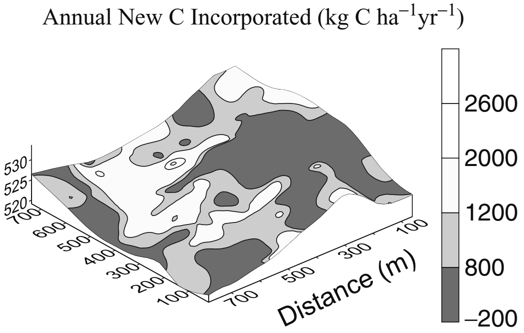

Fig. 8.7 Landscape position influence on annual carbon additions from 1995 to 2003 (Clay et al. 2005)

Table 8.2 The influence of landscape position and ^{13}C fractionation on calculated half-lives of SOC at the Moody field (Modified from Clay et al. 2007)

	13 Fraction considered	
Landscape position	No (years)	Yes (years)
Footslope	49.8	89.1
Lower backslope	56.1	87.8
Backslope	113.1	232
Upper backslope	181	341
Shoulder/summit	78.9	151

areas than footslope areas. These results were attributed to less biomass being produced in the summit than the footslope area. Similar contour maps can be developed for mineralized carbon and the amount of relic carbon remaining in the soil after mineralization. Based on these maps, the data can be aggregated into landscape positions (Table 8.2) and management recommendations can be implemented.

8.2.8 Combining Traditional and Isotopic Measure to Develop C Budgets

Allmaras et al. (2004) developed a C-budgeting approach based on combining experimental and isotopic techniques. The data needed to use calculations derived by Allmaras et al. (2004) required that the experiment contain corn stover harvested and removed treatments. These calculations assume that the removal of above-ground biomass will not influence the sequestering of below-ground biomass. The SOC derived from corn stover (^{s}SOC) is calculated with the equation:

$$^{s}\mathrm{SOC} = \mathrm{SOCr} - \mathrm{SOCh} \tag{8.29}$$

where SOCr was the total corn-derived C in the residue returned treatment and SOCh was corn derived from unharvested material (exudates, roots, and crown) in the stover harvested treatment. The SOCr and SOCh values were calculated by multiplying the *f* value (Eq. 8.20) times the SOC values from the residue returned (SOCr) and harvested (SOCh) plots. This approach requires that ^{13}C isotopic discrimination (Δ) and total SOC at the end of the experiment be measured. Based on this analysis, Allmaras et al. (2004) concluded that harvesting above-ground corn residue over a 13-year period reduced SOC carbon derived from corn by 35%, and that to manage the entire C cycle, roots and rhizodeposition must be considered.

An alternative approach is to combine models with field measurements to assist in developing carbon budgets (Huggins et al. 1998). Clay et al. (2005) used first-order models to calculate the amount of residue returned to the soil from C_3 and C_4 plants over an 8-year period. Based on the mineralization rates and when the C_3 and C_4 residues were returned, the δ^{13}C signature of non-harvested biomass was determined. Based on the rates, carbon turnover, the amount of SOC mineralized, and the amount of fresh biomass incorporated into the SOC over an 8-year period were determined.

8.3 Summary

Even though sensitivity analysis of carbon budget maintenance equations shows that below-ground biomass estimates influence SOC maintenance rate calculations, most experiments do a poor job at estimating below-ground biomass. To overcome this problem simplifying assumptions are accepted. In most situations, the impact of these assumptions on the recommendations is not tested. The minimum data required to estimate SOC maintenance requirements are $\mathrm{SOC}_{\mathrm{initial}}$, $\mathrm{SOC}_{\mathrm{final}}$, and the amount of NHC returned to the soil during the study period. This minimum data set is not available for most studies.

Many experiments are conducted on a specific soil and do not consider how landscape position impacts carbon turnover. The few studies that have been conducted show that landscape position has a large impact on carbon turnover (Fig. 8.7). Campbell et al. (2005) reported that in Colorado, soil organic C gains increased with cropping intensity and tended to be the highest in the lowest evaporation sites and least in the toe slope area. Footslope areas generally have higher turnover rates than summit shoulder areas (Campbell et al. 2005; Clay et al. 2005; Soon and Malhi 2005). Soon and Malhi (2005) reported that the timing of the mineralization may also be impacted by landscape position. In the upper landscape positions, N mineralization was suppressed. Landscape differences can result from two interrelated factors, higher soil water contents, and amount of SOC in footslope than summit/shoulder areas (Clay et al. 2001).

Carbon turnover in production fields can be determined, using non-isotopic techniques, by combining historical soil samples, current soil samples, and whole field yield monitor data. Sensitivity analysis of such data shows that the amount of above-ground biomass that could be harvested decreases with root to shoot ratio (Table 8.1). For example, if root biomass is ignored, analysis suggests that only 20–30% of the above-ground biomass can be harvested, whereas if the root to shoot ratio is 1.0, then between 40% and 70% of the residue could be harvested.

The impact of the root to shoot ratios on calculated maintenance requirements is important because root to shoot ratios are highly variable and almost always underestimate below-ground biomass. Amos and Walters (2006) reported that the net below-ground C deposition in corn at physiological maturity was 29% ± 13% of the shoot biomass (leaves, stems, and husks) in 41 studies. The use of these values is further complicated by the use of different definitions for root to shoot ratio. Converting Amos and Walters (2006) units to units used by Johnson et al. (2006) would reduce the reported values from 0.29 to 0.15 (harvest index 50%).

8.3.1 Recommendations for Estimating Soil Organic Matter Turnover

To accurately measure soil organic matter turnover, several critical measurements are required. First, accurate SOC values must be determined at the beginning and end of the experiment. In addition, soil samples for bulk density must be taken. Second, above-ground biomass returned to the soil must be measured. Third, an understanding of the relationship between above- and below-ground biomass is needed to estimate below-ground biomass. Fourth, if ^{13}C isotopic approaches are being utilized, then no-plant control areas should be integrated into the experimental protocol. These plots are used to get an estimate of ^{13}C enrichment of the relic carbon during the experimental timeframe. To determine carbon budgets using ^{13}C isotopic techniques several equations need to be solved simultaneously.

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Chapter 9
Soil Solarization and Sustainable Agriculture

Trifone D'Addabbo, Vito Miccolis, Martino Basile, and Vincenzo Candido

Abstract Pesticide treatments provide an effective control of soilborne pests in vegetable and fruit crops, but their toxicity to animals and people and residual toxicity in plants and soil, and high cost make their use hazardous and economically expensive. Moreover, actual environmental legislation is imposing severe restrictions on the use or the total withdrawal of most soil-applied pesticides. Therefore, an increasing emphasis has been placed on the use of nonchemical or pesticide-reduced control methods. Soil solarization is a nonpesticidal technique which kills a wide range of soil pathogens, nematodes, and weed seeds and seedlings through the high soil temperatures raised by placing plastic sheets on moist soil during periods of high ambient temperature. Direct thermal inactivation of target organisms was found to be the most important mechanism of solarization biocidal effect, contributed also by a heat-induced release of toxic volatile compounds and a shift of soil microflora to microorganisms antagonist of plant pathogens. Soil temperature and moisture are critical variables in solarization thermal effect, though the role of plastic film is also fundamental for the solarizing process, as it should increase soil temperature by allowing the passage of solar radiation while reducing energetic radiative and convective losses. Best solarizing properties were shown by low-density or vynilacetate-coextruded polyethylene formulations, but a wide range of plastic materials were documented as also suitable to soil solarization. Solar heating was normally reported to improve soil structure and increase soil content of soluble nutrients, particularly dissolved organic matter, inorganic nitrogen forms, and available cations, and shift composition and richness of soil microbial communities, with a marked increase of plant growth beneficial, plant pathogen antagonistic or root quick recolonizer microorganisms. As a consequence of these effects, soil solarization was largely documented to increase plant growth and crop yield and quality along more

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T. D'Addabbo (✉) and M. Basile
Istituto per la Protezione delle Piante, CNR, Via G. Amendola, 122/D, 70126, Bari, Italy
e-mail: t.daddabbo@ba.ipp.cnr.it

V. Miccolis and V. Candido
Dipartimento di Scienze dei Sistemi Colturali, Forestali e dell'Ambiente – Università della Basilicata, Via dell'Ateneo Lucano, 10, 85100, Potenza, Italy

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than two crop cycles. Most important fungal plant pathogenic species were found strongly suppressed by the solarizing treatment, as several studies documented an almost complete eradication of economically relevant pathogens, such as *Fusarium* spp., *Phytophthora* spp., *Pythium* spp., *Sclerotium* spp., *Verticillium* spp., and their related diseases in many vegetable and fruit crops and in different experimental conditions. Beneficial effects on fungal pathogens were stated to commonly last for about two growing seasons and also longer. Soil solarization demonstrated to be effective for the control of bacterial diseases caused by *Agrobacterium* spp., *Clavibacter michiganensis* and *Erwinia amylovora*, but failed to reduce incidence of tomato diseases caused by *Pseudomonas solanacearum*. Solarization was generally found less effective on phytoparasitic nematodes than on other organisms, due to their quicker soil recolonization compared to fungal pathogens and weeds, but field and greenhouse studies documented consistant reductions of root-knot severity and population densities of root-knot nematodes, *Meloidogyne* spp., as well as a satisfactory control of cyst-nematode species, such as *Globodera rostochiensis* and *Heterodera carotae*, and bulb nematode *Ditylenchus dipsaci*. Weeds were variously affected by solar heating, as annual species were generally found almost completely suppressed and perennial species more difficult to control, due to the occurrence deep propagules not exposed to lethal temperature. Residual effect of solarization on weeds was found much more pronounced than on nematodes and most fungal pathogens. Soil solarization may be perfect fit for all situations in which use of pesticides is restricted or completely banned, such as in organic production, or in farms located next to urban areas, or specialty crops with few labeled pesticides. Advantages of solarization also include economic convenience, as demonstrated by many comparative benefit/cost analyses, ease of use by growers, adaptability to many cropping systems, and a full integration with other control tools, which makes this technique perfectly compatible with principles of integrated pest management required by sustainable agriculture.

Keywords Alternatives • Integrated management • Nematodes • Soil solarization • Soilborne pathogens • Weeds

9.1 Introduction

Soil-applied pesticides have been successfully used to control soilborne diseases, weeds, and nematodes in most vegetable and fruit crops over the past decades. Toxicity of these materials to animals and humans and their environmental and economic costs (Pimentel et al. 1992; Ruzo 2006) raised serious environmental and human safety concerns, leading to the phase-out of the most effective and largely used chemical, the methyl bromide (Luken and Grof 2006), and the increasing restrictions on the applications of available pesticides (Perkins and Patterson 1997). The limited availability of chemicals resulted in an increased emphasis on reduced-pesticide or nonpesticidal control methods and, therefore, renewed the interest of farmers and researchers on soil solarization as a simple, environmentally safe, and effective nonchemical control tool.

Mulching soil with plastic films was known since the early 1960s of the past century as an agronomical technique to reduce soil water evaporation and erosion and improve soil physical properties (Waggoner et al. 1960; Burrows and Larson 1962; Lai 1974), whereas control of soil and plant material disease agents by the use of heat, also generated by solar energy, was reported still earlier (Grooshevoy 1939; Newhall 1955). However, soil solarization as actually meant, namely, a technology for soil disinfestation from soilborne pathogens and weeds, originated during the 1970s from the studies conducted in Israel and Jordan (Katan et al. 1976). In the first decade following the publication of Katan et al., a large number of studies focused on the effectiveness of solarization against many soilborne pathogens, weeds, and soil arthropods in many vegetable, field, ornamental, and fruit tree crops. Physical, chemical, and biological principles of solarization and collateral biological, chemical, and physical changes occurring in the soil during and after the solarization process were also largely investigated (Katan et al. 1987; DeVay 1991) (Fig. 9.1). Most of these solarization studies were undertaken in the mediterranean and Middle East countries, namely, Israel (Grinstein and Ausher 1991), Italy (Garibaldi and Gullino 1991), Spain (Bello et al. 2001), Greece (Tjamos et al. 2000), and California (Stapleton and DeVay. 1986), but many reports originated also from many other countries, including also cooler climate areas (Garibaldi and Tamietti 1984). Moreover, trials involved either field or greenhouse cropping systems and were also successfully extended to the disinfestation of seedbeds,

Fig. 9.1 Plots solarized with a polyethilene plastic film in a field solarization trial in Southern Italy (courtesy of dr Nicola Greco)

containerized planting media, and cold frames (Stapleton 2000). Due to the increasing success of concepts of integrated management of agricultural pests (Kogan 1998), research of the following decades generally regarded at solarization as a component of more complex control strategies rather than as a stand-alone technique (Stapleton and DeVay 1995; Chellemi 1998), with the aim to improve the effect of solar heating treatment and overcome its technical and economical limits through the combination with other control methods (Sikora et al. 2005).

Soil solarization can easily be described as a process in which the solar radiation is trapped under a plastic soil mulch during periods of high ambient temperature, causing an increase of temperatures in the upper soil layers to levels lethal or sublethal to soilborne pathogens and weeds. Despite the apparently simple technology, research evidenciated as the effects of soil solarization result from different and complex mechanisms and are affected by a great number of environmental and technical factors, primarily soil temperatures and type of plastic films. Moreover, in addition to soilborne pathogens and pests control, a set of physical, chemical, and biological changes were documented to be raised by solarization in the soil, as influencing soil physical and chemical properties and crop yield.

The aim of this chapter is to provide, according to literature available up to the early months of 2008, an up-to-date review of the above aspects of soil solarization, from the mechanisms and related factors to the effects on different target organisms and soil properties. Moreover, as integrated pest management is a fundament of sustainable agriculture, studies on the potential integration of solarization with other control tools were also largely documented.

9.2 Mechanisms of Solarization

Numerous and complex mechanisms are reported in literature for soil solarization effects, involving also the combination of several interrelated processes (Katan 1987; Stapleton and DeVay 1995; Stapleton 1997), but main effects of solarization treatments were found related essentially to the thermal action of solarization and the consequent chemical and biological changes occurring in the soil.

9.2.1 Thermal Mechanism

Solarization process increases soil temperatures up to levels lethal to many plant pathogens and pests and, therefore, direct thermal inactivation is the most important and normally expected mechanism. Some studies on the biochemical bases of sensitivity of organisms to high temperatures hypothesized that heat sensitivity is related to small differences in cell macromolecules, leading to a lethal increase of intra-molecular hydrogen, ionic, and disulfide bonds (Brock 1978). Sundarum (1986) suggested a reduced cell membrane function beyond an upper limit fluidity exceeded by high temperatures, concluding that mesophylic organisms, including soilborne pathogens and pests, are more sensitive to high temperatures due to the presence of low-melting-point unsaturated lipids in cell membranes, whereas thermotolerant and haemophilic soilborne organisms survive soil solarization due to macromolecules stability at temperatures up to 60°C. Heat inactivation of respiratory enzymes was found by the same authors as a further cause for thermal decline of soilborne microorganisms and weed seeds (Brock 1978; Sundarum 1986).

Pullman et al. (1981) described the thermal effect of solarization on microorganisms and weeds as a function of a logarithmic inverse relationship, changing for the different target organisms, between soil temperature and exposure time. Damage thermal thresholds were found to begin around 39–40°C for most mesophilic soil organisms, whereas temperatures normally achieved during solarization treatment were survived by thermophilic and thermotolerant organisms (Stapleton and DeVay 1995). Thermal inactivation thresholds have been experimentally calculated for a number of important plant pathogenic fungi, nematodes, and weeds. Under laboratory conditions, Porter and Merriman (1983) found that a variety of fungal pathogens, viz. *Fusarium oxysporum* Schltdl., *Pythium irregulare* Buisman, *Plasmodiophora brassicae* Woron, *Sclerotium cepivorum* Berk, *S. rolfsii* Sacc, *Sclerotinia minor* Jagger, *Verticillium dahliae* Kleb., were killed by temperatures within the range 38–55°C, with the lowest sensitivity for *F. oxysporum*, *P. irregulare*, and *P. brassicae*, whereas *V. dahliae*, *S. cepivorum*, and *S. minor* were the most sensitive species. The ED_{90} of *V. dahliae* was about 14 h at 37°C and reduced to about 9 min at 50°C (Pullman et al. 1981a), whereas *Rosellinia necatrix* Berl. ex Prill. (syn. *Dematophora necatrix* R. Hartig) was found highly heat-sensitive, as 50–100% mortality was recorded after 4 h at 38°C (Sztejnberg et al. 1987). *Phytophtora cinnamomi* Rands, *P. cactorum* (Lebert and Cohn) Schrot, and *P. megasperma* Drechsler were killed within 20, 30, and 30 min, respectively, in soil exposed at 45°C (Juarez-Palacios et al. 1991), whereas thermal death of fungal mycelium of *P. cinnamomi* was reported after 1–2 h at 38–40°C (Gallo et al. 2007). In other experiments, chlamydospores of *P. cinnamomi* were killed after only 30 min when directly suspended in water at 38°C (Barbercheck and von Broembsen 1986), or after a 25 min immersion in water at 41°C of infested wheat (*Triticum aestivum* L.) grains (Theron et al. 1982), suggesting that water was probably a more effective heat conveyor than either soil or agar (Benson 1978; Coelho et al. 2001). Other soilborne pathogenic fungi, such as *Macrophomina phaseolina* (Tassie) Goid and *Pythium aphanidermatum* (Edson) Fitzp., showed a lower heat sensitivity, as in soils with a high moisture content microsclerotia of *M. phaseolina* strongly declined within 24 h at 40°C, but were completely inactivated only at 50°C or higher (Mihail and Alcorn 1984; Sheikh and Ghaffar 1987).

Pullman et al. (1981a) reported a gradual accumulation of heat damage by the application of progressive time and temperature levels, up to complete fungal inactivation, suggesting that detrimental effects may be caused to target organisms also by sublethal thermal doses. Heat shock proteins involved in the acquisition of thermotolerance or thermostability were found to be produced by fungal cells during sublethal heating (Plesofsky-vig and Brambl 1985; Lindquist 1986; Freeman et al. 1989). Sublethal temperatures may damage fungal pathogens, reducing germinability and aggressiveness of their propagules and increasing vulnerability to other biotic or abiotic agents (Freeman and Katan 1988; DeVay and Katan 1991). Sclerotia of *S. rolfsii* weakened by sublethal heating were found intensely colonized by *Trichoderma rolfsii* Rifai and other microorganisms (Lifshitz et al. 1983; Greenberger et al. 1984). Under laboratory conditions, vulnerability of propagules of *R. necatrix* to colonization by *Trichoderma* spp. was highly increased after an exposure to sublethal temperatures (Sztejnberg et al. 1987), whereas field tests showed that sublethal heating caused by a short solarization effectively controlled *S. rolfsii*, *F. oxysporum* f. sp. *basilici* (Dzidzariya) Armstr. & Armstr., *F. oxysporum* f. sp. *melonis* W.C. Snyd. and Hans., and *F. oxysporum* f. sp. *radicis-lycopersici* Jarv. and Shoem. when combined with reduced doses of methyl bromide or metham sodium (Eshel et al. 2000). Detrimental effect of sublethal temperatures on soil-borne pathogens was also suggested to explain the higher suppressiveness often observed in solarized soils (Greenberger et al. 1987).

Prolonged permanence at temperatures above 35°C were also found to be lethal to phytoparasitic nematodes or to reduce their infectivity and to increase their biotic and abiotic stresses vulnerability (Heald and Robinson 1987), though thermal effect of solarization on nematodes was stated as strictly species-related (Greco et al. 1998; D'Addabbo et al. 2005). Giblin-Davis and Verkade (1988) reported the death of *Belonolaimus longicaudatus* Rau and *Hoplolaimus galeatus* (Cobb) Thorne after a 2 h exposure of infested soil to 48°C ± 2°C. Juveniles within cysts of *Heterodera glycines* Ichinohe were completely killed within 1 s, 8 min, and 8 h at 63°C, 52°C, and 44°C, respectively (Endo 1962), whereas a 30 min exposure at 60°C was reported to be lethal for the potato (*Solanum tuberosum* L.) cyst nematode *Globodera rostochiensis* Woll. (Evans 1991). Walker (1962) reported a 6 min permanence at 48°C as the thermal death threshold for the eggs and the egg masses of root-knot nematodes, *Meloidogyne* spp., in accordance with the studies of Gokte and Mathur (1995), in which the eradication of root-knot nematodes from grapevine rootstocks was achieved after a 10–20 min treatment at 48–53°C. In recent studies, application of constant temperature-time dosages to soil infested by *M. incognita* Kofoid et White Chitw. resulted in LD_{95} values of 813, 281 and 32.4 min at 39°C, 42°C, and 46°C, respectively (Ruiz et al. 2003).

Time and temperature requirements for thermal death of weeds were also reported to change considerably among the target species. Egley (1990) indicated a 12 h exposure at temperatures from 50°C to 66°C as the LD_{50} of eight common weed seeds, confirming findings of Horowitz et al. (1983) that found an effective weed control by soil temperatures above 45°C. Similarly, in recent laboratory studies Dahlquist et al. (2007) observed that seeds of all tested weed species were killed at 50°C and above, though *Portulaca oleracea* L., *Amaranthus albus* L., *Echinochloa crus-galli* L., and *Solanum nigrum* L. were not affected by heating up to 46°C, 42°C, and 39°C. Purple nutsedge (*Cyperus rotundus* L.) was found to be less heat-sensitive, as its tubers viability decreased in an inverse linear pattern after a 30 min exposure at a 30–90°C temperature range (Rubin and Benjamin 1984). Simulation models were also developed to describe weed mortality as a function of heat treatment duration or daily fluctuating soil temperatures and, therefore, to predict time × temperature combinations needed for an effective weed control by solarization under field conditions (Dahlquist et al. 2007; Miles et al. 2002).

9.2.2 Chemical Mechanism

Chemical changes occurring in the soil after the heat treatment may represent a further mechanism for the solarization effects (Chen and Katan 1980; Chen et al. 1991). An increased concentration of soluble mineral nutrients was generally found in solarized soil (Katan 1987; Stapleton and DeVay 1995; Stapleton 2000), prevalently due to the death and degradation of soil microbiota killed by the heat treatment. Accumulation of toxic ammoniacal nitrogen was found to result from the microaerobic conditions originated by the thermal death of nitrifying microorganisms in soils with high moisture and organic matter content (Hasson et al. 1987), whereas a minimal release of rapidly nitrified nitrogenous compounds was reported in soil with poor organic material when low temperatures raised by an uneffective soil solarization and/or a low moisture content increased survival of soil biota and promoted aerobic conditions (Stapleton et al. 1985). Heat-induced breakdown of organic matter may also generate volatile compounds toxic to soil biota in solarized soils (Gamliel et al. 2000).

9.2.3 Biological Mechanism

An enhanced presence of microorganisms antagonist of plant pathogens was generally observed in solarized soil, due to the increased availability of substrate and nutrients following the death of most mesophilic microorganisms (Stapleton 1981; Gamliel et al. 1989; Stapleton and DeVay 1995). Paul and Clark (1996) hypothesized that higher assimilation efficiency of antagonistic bacteria may favor them in the presence of the heat-induced increased availability of nutrients. Moreover, Gupta and Yeates (1997) suggested that further shifts in soil microflora may be due to the lower grazing pressure on soil microorganisms by solarization-targeted bacterial grazer and predators. These antagonist populations, including *Bacillus* spp., fluorescent pseudomonads, thermotolerant fungi, and some free-living nematodes, were found to survive solarization or rapidly colonize soil and prevent pest recolonization, providing also a better plant growth (Katan 1987; Gamliel and Stapleton 1993a; Stapleton and DeVay 1995). Moreover, fluorescent pseudomonads were also found to be positively affected by the increase of humic substances above reported as following solarization (Chen et al. 1994, 2000). Among microorganisms surviving solar heating, thermotolerant fungi *Trichoderma* spp. were shown to inhibit growth of many fungal pathogens and reduce related diseases (Ben-Yephet et al. 1987; Harman 2000; Suarez et al. 2004).

9.3 Factors Affecting Solarization

Effects of solarization were found related to a combination of many parameters, though most authors agreed that soil temperature and moisture, climate and weather, and type and properties of mulching film are key factors for solarization results (Katan et al. 1987; Stapleton and DeVay 1995).

9.3.1 Soil Temperature

Soil temperature is the main variable for solar heating effect, due to the above-cited critical or lethal accumulation of heat effects over a temperature threshold of about 37°C for most mesophylic organisms. Stapleton (1997) observed that the highest soil temperatures during solarization were achieved near the soil surface in the daytime, whereas temperature decreased by increasing depth and at night. Under a clear plastic mulch, temperatures higher than 50°C were recorded only in the top 5 cm soil, but literature reported temperatures of 40–50°C and 36–40°C down to 10–15 cm and 20–30 cm depth, respectively, during summer solarization in warm areas, whereas no lethal or sublethal thermal levels were generally found at deeper soil layers, where temperature increases by only 3–4°C (Porter and Merriman 1983; Stapleton and DeVay 1983; Greco et al. 1985; Chellemi et al. 1994). Stapleton and DeVay (1986) hypothesized that nematode population reduction found at 46–91 cm depth could be due to further suppressive factors, like releasing of volatile toxic compounds. Thermal levels originated by solarization were generally found much higher under closed greenhouse conditions or in containerized soil than in open field (Cartia 1998; Stapleton et al. 2000; Castronuovo et al. 2005).

Several types of models have been developed to predict temperatures of either bare or mulched soil during solarization (Mahrer 1979; Mahrer 1980). One- or two-dimensional numerical models of Mahrer and Katan (1981) and Mahrer et al. (1984) described soil temperature and moisture regimes of solarized soil on the base of environmental data, soil physical characteristics, and film optical properties, but their use was limited by the requirement of difficultly available weather data. On the same theoretical bases, Ten Berge (1990) and Horton and Chung (1991) developed models predictive of bare soil temperatures on the base of more easily available weather data, like solar radiation, air temperature, wind speed, and total rainfall. The one-dimensional model of Bristow and Campbell (1986) described both heat and moisture transfer through the soil, though with no consideration of mulch density and arrangement effects. Cenis (1989) proposed a site-specific model simulating daily sinusoidal change of temperature in a homogeneous soil, whereas the model of Sui et al. (1992) simulated soil temperature and moisture profiles under various type of mulches. Other models referred more specifically to the effect of mulch optical properties on soil heating (Ham and Kluitenberg 1994; Wu et al. 1996; Ruocco 2000), whereas Graefe (2005) proposed an energy balance model that was also applicable for a two-dimensional ridge surface partly covered by a plastic mulch.

9.3.2 Soil Moisture

Soil moisture is also a critical variable in solarization thermal effect, as heat transfer to microorganisms, weed seeds, and plants in soil is greatly increased by moisture. Moreover, soil moisture favors cell activities in seeds and soilborne microorganisms growth, making them more vulnerable to lethal effects of high temperatures. Modeling studies show that highest soil temperature were only achieved with an increased soil water content (Mahrer et al. 1984; Naot et al. 1987), but a linear association between heat capacity and soil water content was also stated by other authors (De Vries 1963; Sesveren et al. 2006). Adversely, an inverse relationship between soil maximum temperatures and moisture content was described by Al-Karaghouli and Al-Kaysi (2001), concluding that repeated watering during solarization is not needed for soil pathogens eradication.

9.3.3 Climate and Weather

Climate and weather were also found to be primary factors for solar heating success, as they affect the levels of solar radiation and, therefore, soil temperatures. Chellemi et al. (1997) found solarization efficiency as strongly reduced by a cloudy and rainy weather and, more generally, the best results of solarizing treatment were provided in the areas with high summer temperatures. However, even if summer months in warm areas are surely the most suitable periods for solarization, successful applications of this technique against soilborne pathogens, nematodes, bacteria, and weeds were documented also in cooler climates (Raio et al. 1997; Christensen and Thinggaard 1999; Pinkerton et al. 2000; Peachey et al. 2001; Tamietti and Valentino 2006). Effectiveness of soil solarization in unfavorable climatic regions was attributed to adaptability of pathogen heat sensitivity to different climates, which result in lower thermal thresholds in cooler climates (Elmore 1998).

9.3.4 Plastic Film

Function of a plastic film in the solarizing process is to increase soil temperature by allowing passage of solar radiation while reducing energetic radiative and convective losses (Papadakis et al. 2000). Transmission of solar radiation by plastic films was found related to their radiometric properties and mainly transmissivity, as higher values of solar transmissivity coefficient resulted in higher temperature rises under the mulch (Scarascia-Mugnozza et al. 2004; Vox et al. 2005). However, other radiometric properties, i.e., reflectivity, absorptivity, and emissivity, were also involved in the thermal effectiveness of a plastic film (Papadakis et al. 2000). Radiometric properties of a large variety of plastic film were thoroughly documented either in laboratory or field tests (Pearson et al. 1995; Papadakis et al. 2000; Heissner et al. 2005; Vox et al. 2005) (Fig. 9.2).

A wide range of different plastic materials were reported as applicable to soil solarization (Lamberti and Basile 1991), though best solarizing properties were shown by polyethylene and its low-density or vynilacetate-coextruded formulations, either alone or added with inorganic salts, and by copolymer ethylene vynilacetate and polyvinylchloride films (Stevens et al. 1991a). In field and laboratory comparative trials on the radiometric properties of different plastic films, an ethylene-tetrafluoroethylene copolymer film showed better spectroradiometric characteristics compared to ethylene-co-vinyl alcohol, polyethylene, photo-selective red colored and UV-absorbing films, as achieving higher soil temperature and thus improving solarization efficacy (Cascone et al. 2005). Under greenhouse conditions, soil solarization with an ethlylene-tetrafluoroethlylene film, though inducing a lower thermal regime than ethlylene vynilacetate, provided a better management of several important soilborne pathogens (Polizzi et al. 2003). Malathrakis and Loulakis (1989) reported that solarization with polyethylene and polyvinylidene chloride sheets were similarly effective against *S. rolfsii*, but only the latter film significantly reduced cucumber (*Cucumis sativus* L.)

Fig. 9.2 Solarization experiment with different plastic films in a plastic greenhouse in Southern Italy (courtesy of dr Donato Castronuovo)

root rot and vascular browning caused by *Acremonium* spp., Chase et al. (1999a) found a clear thermal-infrared absorbing film as consistently more effective in increasing soil temperature than low-density polyethylene. Numerical and field studies of Al-Kaysi and Al-Karaghouli (2002) showed that mulching soil with a paraffin-wax emulsion film, rather than transparent polyethylene, resulted in more effective soil heating and a faster killing of pathogenic soil fungi.

A high suitability of polyethylene to solar heating was generally stated, due to its high solar radiation transparency, flexibility, tensile strength, and resistance properties (Espí et al. 2006). Thinner polyethylene films were generally found more effective, as less expensive and producing higher temperature increases than thicker ones (Stapleton and DeVay 1986; Abu-Irmaileh, 1991a,b). Use of a double polyethylene layer was documented as more effective than a single layer film, due to a 3–10°C soil temperature increase and then an improved effect on target pests and soil microflora (Ben-Yephet et al. 1987; Cenis 1987; Mahmoud 1996), thus resulting particularly suitable to nursery conditions and in cloudy climate areas (Annesi and Motta 1994; Stevens et al. 1999; Rodríguez Pérez et al. 2004).

The color of solarizing plastics was also investigated by a number of authors, as determining energy-radiating behavior of mulches and their influence on soil water content and microclimate around the plant (Lamont 1993; Streck et al. 1995; El-Keblawy et al. 2006). Haynes (1987) reported that soil temperature can be differentially affected by mulch color, generally following the order: transparent mulch > black mulch > white mulch. Barakat (1987) found that the use of an opaque black film, as blocking the passage of most solar radiation, reduced soil temperatures by several degrees compared to a transparent film, but clear and black plastic mulches resulted in similar soil temperature regimes in other studies (Hasing et al. 2004). High temperatures were found to last consistently longer under the clear film, whereas black polyethylene provided a higher stability and a longer durability under field conditions and an enhanced weed suppression (Dubois 1978; Hancock 1988; Hasing et al. 2004). Solarization with transparent, black, or other color mulches was investigated with mixed results in many experiments (Kadman-Zahavi et al. 1986; Abu-Gharbieh et al. 1991; Ham et al. 1993; Chase et al. 1999; Campiglia et al. 2000; Rieger et al. 2001; Hasing et al. 2004). Black plastic was suggested under special conditions, as in nursery beds or established tree orchards (Stapleton and Garza-Lopez 1988; Abu-Gharbieh et al. 1991; Stapleton 1997). Mulching soil of a newly established fruit orchards with a black polyethylene film resulted in higher weed suppression and lower root-knot nematode galling, when compared to the nonmulched control (Duncan et al. 1992). Some studies reported that solarization with black polyethylene film also reduced populations of many soil phytopathogenic fungi and bacteria and was more effective for preventing weeds (Reynolds 1970; Hawthorne 1975; Lamont 1993). In other experiments, black plastic mulch resulted in higher early yields but reduced total crop yield compared to transparent film (Schonbeck and Evanylo 1998).

Application of plastic films for soil solarization requires specific equipments and time-spending procedures, as well as the plastic disposal at crop end can be expensive and represent a serious environmental problem (Parish et al. 2000).

A number of studies focused on the potential responses provided to these problems by the improvement of plastic technology (Spreich et al. 1990; Doran 2002; Zheng et al. 2005). Mulches of sprayable degradable polymers, applied on soil surface at an appropriate amount, were found to be a feasible and cost-effective alternative to traditional plastic mulch for soil solarization (Gamliel et al. 2001). Soil solarization with sprayable mulches, though soil temperatures were generally lower than under traditional plastic film, was reported to be effective in controlling potato scab and peanut (*Arachis hypogaea* L.) pod wart, or in increasing eggplant (*S. melongena* L.) yield and fruit weight (Mahmoudpour and Stapleton 1997; Gamliel et al. 2001). Mulches based on biodegradable and renewable agricultural raw materials were also tested as a sustainable alternative to the conventional plastic films, due to their easy disposal in the soil or composting plants (Chandra and Rustgi 1998; Narayan 2001; Malinconico et al. 2002; Kirikou 2007) (Fig. 9.3). Starch-based biodegradable films were largely studied for their degradation and morphological behavior (Bastioli 1998; Briassoulis 2004; Heissner et al. 2005; Vox et al. 2005; Scarascia-Mugnozza et al. 2006). These materials generally were found to produce lower temperature levels and for a shorter period, compared to the traditional low-density polyethylene and ethylene vinyl acetate films (Candido et al. 2005; Russo et al. 2005). However, several field tests documented also their successful application in many crops (Chandra and Rustgi 1998; Manera et al. 2002). Under greenhouse and field conditions, soil solarization with a corn starch-based biodegradable film resulted effective for the control of root-knot nematodes (*Melodogyne* spp.) on melon (*Cucumis melo* L.), corky root disease caused by *Pyrenochaeta lycopersici*

Fig. 9.3 Degradation of a biodegradable plastic film after soil solarization in a field experiment in Southern Italy (courtesy of dr Donato Castronuovo)

Schneider and Gerlach in tomato (*Lycopersicon esculentum* L.), *S. minor* on lettuce (*Lactuca sativa* L.) and weeds, improving also crop yield and quality (Panattoni et al. 2004; Cascone et al. 2005; Castronuovo et al. 2005).

9.4 The Effects of Soil Solarization

9.4.1 Effects on Soil Chemical and Physical Properties

Solar heating was normally reported to increase soil content of soluble nutrients, and particularly of dissolved organic matter, inorganic nitrogen forms, and available cations, either under field-scale or in growth chamber simulated solarization (Stapleton et al. 1985; Stevens et al. 1991a; Grünzweig et al. 1999; Chen et al. 2000; Salerno et al. 2000; Ghini et al. 2003). Chen and Katan (1980) observed increased concentrations of dissolved organic matter in saturated extracts of solarized soils, and Gelsomino et al. (2006) recently hypothesized this increase of soluble organic matter as caused by a mild hydrolysis or depolymerization of soil organic matter under the effect of the solarization-induced high temperatures. Short-term availability of soluble forms of nitrogen, particularly NH_4^+ and NO_3^- fractions, was usually found increased after solarization, due to the higher decomposition rates of organic matter and the mineralization of microbial biomass killed by heat (Chen and Katan 1980; Stapleton et al. 1985; Kaewruang et al. 1989a, b; Ahmad et al. 1996; Grunzweig et al. 1998; Freitas et al. 2000; Mauromicale et al. 2005a, b). Relative concentration of different nitrogen forms was described as a function of soil pH and nitrifying microorganisms density, as thermal death of nitrifying bacteria during soil solarization favors the accumulation of soluble ammonium nitrogen, whereas the occurrence of lower temperatures and poor organic matter content allow the survival of nitrifying microorganisms and consequent nitrogen loss due to the easy leaching of $NO3^-$ (Hasson et al. 1977; Kaewruang et al. 1989a).

Most authors reported as uncommon an increase of soil phosphorus content after solar heating (Chen and Katan 1980; Stapleton et al. 1985; Kaewruang et al. 1989b; Chen et al. 1991), though few reports indicated an increased availability of total or water-soluble phosphorous as following the solarization treatment (Kaewruang et al. 1989a; Gelsomino et al. 2006). Potassium, calcium, magnesium, and sodium availability was generally found to increase in soil after solarization (Chen and Katan 1980; Stapleton et al. 1985; Kaewruang et al. 1989b; Gamliel and Katan 1991; Ahmad et al. 1996; Grunzweig et al. 1998).

The increased growth response documented in almost all the solarization studies is mainly due to the above-cited higher levels of macronutrients or the improved uptake of micronutrients solubilized by humic substances (Chen and Aviad 1990; Chen et al. 1991). As a consequence of the enhancing effect of solarization on soil nutrients, Flores et al. (2007) suggested the application of low rates of mineral fertilizers before heating soil, in order to avoid an increased vegetative growth of the plants at the expense of crop yield.

A number of solarization studies reported an increase in electrical conductivity of soil solution (Chen and Katan 1980; Stapleton et al. 1985; Kaewruang et al. 1989a; Ahmad et al. 1996), which was hypothesized to be related to the higher content of ions, released by decomposed and mineralized organic matter migrating in soil solution from deeper to the upper heated soil layers (Chen and Katan 1980). Similarly, diurnal downward movement of soil moisture and solubilized salts was suggested to explain the reduction in soil salinity reported as following soil solarization (Abdel-Rahim et al. 1988; Al-Kaysi et al. 1989). Contrasting effects of heat treatment were described for soil hydraulic conductivity (Chen and Katan 1980; Al-Kaysi et al. 1989). Soil physical properties were generally found limitedly and inconsistently affected by soil solarization (Chen et al. 1991), though Melero-Vara et al., (1989) reported an improvement of soil structure and aggregation as following a solarization treatment.

9.4.2 Effects on Nonpathogenic Soil Microflora

A broad range of soil microorganisms, apart from major plant pathogens, were found to be affected by soil solarization, as most studies agreed that the heating treatment stimulated marked compositional shifts in composition and richness of soil microbial communities (Chen et al. 1991; Schoenfeld et al. 2003; Palese et al. 2004; Culman et al. 2006; Gelsomino et al. 2007). Alabouvette et al. (1996) hypothesized that heat-induced shifts in soil microbial balance favored saprophytic microbiota, thus increasing competition for nutrients and resulting in a higher soil suppressiveness. Recent greenhouse solarization studies documented negative effects of heating treatment on microbial biomass and enzymatic activities, but a protective role of organic matter against heat detrimental effect (Okur et al. 2006; Scopa and Dumontet 2007).

Some authors described a general reduction of soil total bacterial population by soil solarization (Mahmoud 1996; Patel and Patel 1997; Itoh et al. 2000; Barbour et al. 2002; Sharma et al. 2002), whereas other reports documented a decrease of soil fungal population but no effect on bacteria (Coates-Beckford et al. 1997; Shukla et al. 2000). However, most studies on solarization effects on soil bacterial population focused on microorganisms beneficial to plant growth, antagonistic to plant pathogens, or quick recolonizer of root systems in solarized soil (Stapleton and DeVay 1984; Stevens et al. 1991b; Wadi 1999). Some of these investigations indicated an increase of total bacteria and actinomycetes populations in solarized soil (Kaewruang et al. 1989; Khair and Bakir 1995; Khaleeque et al. 1999). Stevens et al. (2003) reported a shift of bacterial population in solarized soil to Rhizobacteria, *Bacillus* spp., and fluorescent pseudomonads. Stapleton and DeVay (1982, 1984) found that the population densities of fluorescent pseudomonads, *Bacillus* spp., Actinomycetes, and *Agrobacterium* spp. were greatly reduced after solarization. A suppression of various soil bacteria, with a lower effect on Actinomycetes, was found also by Ristaino et al. (1991) and Gamliel and Katan (1991). Fluorescent pseudomonads were stated as quick recolonizer of solarized soil (Stapleton and DeVay 1982; Stapleton and DeVay 1986; Gamliel et al. 1987), providing a degree of protection against fungal root pathogens and stimulating plant growth (Lifshitz et al. 1983; Greenberger et al. 1984; Stapleton and DeVay 1984; Freeman and Katan 1988; Thomashow and Weller 1990; Keel 1992; Chen et al. 2000). A number of studies documented *Bacillus* species as predominant Gram-positive bacteria surviving soil solarization and playing a major role in disease suppressiveness of solarized soils, due to either their aggressive growth or production of antibiotics (Stapleton and DeVay 1982; Stapleton and DeVay 1984; Katan 1987). Endorhizosphere *Bacillus* strains selected from tomato root tips after soil solarization were found to be very efficient in inhibiting mycelial growth of *V. dahliae* in vitro and controlling Verticillium wilt of solanaceous hosts in field trials (Tjamos and Paplomatas 1987; Tjamos et al. 2004). Moreover, population of another antagonist of *V. dahliae*, *Talaromyces flavus* (Klöcker) Stolk and Samson, was also found to survive solarization and significantly increase in plant rhizosphere (Kim et al. 1988; Tjamos and Fravel 1995).

A number of studies specifically investigated the effect of solarization on population of soil rhizobia, due to their importance as nitrogen-fixing bacteria. Heat treatment was found to reduce soil population of *Rhizobium* spp. and consequently root nodulation of early-stage plants (Abdel-Rahim et al. 1988; Chauhan et al. 1988; Linke et al. 1991; Mahmoud 1996), though a quick recover of these bacteria occurred after the establishment of a legume crop (Linke et al. 1991). Mauromicale et al. (2005a, b) also reported a delay of root nodulation and a consistent reduction of a number of nodules per plant in faba bean (*Vicia faba* L.) and chickpea (*Cicer arietinum* L.), and the adverse effect of soil solarization on native soil rhizobia was also suggested as a potential technique for their replacement with other inoculant beneficial strains (Rupela and Sudarshana 1990). However, Arora and Pandey (1989) and Nair et al. (1990) inversely observed an increase of rhizobial root nodulation in solarized soil.

Few and contradictory studies are available on the side effects of solarization on arbuscular mycorrhizal fungi (AMF), but most reports indicate no damage of soil heating on native AMF and an enhancement of mycorrhizal colonization and plant growth (Pullman et al. 1981; Afek et al. 1991). Daft et al. (1987) found spores of *Glomus clarum* Nicol. and Schenck as inactivated at 45°C, and Menge et al. (1979) reported thermal death of *G. fasciculatum* (Thaxter) Gerdeman & Trappe after 10 min at 51.5°C. Soulas et al. (1997) observed that ectomycorrhizal fungi, as suppressed at temperatures above 45°C, were among the soilborne fungi most sensitive to solar heating, and suggested that soil solarization may be an effective disinfection method for a controlled mycorrhization in forest nurseries. No differences in the extent of AMF internal infections were found by Stapleton and DeVay (1984) in roots from solarized or untreated soils, though in other trials indigenous AMF populations were reduced to undetectable levels after 8-week solarization, whereas inoculated *Glomus intraradices* Schenk and Smith population remained viable (Bendavid-Val et al. 1997). Camprubí et al. (2007) reported that AMF propagules were only reduced, but not completely eliminated, by solarization, and that inoculum of *G. intraradices* completely lost its mycorrhizal potential when submitted at a 50°C temperature. Schreiner et al. (2001) hypothesized that reduction of AMF following solarization may be indirectly due to the suppression of weeds that would maintain the fungi over the winter.

9.4.3 Effect on Fungal Pathogens

Suppressivity of soil solarization on soilborne fungal pathogens is generally related to numerous variables in climate, soil conditions, population, and distribution of fungal propagules in soil (Pullman et al. 1979). However, a satisfactory fungicidal effect of solar heating treatment was documented on the most economically important plant pathogenic species.

Suppression of *Fusarium* spp. wilt diseases by soil solarization was largely investigated on many crops and in different experimental conditions. Gamliel and Katan (1993) hypothesized that, in addition or in the absence of direct thermal effect on pathogen survival, fluorescent pseudomonads and other microorganisms may be involved in this suppressive effect. Heat sensitivity of *F. oxysporum* was found to change among the different special forms (Shlevin et al. 2004), but field solarization effectively reduced incidence of *F. oxysporum* wilt in cumin, *Cuminum cyminum* L. (Lodha 1995; Israel et al. 2005), corn, *Zea mays* L. (Ahmad et al. 1996), cotton, *Gossypium hirsutum* L. (Katan et al. 1983), watermelon, *Citrullus lanatus* (Thunb.) Matsum and Nakai (Martyn and Hartz 1986), and cabbage, *Brassica oleracea* var. *capitata* L. (Ramirez-Villapudua and Munnecke 1987, 1988). Tomato Fusarium wilt disease was successfully controlled by soil solarization in field trials in Florida (Chellemi et al. 1997), Israel (Gamliel and Katan 1993), and Turkey (Yücel and Çınar 1989), but reduction of fungal density was limited to the upper 5 cm of solarized soil in another study (Chellemi et al. 1994). Field studies in Australia reported that solarization treatment reduced inoculum levels of *Fusarium oxysporum* sp. *dianthi* Snyd. and Hans., but not disease symptoms in carnation (*Dianthus caryophyllus* L.) and watermelon (Porter and Merriman 1985). Field tests in potato and watermelon crops documented also a great reduction or a complete eradication of *F. solani* between 0 and 30 cm depth after a 30–60-day soil solarization (Mansoori and Jaliani 1996; Triki et al. 2001). Under greenhouse conditions, solarization was effective against *F. oxysporum* f. sp. *dianthi* in carnation (Elena and Tjamos 1992), successfully controlled Fusarium wilt disease in tomato (Ioannou 2000) and reduced by 69–95% population of *Fusarium oxysporum* f. sp. *radicis-lycopersici* in Israel (Shlevin et al. 2003). Moreover, greenhouse solarization provided an almost complete control of *Fusarium oxysporum* f. sp. *niveum* in watermelon (Gonzáles-Torres et al. 1993) and *F. oxysporum* f. sp. *melonis* in melon (Tamietti and Valentino 2006).

A satisfactory control of soil densities of *Phytophthora* spp. and related diseases was documented in several solarization studies (Pinkas et al. 1984; Lopez-Herrera et al. 1997; McGovern et al. 2000; Benlioglu et al. 2005). Pinkerton et al. (2002)

observed a complete eradication of *Phytophthora cinnamomi* Rands from solarized soil, confirming similar findings of Barbercheck and Von Broembsen (1986) in South Africa and absence of activity of *P. cinnamomi* at 30 and 45 cm depth 2 or 4 weeks after the solar treatment, respectively, previously found by Pinkerton et al. (2000). Soil population of *P. cactorum* was strongly reduced or completely suppressed by soil heating in field trials in California and Spain (Hartz et al. 1993; Porras et al. 2007b), as well as a significantly lower infection of *Phytophthora fragariae* Hickman and *Phytophthora citricola* Sawada was also observed in strawberry (*Fragraria x ananassa* Duch.) roots from solarized soil (Hartz et al. 1993; Pinkerton et al. 2002). Field solarization trials in watermelon showed that propagules of *Phytophthora drechsleri* Tucker were greatly reduced or completely eliminated at 0–25 cm depth in solarized soil (Mansoori and Jaliani 1996), and soil densities of *Phytophthora nicotianae* Breda de Haan, *Phytophthora solanacearum* (Mont.) de Bary and *Phytophthora capsici* Leonian significantly decreased down to a 10–15 cm depth (Chellemi et al. 1994; Coelho et al. 1999, 2000). Finally, cherry (*Prunus cerasus* L.) crown rot caused by *Phytophthora cambivora* (Petri) Buisman was controlled for more than 12 months after solarization in Australia (Wicks 1988).

Application of solarization was successfully investigated also for the control of Verticillium wilt caused by *V. dahliae* in olive (*Olea europaea* L.) orchards (Tjamos et al. 1991; López Escudero and Blanco López 2001). Moreover, population of *V. dahliae* was eliminated down to 120 cm depth in a solarized grove of pistachio, *Pistacia vera* L. (Ashworth and Gaona 1982), and symptoms of Verticillium wilt were reduced by 86–100% also in apricot (*Prunus armeniaca* L.) and almond (*P. amygdalus* Batsch.) (Stapleton et al. 1993). Trials on field vegetable crops indicated an effective control of artichoke (*Cynara scolymus* L.) verticillium wilt throughout three successive cropping seasons following solarization (Tjamos and Paplomatas 1988) and a consistent reduction also in potato (Davis and Sorensen 1986; Lazarovits et al. 1991), eggplant (Pinkerton et al. 2000; Ioannou 2001**)**, and cotton (Pullman et al. 1981b; Melero-Vara et al. 1995). Morgan et al. (1991) demonstrated an effective control of Verticillium wilt in established tomato plants also by the application of solarizing mulches to planted soil. Positive results against Verticillium wilt were provided also by greenhouse solarization studies on tomato in Crete (Bourbos and Skoudridakis 1996), and Cyprus (Ioannou 2000), and on eggplant in Northern Italy (Tamietti and Valentino 2001).

Variable, though always significant, effects of solarization on incidence of diseases caused by *Sclerotium rolfsii* were described in various studies (Reynolds 1970; Grinstein et al. 1979a; Mihail and Alcorn 1984; Stevens et al. 1990b; Ristaino et al. 1991; Chellemi et al. 1997; Shlevin et al. 2003). Sclerotial viability of *S. rolfsii* was quickly reduced by more than 95% at 2.5 cm depth in solarized fruit orchards soil, though lower effects were found in deeper soil layers (Stapleton et al. 1989). Negligible or undetectable levels of inoculum of *S. cepivorum*, the agent of white rot in garlic (*Allium sativum* L.), were observed after solarization treatments in Spain (Basallote-Ureba and Melero-Vara 1993; Melero-Vara et al. 2000) and in New Zealand experimental sites (McLean et al. 2001). Lettuce drop caused by

Sclerotinia minor was also largely documented for a positive control by solarization (Hawthorne 1975; Vannacci et al. 1988; Sinigaglia et al. 2001; Patricio et al. 2006, 2007). Mortality of sclerotia of *S. sclerotiorum* (Lib.) de Bary exceeded 90% after soil solarization in Israel (Ben-Yephet 1988) and ranged from 53% to 100%, according to solarization period and experimental site, in New Zealand (Swaminathan et al. 1999). Phillips (1990) hypothesized this reduction of sclerotial viability as mainly due to microbial colonization and degradation of sclerotia weakened by sublethal temperatures raised by soil solar heating.

Control of *M. phaseolina* (Tassie) Goid by soil solarization was similarly reported to require optimal temperature and moisture conditions (Mihail and Alcorn 1984; Sheikh and Ghaffar 1987), due to the lower heat sensitivity of this species (Bollen 1985). Following soil solarization in field, no reduction of *M. phaseolina* inoculum was found at any soil depth by Hartz et al. (1987), whereas significant suppressions of pathogen population and reduced incidence of dry root rot symptoms were observed in clusterbean, *Cyamopsis tetragonoloba* (L.) Taub. and corn (Lodha 1995; Hameed and Aslam 1996; Lodha et al. 1997).

A number of reports documented also a consistent effect of soil solarizing on *Rhizoctonia solani* Kühn in various crops (Pullman et al. 1981; Chet et al. 1982; Kaewruang et al., 1989a,b; Keinath 1995; Katan 1996). In particular, final incidence and progress of crown rot and blight in impatiens, *Impatiens walleriana* Hook., and of strawberry and lettuce bottom rot caused by *R. solani* were efficiently reduced following a solarization treatment (McGovern et al. 2002; Pinkerton et al. 2002; Patricio et al. 2006; Patricio et al. 2007).

Under greenhouse conditions, tomato corky root rot disease caused by *Pyrenochaeta lycopersici* was effectively controlled by soil solarization in Canary Islands (Díaz Hernández et al. 2005), in Italy (Garibaldi and Tamietti 1984; Cartia et al. 1989; Cascone G D'Emilio A 2000), and in Portugal (Moura and Palminha 1994). Positive results were reported also in field experiments on furrow-irrigated soils in Egypt (Abdel-Rahim et al. 1988), whereas only a partial control was observed in four trials in Cyprus (Ioannou 2001). Pink root disease induced by *P. terrestris* (Hansen) Gorenz et al. in chive (*Allium schoenoprasum* L.) roots and in onion (*Allium cepa* L.) seedlings and bulbs was also generally found as dramatically reduced by soil solarization (Hartz et al. 1989; Gamliel et al. 2004; Chan-Jung et al. 2007).

Field soil solarization was effective in dramatically reducing or completely eliminating the infection of *Pythium* spp. in carrot (*Daucus carota* L.) and strawberry roots (Becker and Wrona 1995; Pinkerton et al. 2002), as well as reduced inoculum levels of *P. aphanidermatum* in watermelon and potato down to 25–30 cm soil depth (Mansoori and Jaliani 1996; Triki et al. 2001). Summer soil solarization in greenhouse reduced *Pythium* root rot even in the temperate climate of Denmark (Christensen and Thinggaard 1999).

Other fungal pathogens were also investigated for a potential control by soil solar heating treatment. Field and glasshouse experiments documented a high effectiveness of solarization against *Plasmodiophora brassicae*, the agent of crucifers clubroot disease (White and Buczacki 1979; Horiuchi and Hori 1983; Myers et al. 1983), though heat sensitivity of this pathogen was related to suitable soil moisture conditions (Porter et al. 1991). An effective management of *Rosellinia necatrix* (syn. *Dematophora necatrix*) was achieved by soil solarization in apple (*Malus domestica* Borkh.) and avocado (*Persea americana* Mill.) orchards (Sztejnberg et al. 1987; Freeman et al. 1990; Lopez-Herrera et al. 1998) and in apple nurseries (Sharma et al. 2002). Survival of the melon necrotic spot virus-vector *Olpidium bornovanus* (Satiyanci) Karling (syn. *O. radicale*) was strongly reduced in greenhouse trials, either in soil (Horita and Manabe 2005) or soilless cultivation (Guirado et al. 2005). Soil solarization in greenhouse demonstrated also to be an effective tool for the control of stem canker by *Didymella lycopersici* Kleb. in the hot summer climate of Morocco (Besri 1982).

Suppressive effect of soil solarization on fungal pathogens was investigated also in nursery or containerized soil, where solar heating demonstrated to be as effective as steaming or fumigation in reducing soil infectivity of *Pythium* spp., *Fusarium* spp., and *R. solani* in forest nurseries (Annesi and Motta 1994; Le Bihan et al. 1997; Salerno et al. 2000)**.** Summer soil solarization in forest plant nursery resulted in a significant reduction of preemergence damping-off disease of seeds of *Pinus radiata* D. Don and *Eucalyptus obliqua* L'Herit (Kassaby 1985). In the same study, solarization reduced also post-emergence mortality of *P. radiata* seedlings and eradicated *P. cinnamomi*, *F. oxysporum* and *Pythium* spp. from artificially inoculated pine roots. Kaewruang et al. (1989) reported an effective control of root rot of gerbera (*Gerbera jamesonii* Bolus ex Hook.) by polyethylene bag solarization of potting mixes infested with *P. cryptogea* Pethybr. and Laff., *F. oxysporum* and *R. solani*. Inocula of *P. myriotylum* Drechsler, *P. nicotianae*, and *S. rolfsii* were killed within 3–10 days, according to species sensitivity and inoculum depth, in solarized mounds of potting medium (Duff and Barnaart 1992). Solarization of shallow layers of growth medium in containers provided a high reduction of melon collapse caused by *Monosporascus cannonballus* Pollack and Uecker and a fast decline of ascospore viability (Cohen et al. 2000; Pivonia et al. 2002). Finally, soil solarization was successfully evaluated also for recycling piles of spent potting media (Zinati et al. 2002).

Beneficial effects of soil solarization on fungal pathogens control were commonly reported to last for about two growing seasons (Usmani and Ghaffar 1982; Stapleton and DeVay 1986; Greenberger et al. 1987; Davis 1991), and other studies also documented a suppression of soilborne disease for 1–3 years following solarization (Stapleton and DeVay 1982; Gamliel and Katan 1993; Ioannou 2000; Stevens et al. 2003). Solarization was found effective for at least two or three seasons for the control of Fusarium wilt in cotton, Verticillium wilt and shellspots in peanut, pink root of onion and *Pythium* tomato root rot (Katan 1981; Katan et al. 1983; Rabinowitch et al. 1985). Long-term effects of solarization against Verticillium wilt were documented in successive cropping seasons of safflower, *Carthamus tinctorius* (L.) Mohler et al., cotton and artichoke (Pullman et al. 1981; Tjamos and Paplomatas 1988), but also in the control of corky root in tomato and *S. cepivorum* white rot disease in onion (Abdel-Rahim et al. 1988; Satour et al. 1989). Diseases caused by *S. minor* and *R. solani* on lettuce were severely reduced in the second crop following solarization in a 2-year experiment (Patricio et al. 2006). Long-term effects were also reported on soilborne pathogens of tree crops, as no *R. necatrix* white root rot disease developed over 3 years and no death of replanted apple trees occurred up to 2 years in solarized apple orchards (Freeman et al. 1990). Effects of heat treatment on suppression of *V. dahliae* soil population and on tree recovery was observed for at least 3 years in olive orchards (Tjamos et al. 1991; López Escudero and Blanco López 2001). Effect of preplant soil solarization against *P. cinnamomi* extended over more than 5 years in avocado orchards, but Gallo et al. (2007) found that dead plant percentage was significantly lower than in nonsolarized soil also 11 years after the heat treatment. Long-term effect of solarization on soil pathogens cannot be explained solely by thermal inactivation, as it also involves a rapid soil recolonization by aggressive populations of heat-tolerant bacteria, actinomycetes and fungi, antagonistic to plant pathogens and contributing to soil suppressiveness (Tjamos and Paplomatas 1988; Kaewruang et al. 1989; DeVay 1991; Gamliel and Katan 1993; Pinkerton et al. 2000).

9.4.4 Effect on Bacteria and Viruses

Survival of plant pathogenic bacteria in solarized soil was investigated in a limited number of studies. *Agrobacterium* species were found highly sensitive to solarization, as bacterial population was reduced up to 72% in the studies of Stapleton and DeVay (1984), and decreased by 99% and 92% after solarization treatment in two italian nurseries (Raio et al. 1997). In this study, two strains of *A. tumefaciens* Smith and Townsend were eliminated within 4 weeks or markedly reduced after 2 months in sandy loam and silty clay soil, respectively. Khlaif (2003) reported consistent, though related to temperature and soil type, effects of soil solarization on *Agrobacterium* spp. population and on number of crown galls on peach, *Prunus persica* (L.) Batsch, and bitter almond roostock seedlings. Causal agent of tomato canker, *Clavibacter michiganensis* subsp. *michiganensis* (Smith) Davis et al., was also stated highly heat-sensitive, as Shlevin et al. (2004) estimated 7 days ED_{80} values and Antoniou et al. (1995) reported that population of bacteria strains of *C. michiganensis* subsp. *michiganensis* sharply declined 4–6 weeks after soil tarping in plastic tunnels. Tent solarization of apple and pear (*Pyrus communis* L.) trees infected by *Erwinia amylovora* (Burrill) Winslow et al. stopped canker expansion and eradicated bacterial population from many treated trees, though the results were dependent on tree species and ambient temperatures (Thomson 1996). Soil solarization failed to reduce the incidence of tomato bacterial diseases caused by *Ralstonia solanacearum* (Smith) Yabuuchi et al. (syn. *Pseudomonas solanacearum* Smith) either in the field (Chellemi et al. 1994, 1997, 1999) or in plastic greenhouse (Horiuchi 1991), though bacterial population was reduced by combining solarization with a chemical treatment (Chellemi et al. 1999).

Fate of plant viruses after a soil solarization treatment was almost completely ignored by researchers, as only one study documented a stabilizing effect of heat treatment on tobacco mosaic virus degradation in a sandy loam soil (Triolo and Materazzi 1992).

9.4.5 Effect on Phytoparasitic Nematodes

Effectiveness of soil solarization on phytoparasitic nematodes was generally found less consistent than on phytopathogenic fungi and weeds (Lamberti and Greco 1991; McGovern and McSorley 1997). Greater soil depths inhabited by phytopathogenic nematodes and their rapid migration to upper soil layers after solarization treatment, as resulting in a quicker recolonization of solarized soil compared to fungal pathogens and weeds, were hypothesized to account for this lower effectiveness (Porter and Merriman 1983; Heald and Robinson 1987; Abdel-Rahim et al. 1988; Cartia et al. 1989; Stapleton and Heald 1991). Nematode soil recolonization was found to be delayed by repeating solarization treatment for 2 or 3 years (Candido et al. 2008), though Sharma and Nene (1990) reported a similar suppression of nematode population for single- and two-season field solarization. Moreover, solarization effect on soil nematode densities was also observed to be sometimes not immediately evident or, inversely, to last for several months, due to biotic and abiotic changes occurring in the solarized soil. Stapleton and DeVay (1983) observed that suppressive effects of solarization on *Helicotylenchus digonicus* Perry became evident only 3 months after the treatment, whereas Walker and Wachtel (1988) reported the infection of juveniles of *Meloidogyne javanica* Treub by *Pasteuria penetrans* Sayre and Star as increased for 10 months after soil solarization.

Since the first demonstration of soil solarization effectiveness against phytonematodes (Katan et al. 1976), nematicidal effects of solar heating were largely investigated on many genera of plant-parasitic nematodes.

Porter and Merriman (1983) documented a high sensitivity to solarization treatment for *Mesocriconema xenoplax* (Raski 1952) Luc & Raski 1981, *M. javanica*, *Pratylenchus penetrans* Cobb and *Tylenchulus semipenetrans* Cobb within a 38–55°C temperature range. Densities of reniform nematode, *Rotylenchulus reniformis* Linford & Oliveira, were strongly reduced by solarization in field experiments on cowpea (Heald and Thomas 1983; Heald and Robinson 1987), though a quick nematode recolonization was observed in other studies (McSorley and Parrado 1986; Sharma and Nene 1990). Thickness, but not color, of mulching film and season of treatment were found to affect suppressivity of heat treatment on *R. reniformis* (Coates-Beckford et al. 1997; Coates-Beckford et al. 1998). Soil solarization showed a great effectiveness against the bulb nematode *Ditylenchus dipsaci* Filipjev, as only 10%, 6%, and 2% of *D. dipsaci* population was found still viable after 4, 6, and 8 week solarization, respectively, in southern Italy, (Greco et al. 1985), and garlic bulbs were found throughout the growing season in solarized fields heavily infested by *D. dipsaci* in Israel (Siti et al. 1982). Cyst-forming nematodes have been also reported to be effectively controlled by soil solarization, as hatching of the golden cyst nematode *G. rostochiensis* from solarized soil was reduced by 100%, 68%, and 59%, at 5, 10, and 15 cm depth, respectively, compared to nontreated soil (LaMondia and Brodie 1984). Soil solarization in southern Italy strongly suppressed viability and reproduction of *G. rostochiensis* either in the soil or on potato roots (Greco et al. 2000) and reduced to only 24–38% egg survival of the carrot cyst nematode, *Heterodera carotae* Jones (Greco et al. 1985). A suppressive effect of soil solarizing treatment was reported also on the population of *Heterodera ciceri* Vovlas et al. in soil and in chickpea roots (Di Vito et al. 1991) and on *Heterodera cajani* Koshi (Chauhan et al. 1988; Sharma and Nene 1990).

Some field studies documented the failure of soil solarization for the control of root-knot nematodes, *Meloidogyne* spp. (Greco et al. 1985; Barbercheck and Von Broembsen 1986). Failure was generally attributed to a protective role against stress factors exerted by the gelatinous matrix aggregating *Meloidogyne* egg masses (Daulton and Nusbaum 1961; Orion 1995), though Nico et al. (2005) adversely found no effect of this gelatinous matrix on survival of *M. incognita* eggs in solarized soil. However, a successful application of solar heating against root-knot nematodes was also reported in other field researches, as soil solarization significantly decreased root galling of *M. incognita* on lettuce and cantaloupe in a 3-year experiment in Italy (Lamberti et al. 2000), almost completely suppressed root-knot nematode down to 20 cm depth in a 4-year investigation in Croatia (Ostrec and Grubisic 2003), and reduced root-knot severity and population densities of *M. incognita* in Florida (McGovern et al. 2002). An excellent control of root-knot nematodes by soil solarization was generally found under greenhouse conditions (Cenis 1984; Cartia et al. 1989), though Ioannou (2000) achieved only a 50% reduction of *M. incognita* infestation on tomato after 8-week soil solarization in Cyprus. In more recent greenhouse experiments, percentage plant infestation, root galling, and soil population densities of *Meloidogyne* spp. were strongly reduced or almost completely suppressed following a solarization treatment (Ostrec and Grubisic 2003; Candido et al. 2008) (Fig. 9.4).

An effective application of solarization was demonstrated against many other nematode species, such as *Pratylenchus thornei* Sher and Allen (Katan et al. 1976; Grinstein et al. 1979b; Greco et al. 1990a), *Radopholus similis* (Cobb) Thorne (Bhattacharya and Rao 1984), *Hirschmanniella mucronata* (Das) Luc and Goodey (Sivakumar and Marimuthu 1987), *Helicotylenchus* spp. (Sharma and Nene 1990;


[redacted]

Fig. 9.4 Effect of soil solarization on root galling in tomato plants in soil infested by the root-knot nematode *Meloidogyne incognita* in plastic greenhouse in Sothern Italy. On the left a tomato root from solarized soil, on the right a root from nonsolarized soil, deformed by large galls

Coates-Beckford et al. 1997; Coates-Beckford et al. 1998), or rice and wheat nematodes *Aphelenchus* spp., *Helicotylenchus* spp., *Hirschmaniella* spp., *Pratylenchus* spp., and *Tylenchorhynchus* spp. (Stapleton and Heald 1991; Pokharel 1995; Ganguly et al. 1996). Kluepfel et al. (2002) found that solarization in a peach orchard shifted soil microflora toward microbial species suppressive to *M. xenoplax*. Moreover, field trials in Florida reported also the suppression of *B. longicaudatus*, *Criconemella* spp., and *Dolichodorus heterocephalus* Cobb throughout the growing season following solarization, whereas uncertain results were found for *Paratrichodorus minor* (Colbran) Siddiqi (Chellemi et al. 1993; McSorley and McGovern 2000; McGovern et al. 2002). Bello et al. (2004) suggested that the ineffective management of the virus-vector nematode *Xiphinema index* Thorne et Allen by soil solarization in vineyard replant could be due to nematode survival on grapevine roots still viable up to 1 year after soil heating. Potential of soil solarization was tested also for the control of phytoparasitic nematodes in confined volumes of soils (Giblin-Davis and Verkade 1988). Heat treatment of soil in black polyethylene sleeves reduced by 89–100% the populations of *T. semipenetrans*, *Pratylenchus vulnus* Allen *et* Jensen, or *M. xenoplax* (Stapleton et al. 1999), and solarization of soil piles reduced by 95% egg hatch of *M. incognita* (Nico et al. 2003). Population density and infectivity of both *M. incognita* and *R. reniformis* were reduced by solarization in nursery beds, though *R. reniformis* showed a higher heat susceptibility (Gaur and Dhingra 1991).

A number of studies investigated the impact of solarization treatment on total soil nematophauna, agreeing that solarization dramatically also decreased the abundance of free-living nematodes (Stapleton and DeVay 1983; Stapleton and Heald 1991). However, free-living nematodes were found more likely to survive solarization or rapidly colonize soil after solarization compared to the plant-parasitic nematodes (Stapleton 2000; Ostrec and Rubisic 2003) and Nasr Esfahani (2007) recently reported that recover of soil nematophauna can be accelerated by combining the heat treatment with organic amendments. Overman (1985) found that soil solarization was more effective at reducing total soil nematophauna than cover crops or herbicide fallow, and Culman et al. (2006) documented a significant decrease of nematophauna in solarized rice fields. Analysis of the impact of soil solarization on different soil nematode trophic groups showed that solarization disturbance on nematode communities disappeared at the end of the experiment and that omnivorous nematodes were more heat-sensitive than bacterivores and fungivores, whereas lowest sensitivity was exhibited by herbivores (Wang et al. 2006).

Long-term effectiveness of solarization on phytoparasitic nematodes was investigated with contrasting results, as under greenhouse conditions visual symptoms of root-knot nematode infection on cucumber were eliminated up to 1 year after soil solarization in Quatar (Atta-Aly 2007), whereas slight or no effects on *M. incognita* or *M. javanica* infestation on tomato were found after the same time interval in other trials in Cyprus and southern Italy (Ioannou 2000; Candido et al. 2008). Under field conditions, several reports stated that *M. incognita* infestation on cabbage and sweetpotato was reduced significantly for 2 consecutive years following solarization (Stevens et al. 2003). The rapid nematode soil recolonization after the thermal treatment is the main reason for the shorter residual effect of solarization on nematodes, though repeated solarization treatments may delay recolonization and progressively reduce population densities under economic threshold, thus enhancing the nematicidal effect (Candido et al. 2008).

9.4.6 Effects on Weeds

Weed management by soil solarization was widely investigated with variable responses either in field or greenhouse studies (Elmore 1991b; Yaduraju and Mishra 2004), though the best results were always reported in hot climate countries (Al-Masoom et al. 1993; Saghir 1997) (Fig. 9.5).

Solarization effects on weed population was hypothesized to be due to different mechanisms, such as changes in cell metabolism and ultrastructure (Singla et al. 1997), microbial parasitism on seeds weakened by sublethal temperatures, seed dormancy interruption by raising temperatures, and foliar scorching of weeds under the plastic mulch (Egley 1990; Katan and DeVay 1991). Moreover, imbalance of O_2 and CO_2 or release of acetaldehyde, ethylene, and other volatile toxic compounds were also reported as accounting for weed death (Rubin and Benjamin 1984; Gamliel et al. 2000).

Weed sensitivity to solarization treatment may be largely variable according to the different species (Economou et al. 1997; Elmore 1998). Based on heat sensitivity, Restuccia et al. (1994) classified weed species as sensitive, resistant, or not well defined (Table 9.1). The first group included about 80 annual species, further sub-

Fig. 9.5 Effects of soil solarization in field on weed infestation in an experiment in Southern Italy. On the left melon plants free of weeds in solarized soil; on the right the heavy weed infestation in nonsolarized soil

Table 9.1 Classification of weed species according to sensitivity or resistence to soil solarization as reported by literature

Sensitive species	Annuals autumn–winter cycle	*Anagallis cerulea* (Gouan) Schreb., *Arum italicum* Mill., *Avena fatua* L., *A. sterilis* L., *Borago officinalis* L., *Brassica nigra* Koch, *Capsella bursa-pastoris* (L.) Medicus, *C. ribella* Reuter, *Centaurea iberica* Trevir., *Coronopus didymus* (L.) Smith, *Chrisantemum coronarium* L.,*Daucus aureus* Desf., *Emex spinosa* L., *Erodium* spp., *Heliotropium suaveolens* Caruel, *Hordeum leporinum* LK., *Lactuca scariola* L., *Lamium amplexicaule* L., *Medicago polymorpha* L., *Mercurialis annua* L., *Montia perfoliata* (Donn. ex Willd) Howell, *Notobasis syriaca* (L.) Cass., *Papaver dibium* L., *P. roheas* L.[a], *Phalaris brachystachys* LK., *Ph. paradoxa* L., *Poa annua* L., *Polygonum equisetiforme* S., *Raphanus raphanistrum* L., *Senecio vernalis* Raf., *S. vulgaris* L., *Sinapis arvensis* L., *Sisymbrium* spp., *Solanum nigrum* L., *Sonchus oleraceus* L., *Stellaria media* (L.) Villars, *S. neglecta* Weihe, *Urtica membranacea* Poir, *U. urens* L.,*Veronica* spp.[a]
	Annuals spring–summer cycle	*Abutilon theophrasti* Medic., *Amaranthus albus* L., *A. blitoides* S. Watson, *A. retroflexus* L., *Cartamus syriacum* Willd, *Chenopodium album* L., *Ch. pumilio* R.BR., *Ch. murale* L., *Commelina communis* L., *Conyza bonariensis* (L.) Cronq., *Crysanthemum segetum* L., *Datura stramonium* L., *Digitaria sanguinalis* (L.) Scop., *Echinochloa crus-galli* (L.) Beauv., *E. colomum* (L.) L.K., *Elusine indica* Gaertn, *Eragrostis megastachya* L.K., *Fumaria judaica* Boiss, *F. muralis* Koch, *F. officinalis* L., *Geranium molle* L., *Ipomea lacunosa* L., *Malva parviflora* L., *M. silvestris* L., *Orobanche aegyptiaca* L., *O. crenata* Forsk., *O. ramosa* L., *Setaria glauca* P.B., *S. viridis* (L.) P.B.[a], *Polygonum persicaria* L., *Sida spinosa* L., *Solanum nigrum* L., *Tribulus terrestris* L., *Vicia sativa* L.[a], *Xantium pensilvanicum* Wallr., *Xantium spinosum* L.
	Perennials	*Chloris gayana* Kunth, *Cirsium arvense* (L.) Scop. (rizoma-propagated)[a] *Convolvulus althaeoides* L., *C. arvensis* L. (seed and rizoma-propagated), *Cynodon dactylon* (L.) Pers. (seed-propagated), *Equisetum arvense* L., *E. ramosissimum* Desf., *Oxalis corniculata* L., *Plantago* spp., *Sorghum halepense* (L.) Pers. (seed-propagated)
Resistent species	Annuals	*Conyza canadensis* L., Coronilla scorpioides (L.) Koch, *Anchusa aggregata* Lechm., *Astragalus boeticus* L., *Melilotus sulcatus* Desf., *Scorpiorus muricatus* L., *Lavatera cretica* L., *Malva nicaeensis* All., *Lathyrus ochrus* (L.) DC
	Perennials	*Cyperus esculentus* L., *C. rotundus* L.
Not defined species	Annuals	*Xantium strumarium* L., *Portulaca oleracea* L., *Solanum luteum* L.
	Perennials	*Cynodon dactylon* (L.) Pers.(rizoma-propagated), *Sorghum halepense* (L.) Pers. (rizoma-propagated)

[a] Candido et al. 2006, 2008

divided into autumn–winter, spring–summer, and indifferent time germinating weeds. Compared to summer annual species, winter annual species, as they germinate in shorter day and lower temperature conditions, are more temperature-sensitive and require smaller temperature increases to be effectively controlled. A 1-week solarization was enough to control many susceptible winter annuals such as *Poa, annua*, *Montia perfoiata* (Donn ex Willd.) Howell and *Senecio vulgaris* L. (Katan and DeVay 1991), whereas summer annual species required higher solarization temperatures and/or a longer duration (Egley 1990). Solarization-resistant group included either annual species, like leguminous *Astragalus boeticus* L., *Scorpiurus muricatus* (L.) Lam., *Coronilla scorpioides* (L.) Koch, and *Melilotus sulcatus* Desf., asteraceous *Conyza canadiensis* (L.) Cronquist, and malvaceous *Lavatera cretica* L. and *Malva nicaeensis* All., or perennials, like *Cyperus* spp. Annual weeds *P. oleracea*, *X. strumarium,* and *S. luteum* Miller, and perennials *C. dactylon* and *Sorghum halepense L. Pers.* were classified as undefined behaviour species. Moreover, recent solarization studies in lettuce crop included leguminous weed *Lathyrus ochrus* (L.) D.C. among solarization-resistant species in field, while perennial *Cirsium arvense* (L.) Scop. was stated as sensitive to solarization treatment by Candido et al. (2006).

An effective control of annual weeds by solarization was generally documented, as in a prolonged experimental program Stapleton et al. (2005) found that solar heating reduced by nearly 100% a wide range of annual weed species, including yellow sweetclover (*Melilotus officinalis* L. Lam.), chickweed (*Stellaria* spp.), annual bluegrass (*P. annua* L.), shepherdspurse (*Capsella bursa-pastoris* L. Medikus), crabgrass (*Digitaria* spp.), and spotted spurge (*Euphorbia maculata* L. Small). Emergence of other annual summer or winter species, such as *Amaranthus* spp, *Chenopodium* spp, *Coronopus didymus* (L.) Sm., *Digitaria sanguinalis* (L.) Scop., *E. crus-galli*, *Eleusine indica* (L.) Gaertner., *Galinsoga parviflora* Cav., *Medicago arabica* (L.) Huds., *S. nigrum*, and *Sonchus oleraceus* L., was almost completely suppressed by soil solarization in other field and greenhouse trials (Elmore,1993; Moya and Furukawa 2000; Patricio et al. 2006; Candido et al. 2008). Egyptian broomrape (*Orobanche aegyptiaca* L. Pers.) and bean broomrape (*O. crenata* Forsk) were effectively controlled in carrot and eggplant and tomato crop, respectively, following a solarization treatment (Jacobsohn et al. 1980; Abdel-Rahim et al. 1988), though the best control of the above *Orobanche* species by solarization was found in hot seasons (Sauerborn et al. 1989). Hemp (*O. ramosa* L.) and nodding broomrape (*O. cernua* Loefl) were completely absent from solarized soil in field and greenhouse experiments on tomato (Abu-Irmaileh 1991a; Mauromicale et al. 2005). A solarization-tolerant behavior was often reported for *P. oleracea* (Elmore 1991b), and its seed germination was found to decrease only after a 2 or 1 h exposure to 60°C or 65°C, respectively (Verdu and Mas 2004). However, Dahlquist et al. (2007) reported a 39°C temperature sublethal to seeds of *P. oleracea*, and Patricio et al. (2006) found infestation of *P. oleracea* drastically reduced by field soil solarization. *Cuscuta* spp. was found tolerant to soil solarization by Abu-Irmaileh and Thahabi (1997), but Haidar and Iskandarani (1999) observed a strong reduction of soil seed bank *Cuscuta* spp. after a solarization treatment.

Perennial weeds were more difficult to control than annual species, maybe due to the occurrence of propagules at soil depths not exposed to lethal temperature (Rubin and Benjamin 1984). Thermal death of seeds of *S. halepense* and *Convolvulus arvensis* L. was observed only in the upper 3–4 cm of solarized soil (Standifer et al. 1984; Katan and DeVay 1991). Rubin and Benjamin (1984) reported that the heat sensitivity of rhizomes of *C. dactylon* (L.) Pers. and *S. halepense*, whereas sprouting of tubers of *C. rotundus* was increased by solarization in several field trials ((Egley 1983; Kumar et al. 1993; Elmore et al. 1997; Miles et al. 2002; Roe et al. 2004). Stimulation of *Cyperus* spp. emergence was found related to pronounced diurnal temperature fluctuations during solarization and was also influenced by polyethylene mulch properties (Miles et al. 1996; Webster 2005). Most studies documented failure of solarization for the control of perennial weeds and in particular of *Cyperus* spp. (Duranti and Cuocolo 1988; Rosskopf et al. 1999; Stapleton et al. 2005; Candido et al. 2008). Other authors observed only a partial elimination (Herrera and Ramirez 1996; Kamra and Gaur 1998), or a fast recover of *C. rotundus* following the removal of plastic film (Lira-Saldivar et al. 2004). A number of reports documented also an effective control of *Cyperus* spp. and other perennial weeds by solarization, either alone or combined with low rates of herbicides (Mushobozy et al. 1998; Marenco and Lustosa 2000; Ozores-Hampton et al. 2001; Gilreath et al. 2005). Extending solarization period up to 8–10 weeks was found to improve the control of *C. rotundus* and other perennial weeds (Rubin and Benjamin 1983; Chase et al. 1998), and in other studies 90-day solarization provided a significant reduction of the weed population which included *C. rotundus* (Stevens et al. 1990a; Ricci et al. 2000). Effect of extended soil solarization on *Cyperus* spp. was found relatively improved by the application of heat-retentive mulches, which provided the death of greater proportions of emerged weeds by foliar scorching (Chase et al. 1998, 1999a) and, moreover, a better residual weed control and a reduced effect of seed depth (Chase et al. 1999b). In other field and greenhouse reports, Patterson (1998) observed that the translucent solarizing mulches were strongly reduced or had totally suppressed emergence and growth of *C. rotundus*, compared to a conventional, opaque, white/black polyethylene film.

Species-dependent heat sensitivity of weeds does not allow a complete control of weed flora by solarization. In a large field survey in food legume crops, solarization suppressed 80% of weeds, without affecting or stimulating species with bulbs, heat-tolerant seeds, deep root systems, or perennial organs (Linke 1994). Approximately 40% of present weed species were found not sensitive to solarization by Marenco and Lustosa (2000), and several weed species were reported as differently tolerant to solar heating by Satour et al. (1991). Tamietti and Valentino (2000) found monocotyledon species less controlled by solarization than dicotyledons, whereas Abdel-Rahim et al. (1988) documented the heat treatment as very effective on a wide spectrum of weeds, except annuals species like *Avena sterilis* L., *A. retroflexus* L., *P. oleracea*, *Xantium strumarium* L., *Malva* spp. and perennials *Cirsium arvense* (L.) Scop., *Cynodon dactylon* (L.) Pers., *Cyperus* spp., and *Sorghum halepense* (L.) Pers.

Length of mulching period, maximal soil temperatures, seed's vigor, and germination depth were also identified as main factors for solarization effectiveness on weeds (Abu-Irmaileh 1991b; Elmore 1991a). Horowitz et al. (1983) found that weed control was related to the number of days with temperatures above a 45°C threshold, though heat-sensitive species were killed after shorter solarization periods than heat-tolerant weeds (Standifer et al. 1984). Arora and Yaduraju (1998) reported that weed control was inversely related to seed depth in soil, as seeds in deeper soil layers were often found to escape the solarization effect (Egley 1983; Horowitz et al. 1983; Rubin and Benjamin. 1984). Standifer et al. (1984) showed that seeds of *C. rotundus* and *E. crus-galli* were killed only in the upper 3–4 cm and those of *E. indica* and *Commelina communis* L. within the upper 5 and 11 cm, respectively. Similarly, survival of *Poa annua* seeds was reduced in the upper 5 cm solarized soil and enhanced at deeper profiles (Peachey et al. 2001). As a consequence, soil disturbance after soil solarization reduces treatment effectiveness, due to the recontamination by viable seeds in deeper soil layers (Egley 1983; Abu-Irmaileh 1991a). Soil and seeds moisture are also involved in weed thermal death, as dry seeds were found still viable up to 120°C while exposure to 50°C was lethal to hydrated seeds (Rubin and Benjamin 1984). Moreover, seeds of various weeds survived a 70°C exposure for up to 3 and 7 days at 19% and 2% soil moisture regimes, respectively (Egley 1990). Wet soil solarization generally provided a more effective weed control than dry soil treatment (Horowitz et al. 1983; Arora and Yaduraju 1998), though Sales Beuno et al. (2003) found weed emergence negatively related to substrate permanence under moist conditions prior to solarization, and other authors reported a single preliminary irrigation as effective as repeated watering (Grinstein et al. 1979c; Horowitz et al. 1983). No effect of irrigation was found on germination or seed viability of *Striga asiatica* (L.) Kuntze in solarized soil (Osman et al. 1991). Color of solarizing mulches may also influence the herbicidal effect of solarization, as both black and clear films reduced weed populations, but a lower control and a shorter residual activity were provided by black compared to clear polyethylene film (Horowitz 1980; Horowitz et al. 1983; Standifer et al. 1984; Campiglia et al. 2000). Finally, Abu-Irmaileh (1991b) found that a further black polyethylene soil mulch after solarization may improve the treatment effect.

Solarization demonstrated to be an effective and inexpensive herbicidal treatment also in nursery beds (Patel et al. 1995; Eleftherohorinos and Giannopolitis 1999; Kumar and Sharma 2005), containerized soil and potting mixes (Stapleton et al. 2002), and even in newly established fruit orchards (Abu-Irmaileh 1994).

Residual effect of solarization treatment was found much more pronounced on weeds than on nematodes and most fungal pathogens, as Candido et al. (2008) reported a consistent reduction or a total suppression of annual and some perennial species present in a solarized greenhouse throughout 2 years following the treatment, and also later for *C. dactylon*. In previous experiments, soil of an olive orchard was weed-free for at least 3 years after solarization (Lopez-Escudero and Blanco-Lopez 2001), and residual effects of soil solarization on *C. rotundus* and *C. esculentus* were observed during four cropping seasons in a tomato–cucumber rotation (Gilreath et al. 2005). Moreover, persistence of weed control may be prolonged by the absence of soil disturbances after the treatment (Bell and Elmore 1983).

9.4.7 Effect on Plant Growth and Crop Yield

Favorable effects of soil solarizarion on plant growth and crop yield were largely documented in many studies (Stapleton and Devay 1984; Davis 1991; Gamiel and Katan 1991). Increased growth response following solarization extended also to nursery seedlings and deciduous tree crops (Stapleton and DeVay 1982; Salerno et al. 2000), and resulted particularly evident under greenhouse conditions, where crop yield and quality was found to last for more than two crop cycles (Candido et al. 2008) (Fig. 9.6). However, solarization was also reported for a negative growth response, as Bendavid-Val et al. (1997) found a growth retardation of carrot and onion sown in solarized soil and Caussanel et al. (1998) related the reduced yield of corn salad, *Valerianella locusta* (L.) Laterrade, after the heat treatment to a suppressed mycorrhizal root infection. Earliness and shorter duration of vegetable crops were also documented by several authors in addition to the increased yield (Chen et al. 1991; Stapleton and DeVay 1995; Sinigaglia et al. 2001; Patricio et al. 2006).

Fig. 9.6 Increased growth response of tomato plants in solarized soil in a plastic greenhouse in Southern Italy. In background the solarized soil with larger tomato plants; in foreground the smaller tomato plants in nonsolarized soil

Gruenzweig et al. (1993) related increased growth response of solarization to a number of physiological changes, as increased photosynthetic activity and protein levels, accelerated tissue development and delayed senescence occurring in the late developmental stages of plants grown in solarized soil. Higher concentrations of gibberellins, linearly related to leaf dry weight increase, reported by Grunzweig et al. (2000) in tomato plants from solarized soil, may suggest that also an alteration of normal plant hormonal balances was stimulated in heat-treated soil.

Most authors agreed that the increased growth response of solarization is not strictly disease-dependent, as occurring also in pathogen-free soils (Abd El-Megid et al. 1998), but rather the result of several effects on soil and plant previously described, including the increase of soluble mineral nutrients and mineralized organic matter (Chen and Katan 1980; Stapleton et al. 1984; Chen et al. 1991; Chen et al. 2000) and of growth regulator factors (Grünzweig et al. 2000), the increased soil biological activities and the control of minor pathogens (Gruenzweig et al. 1993; Gamliel and Stapleton 1995; Tjamos and Fravel 1995; Le Bihan et al. 1997).

9.5 Soil Solarization and Integrated Pest Management

Integrated pest management, i.e., the combined use of multiple control methods to maintain pest damage below an economic threshold, is one of the fundaments of sustainable agriculture, as choice of pest management tactics specifically addressed to cropping systems and technical conditions optimizes performances of existing tactics and eliminates unnecessary pesticide applications (Mullen et al. 1997; Perrin 1997; Martin 2003). Soil solarization demonstrated a large suitability for integrated pest management strategies, as adaptable to most cropping systems and compatible or synergistic with a large number of chemical, biological, and cultural control methods (Stapleton and DeVay 1995; Katan 2000; Stapleton 2000). General achievement of integrated pest management and need for large spectrum control strategies led a number of researchers to investigate effects and mechanisms of the combination of solarization with almost all the available alternative tactics for the control of soilborne pathogens, nematodes, and weeds.

Integration of solarization with reduced rates of fumigants provided additional suppressive effects on many fungal pathogens, though this improved control was not evident in soils with a long previous fumigation history (Albregts et al. 1996) (see Fig. 9.7). Synergistic application of solarization and methyl bromide, metham sodium, 1,3-dichloropropene + chloropicrin, or dazomet was positively verified for reducing incidence viability and symptoms of *V. dahliae*, *F. oxysporum*, and *S. rolfsii* (Frank et al. 1986; Ben-Yephet et al. 1988; Eshel et al. 2000; Yucel et al. 2007); *Rhizoctonia* spp., *P. cactorum*, and *P. capsici* (Yucel 1995; Benlioglu et al. 2005); *P. nicotianae*, *F. oxysporum*, and *S. rolfsii* (Chellemi et al. 1994, 1997; Stevens et al. 2003; Chellemi and Mirusso 2006); *P. lycopersici* and *P. terrestris* (Tjamos 1984; Porter et al. 1989); and *P. brassicae* (Porter et al. 1991). Sequence of treatments was shown to play an important role in the final result, as Eshel et al.

Fig. 9.7 Different growth of eggplant in a plastic greenhouse experiment in Southern Italy. In foreground a solarized plot, in the center a nonsolarized plot

(2000) found application of field sublethal heating followed by fumigation treatment significantly more effective than the opposite sequence. Moreover, additional soilborne disease agents were found to be controlled by pre-wetting soil with metham sodium before solarization (Frank et al. 1986; Tjosvold 2000). Nematicidal effect of soil solarizing treatment was also found to be enhanced by combination with low doses of fumigant nematicides, such as 1,3-dichloropropene (Stapleton and Devay 1983), ethylene dibromide (Barbercheck and Von Broembsen 1986), methyl bromide (Cartia et al. 1989), metham sodium, or dazomet (Yucel et al. 2007). Combination of soil solarization with reduced dosages of 1,3-dichloropropene further reduced populations of root-knot nematodes on tomato and pepper (*Capsicum annuum* L.) and of *G. rostochiensis* on potato in USA (LaMondia et al. 1986; Chellemi and Mirusso 2006) and densities of *H. carotae* on carrot and *D. dipsaci* on onion in Italy (Greco et al. 1990; Greco et al. 1992). Association of solar heating with granular nematicides also demonstrated to be effective for reducing root galling by *M. incognita* on lettuce and melon (Lamberti et al. 2000). However, other field experiments in California showed no improved control of *M. incognita* and *C. xenoplax* by nematicide-combined solarization (Stapleton et al. 1987). Finally, Peachey et al. (2001) documented an improved solarization suppressiveness on weeds by the integration with low rates of metham sodium.

Biocidal activity of organic amendments was hypothesized to be originated by a shift of soil microflora toward antagonistic populations and/or by toxic compounds released during organic matter breakdown (Stirling 1988). Synergism of solarization with amendments may be due to the enhancement of these mechanisms, as Gamliel and Stapleton (1997) found a significantly higher concentration of many volatile compounds released from decomposing organic materials into the solarized soil atmosphere.

An effective integration of solarization treatment with a variety of organic amendments, such as composts, crop residues, green manures, and animal manures, was reported for the control of soilborne pathogens (Kodama and Fukui 1982; Freeman and Katan 1988; Gamliel and Stapleton 1993a,b; Chellemi et al. 1997). High-nitrogen organic materials were effective in reducing inoculum densities of various soilborne pathogens, including heat-resistant species like *M. phaseolina*, and nematodes (Chun and Lockwood 1985; Lodha 1995; Rodriguez-Kabana 1986). Combination of solarization with these materials may be highly effective, as ammonia and/or nitrous acid generated during the decomposition process are retained for longer periods and more effectively diffused in plastic covered soil (DeVay and Katan 1991; Lazarovits et al. 2001; Lodha et al. 2003). Chicken litter amendments were found to improve solarization effect on *P. ultimum* in lettuce (Gamliel and Stapleton 1993), *Rhizoctonia* spp. and *P. cactorum* on strawberry (Benlioglu et al. 2005), and *S. rolfsii* on tomato (Stevens et al. 2003), and integration with urea or farmyard manure was highly effective in reducing *F. oxysporum* f. sp. *cumini* and *M. phaseolina* (Lodha 1995). Ndiaye et al. (2007) reported a strong reduction of inoculum density of *M. phaseolina* and charcoal rot symptoms severity on cowpea, *Vigna unguiculata* (L.) Walpers, by combining solarization with nitrogen-enriched millet residues, whereas no effectiveness was derived from the integration of solarization and butchering residues (Kurt and Emir 2004). Combination of soil solarization with various organic amendments (broiler litter, cottonseed meal, feather meal, soybean oilcake, and urban plant debris) also demonstrated to improve root-knot nematode suppression, compared to single treatments alone, under different conditions (Gamliel and Stapleton 1993b; Stevens et al. 2003; Chellemi 2006; Oka et al. 2007). Moreover, Greco et al. (1992) reported an improved suppression of bulb nematode *D. dipsaci* on onion (*A. cepa* L.) by solarization of soil previously amended with wheat straw, though combination was ineffective on carrot cyst nematode *H. carotae* on carrot. Field studies in Lebanon also reported the synergism of solarization with chicken manure for weed control, as seed germination of *O. crenata* and *Cuscuta campestris* Yunck. was strongly suppressed in amended and then solarized soil (Haidar et al. 1999; Haidar and Sidahmed 2000). Mallek et al. (2007) suggested that amendments with dried crop residues of onion and garlic (*Allium sativum* L.) may improve weed control of solar heating in unfavorable climate or shorter treatment conditions.

Toxic volatiles, mainly isothiocyanates and aldehydes, released during the degradation of crucifer residues into the soil, were found responsible for the inhibition or reduction of many soilborne pathogens and pests (Angus et al. 1994; Keinath 1996; Mayton et al. 1996; Matthiessen and Kirkegaard 2006). Gamliel et al. (2000) reported that concentration of volatiles was directly related to soil temperature and partial anaerobic conditions occurring under a plastic mulch. The improvement of solarization performances by the combination with brassicaceous green manure was reported since the early 1980s (Horiuchi et al. 1982), and largely investigated under various experimental conditions throughout the following decades. Association of sublethal heating with crucifer amendments reduced germination of *P. ultimum* and *S. rolfsii* under laboratory conditions (Stapleton et al. 1995), and effectively controlled *M. phaseolina* in field trials (Lodha et al. 2003). Field integration of solarization with brassicaceous amendments was highly effective for the control of *F. oxysporum* f. sp. *conglutinans* and *M. phaseolina* (Ramirez-Villapudua and Munnecke 1987; Ramirez-Villapudua and Munnecke 1988; Souza 1994; Lodha 1995), but also improved suppression of various other soilborne pathogens (Gamliel and Stapleton, 1993a, `b; Gamliel et al. 2000). Incorporation of oil-cakes or green residues of mustard, *Brassica juncea* (L.) Czern., prior to solarization drastically reduced inocula of *F. oxysporum* f. sp. *cucumis* and *M. phaseolina* (Lodha et al. 1997; Lodha and Mawar 2000; Israel et al. 2005), whereas cabbage residues did not enhance solarization effect on soil population of *Phytophthora* spp. (Coelho et al. 1999). Under greenhouse conditions, solarization integrated with cruciferous biofumigation provided an effective reduction of Pyrenochaeta corky root disease on tomato (Díaz Hernández et al. 2005), and effectively controlled infestation of root-knot nematodes and weeds on melon and pepper (Ploeg and Stapleton 2001; Guerrero et al. 2005). Additive effects could also be obtained from the integrated application of solarization and noncruciferous amendments, as Pinkerton et al. (2000) recorded an improved suppression of *P. cinnamomi* and *V. dahliae* when solarization was combined with green manures of sudangrass, *Sorghum bicolor* (L.) Moench *subsp. drummondii*, and barley (*Hordeum vulgare* L.), and Flores-Moctezuma et al. (2006) reduced damage of *S. rolfsii* in onion seedlings by integrating solar heating with green manures of parthenium weed, *Parthenium hysterophorus* L. Moreover, Lira-Saldivar et al. (2004) documented that leaf resin extract of *Larrea tridentata* (DC) Coville effectively reduced soilborne pathogens incidence and provided a partial protection against nematodes when combined with solarization. Blok et al. (2000) hypothesized the release of toxic compounds as a main mechanism also for the synergistic effect of these noncruciferous green manures in solarized soil.

Inorganic amendments were also reported for an improvement of soil solarization effects (Stapleton et al. 1990). Solarization integrated with calcium cyanamide strongly suppressed or almost completely eliminated population of *F. oxysporum* and *F. solani* f. sp. *cucurbitae* Snyd. and Hans. on a cactus species, *Hylocereus trigonus* (Haw.) Saff., and cucumber, respectively (Bourbos et al. 1997; Choi et al. 2007). Lower soil densities of phytonematode *B. longicaudatus* were observed by McSorley and McGovern (2000) by combining solarization with ammonium bicarbonate or ammonium sulfate application.

Integration of solarization with biocontrol agents may represent a further alternative for an improved management of soil pests (Katan 2000). Populations of the antagonistic fungus *T. harzianum* were found to be not reduced and increase gradually in plant rhizosphere following the heat treatment (Porras et al. 2007a; Jayaraj and Radhakrishnan 2008). Chet et al. (1982) stated that coating iris bulbs with a preparation of *T. harzianum* was highly effective in reducing incidence of diseases caused by *R. solani* and *S. rolfsii* under greenhouse conditions, and integration of solarization with *T. harzianum* provided a significant control of Fusarium crown and root rot of tomato under field and greenhouse conditions (Yücel and Çınar 1989; Sivan and Chet 1993). Application of *T. harzianum* strains after soil solarization caused a total loss of inoculum viability of *Armillaria* spp. (Otieno et al. 2003), or strongly reduced incidence of *Pythium* damping-off on tomato (Jayaraj and Radhakrishnan 2008). Adversely, combination of soil solarization with *T. harzianum* did not provide any additive control of *R. solani* on bean, *Phaseolus vulgaris* L., *P. ultimum* on cucumber, and *F. oxysporum* f. sp. *basilici* on basil, *Ocimum basilicum* L. (Minuto et al. 1995). Other biocontrol agents were also demonstrated to improve suppressiveness of solarized soil. Combination of soil solarization with *Gliocladium virens* Miller, Giddens et Foster proved to be a potential control strategy against *S. rolfsii* southern blight on tomato and pepper (Ristaino et al. 1991, 1996). Application of fluorescent *Pseudomonas* strains to solarized soils reduced incidence of *R. solani* and *Pythium* spp. diseases in tomato and impatiens (McGovern et al. 2002; Jayaraj and Radhakrishnan 2008), and decreased bacterial wilt caused by *R. solanacearum* in ginger, *Zingiber officinale* Roscoe (Anith et al. 2000). Treatments with commercial formulations of *Streptomyces* spp. improved solarization effectiveness against *Pythium* spp., *R. solani*, and Fusarium and Verticillium wilts, whereas variable effects were found on *P. lycopersici* tomato corky root rot in greenhouse (McGovern et al. 2002; Minuto et al. 2006). Integration of soil solarization with a soil drench of *Bacillus subtilis* (Ehrenberg) Cohn reduced crown galls caused by *A. tumefaciens* on cherry rootstock in nurseries (Gupta and Khosla 2007), and use of mixed antagonistic strains of *B. subtilis*, *T. harzianum*, and/or *Fusarium* spp. as seed inoculants reduced the symptoms of *R. solani* on beet in solarized soil (Gasoni et al. 2007). Biocontrol agents also improved the effect of solar heating on root-knot nematodes, as solarization combined with commercial formulations of plant growth-promoting rhizobacteria or *B. firmus* Bredemann and Werner was as effective as a chemical treatment for the control of *Meloidogyne* spp. on tomato and pepper (Kokalis-Burelle et al. 2002; Giannakou et al. 2007). Treatments with a formulation of *Pasteuria penetrans* after solarization resulted in an additive suppression of *M. javanica* and *M. incognita* on cucumber (Tzortzakakis and Gowen 1994), whereas no further nematicidal effect was derived by combining the heat treatment with a commercial formulation of fungus *Paecilomyces lilacinus* (Thom) Samson (Anastasiadis et al. 2008). Hatcher and Melander (2003) also suggested an integrated use of soil solarization with biocontrol agents for the control of heat-resistant weeds normally escaping heat treatment alone.

Adoption of suitable agronomical practices or a proper soil management may also represent valuable options for an enhancement of solarization effects. Ioannou (2001) reported that use of eggplant seedlings grafted on resistant tomato rootstocks provided a complete protection from Verticillium wilt, corky root rot, and root-knot nematodes in solarized soil. Johnson et al. (2007) documented an effective suppression of *C. esculentus* to manageable levels by combining a prolonged summer soil solarization with a fallow tillage, and Sotomayor et al. (1999) obtained a successful control of *M. arenaria* Neal by combination of solarization and soil flooding. Finally, Perrin et al. (1998) suggested that a proper management of mycorrhizal symbiosis in solarized soil may provide a valid alternative to soil fumigation, as also demonstrated by the enhanced suppression of pink root disease in chive resulting from AMF symbiosis in solarized soil (Gamliel et al. 2004).

9.6 Conclusion

Many definitions of sustainable agriculture are reported by literature, but all are related to the basic concept of a profitable crop production with no environmental pollution and depletion of farm and natural resources, including effects on soil, water, and biodiversity (Doran 2002; Francis et al. 2006). Soil solarization seems to fit the fundaments of sustainable agriculture as providing an effective and environmentally safe control of many soilborne pests and more competitive market positions and higher prices to pesticide-free products.

Benefit/cost analysis demonstrated that solarization can also be more convenient than other control techniques, due to its lower costs (Yaron et al. 1991; Elmore 1991a; Bell 1998; Esperancini et al. 2003; Hasing et al. 2004). Potential integration of this technique within more complex pest management strategies is another main advantage of soil solarization, as they are technically combinable with most other available control methods.

However, climate, season, and cropping system specificity still represent serious limits for a further diffusion of soil solarization practice, as effective results are mostly provided by summer application to specific cropping systems, i.e., greenhouse and field horticulture and fruit orchards, in warm climates. Adversely, solarization is less effective and more expensive in cooler regions and not suitable for rain-fed agronomic crops in large areas.

Further limits of solarization commonly reported by literature, such as a difficult and expensive final disposal of plastic films or a treatment duration generally too long for intensive cropping systems, may be overcome, through an improvement of plastic mulches technique. Disposal of plastic residues can be favored by using biodegradable films, as well as the use of high thermal efficiency films or a combination with other control tools may shorten the length of the solarization period. Moreover, combined treatments may also improve results of heating treatment in deeper soil layers, where the thermal effect is normally weaker or completely absent.

Future perspectives for the use of stand-alone solarization will be probably represented by application in greenhouse cropping systems, where high crop values and environmental benefits highly enhance economic convenience of this technique. Based on similar considerations, a great potential for solarization application can also be expected for disinfestation of seedbeds and planting substrates in nurseries (Chaube and Dhananjay 2003), or for preplant disinfestation from fungal pathogens and nematodes in greenhouse or fruit orchards (Jensen and Buszard 1988; Stapleton et al. 1989; Duncan et al. 1992; Rieger et al. 2001). Moreover, soil solarization can also be a valuable soil disinfestation tool for irrigated agriculture in field conditions, when specific crop pest problems do not allow use of pesticides (because of lack of registration, crop tolerance, and hazardous or expensive application) and no other control tool is available, or when heating treatment can solve more than one pest problem (Elmore 1990). Finally, situations where chemical soil disinfestants are forbidden or not advisable, i.e., in farms organically managed or too close to urban or residential areas, can represent further preferential applications of soil solarization in the field.

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Chapter 10
Soil Functions and Diversity in Organic and Conventional Farming

Supradip Saha

Abstract Intensification of modern agriculture is one of the greatest threats worldwide and it has led to growing concern about conserving biodiversity and its role in maintaining functional biosphere. It is now clear that agricultural intensification can have negative local consequences, such as increased erosion, lower soil fertility, and reduced biodiversity; negative regional consequences, such as pollution of ground water and eutrophication of rivers and lakes; and negative global consequences, including impacts on atmospheric constituents and climate. Concerns about the ability to maintain long-term intensive agriculture are also growing. Organic farming is now seen by many as a potential solution to this continued loss of biodiversity due to recycling of natural resources and no negative impact of synthetics. Though almost all soil processes are regulated by soil microbes, the link between microbial diversity and soil function is not well understood.

This review article assesses the impacts on biodiversity of organic farming, relative to conventional agriculture, through a review of comparative studies of the two systems, in order to determine whether it can deliver on the biodiversity benefits. It also identifies and assesses soil processes regulated by microbes under organic and conventional management practices. It also highlights changes during conversion from conventional to organic cultivation regarding biological processes as well as abundance of microbes. It emphasized tools to measure functional diversity and activity of microbes including molecular tool. The review also draws attention to four key issues: (1) differences in functional diversity under organic and conventional management practices; (2) variation in soil processes due to organic management practices; (3) molecular tools and comparative studies related to analysis of microbial biomass or characterization; and (4) changes during conversion to organic farming.

Concerning environmental protection, in general, the risk of adverse environmental effects is lower with organic than with conventional farming methods,

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S. Saha (✉)
Indian Council of Agricultural Research,
Vivekananda Institute of Hill Agriculture, Almora –263 601,
Uttarakhand, India
e-mail: s_supradip@yahoo.com

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though not necessarily so; with reference to soil fertility and nutrient management, organic farming is suited to improve soil fertility and nutrient management markedly on the farm level; regarding biodiversity, comparison studies show that organic farming has more positive effects on biodiversity conservation. Organic farming identifies a wide range of soil microbial community that benefit from organic management through increases in abundance and/or species richness. Management practices used in organic farming are particularly beneficial for farmland wildlife. Although the continuing debate on the issue of adoption of organic farming has not come out with clear-cut resolution in many parts of the world, the biodiversity aspect in soil functions will be on the positive side for the foreseeable future.

Keywords • Comparison • Functional diversity • Molecular tool • Organic farming • Soil processes

Abbreviations

AMF	Arbuscular mycorrhizal fungi
ARDRA	Amplified rDNA restriction analysis
C/N	Carbon-to-nitrogen ratio
FAME	Fatty acid methyl esters
FISH	Fluorescent in situ hybridization
PCR-DGGE	Denaturant gradient gel electrophoresis
PCR-TGGE	Temperature gradient gel electrophoresis
Pg	Pico gram
PLFA	Phospholipid fatty acids
RT-PCR	Reverse transcription polymerase chain reaction
T-RFLP	Terminal restriction fragment length polymorphism
USLE	Universal soil loss equation

10.1 Introduction

The continued threat to the world's natural resources is exacerbated by the need to feed more than six billion people mostly through unsustainable farming practices. Till today very little efforts have been devoted to exploring and characterizing the significance of belowground biodiversity, as most studies were related to aboveground components (Wardle 2002; Bardgett 2005). Both aboveground and belowground components of terrestrial ecosystems are closely related, with soil organisms being intimately linked to plant communities (Bardgett 2005). Indeed, plants provide a source of C and other nutrients for the soil decomposer community in the form of plant litter and root exudates and, in turn, the soil biota, particularly its microbiota, decomposes soil organic matter, stabilizes soil structure and, through its essential role in the cycling of elements, releases nutrients for plant growth (Porazinska et al. 2003). In addition, although abiotic factors have traditionally been interpreted as the engineers of the vegetation patterns observed in terrestrial ecosystems, more recently, biotic interactions in the soil have also been reported as major drivers of the composition of plant communities (Hooper et al. 2000; Wardle and Zackrisson 2005). Therefore, in order to understand the complex patterns of biodiversity in soil ecosystem and, above all, their relationship to ecosystem function, a combined aboveground–belowground approach is required.

There is growing concern about biodiversity conservation and its role in maintaining functional biosphere. A large number of experimental evidence has concluded that most organisms are functionally redundant and that the functional characteristics of component species are at least as important as the number of species for maintaining essential processes (Bardgett and Shine 1999; Andren and Balandreau 1999). As per "insurance hypothesis," some minimum number of species is essential for ecosystem functioning under steady conditions and that a large number of species is probably essential for maintaining stable processes in changing environments (Loreau et al. 2001). However, theories on terrestrial ecosystems have been developed from aboveground observations, whereas comparatively few studies have been made in soil (Griffiths et al. 2000; Ohtonen et al. 1997; Wardle and Giller 1996). The links between aboveground and belowground ecosystem have not been studied in details and so poorly understood. Hence biodiversity and soil functioning are therefore explainable in a limited manner.

Loss of biodiversity due to intensive agriculture has fuelled the debate over the sustainability of current farming practices. Initially within Europe these fears have crystallized and then it has spread globally. A growing number of studies show that organic farming leads to higher quality soil and more biological activity than conventional farming, although the conclusion is not unanimous.

In this brief review the relationship between microbial diversity and soil functionality is discussed in the context of organic and conventional farming. To provide comprehensive view of the complex relations between microbial diversity and soil functionality under organic and conventional management practices, we consider: (1) the functional diversity of microbes under organic and conventional management; (2) quantitative and qualitative differences in soil functions; (3) molecular tool to measure microbial diversity and related limitations; and (4) functional changes during conversion to organic agriculture.

10.2 Ecosystem Functions and Soil

Biotic control over the functioning of soil ecosystems also follows the model described by Chapin et al. (1997) for universal ecosystem. Types of soil biota and their composition are likely to alter soil ecosystem processes through changes in the functional traits (Fig. 10.1). It can alter ecosystem processes, such as phosphorous transformation and availability by plants, which in turn modifies community

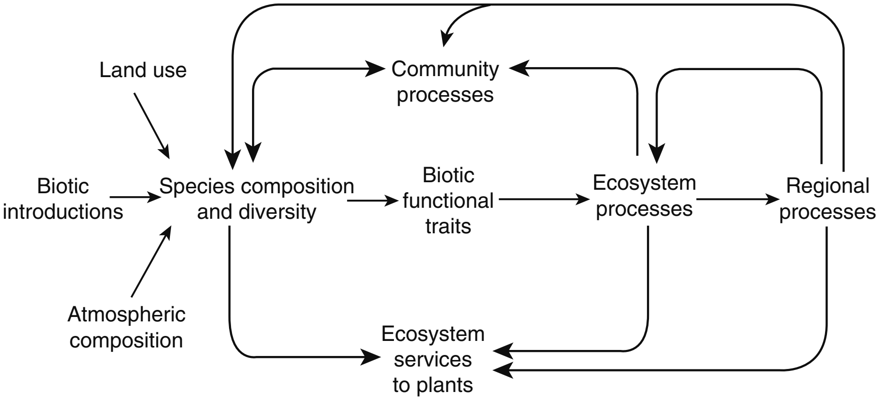

Fig. 10.1 Model representing components of soil ecosystem processes (Modified from Chapin et al. 1997). It depicts biotic control over the functioning of soil ecosystem. Biotic introductions, land use and atmospheric compositions influences species composition and diversity, which controls the biotic functional traits and ecosystem processes

processes. Changes in ecosystem processes can also alter regional processes such as methane emissions from rice field or gaseous nutrient transfers to aboveground ecosystems, extending the impacts beyond the original zone (Fig. 10.1). Some alteration in ecosystem diversity and regional processes change ecosystem services to plants, such as unavailability of nutrients (Nannipieri et al. 2003). Biodiversity can influence these same processes, for two reasons. First, the number of species in a community is a measure of the probability of the presence of species with particularly important traits; second, greater diversity allows a greater range of traits to be represented in the ecosystem, providing opportunities for more efficient resource use in a variable environment.

Changes in species composition and diversity will affect the functioning of ecosystems most strongly when species differ in their effects on ecosystem processes or in their response to environmental changes.

Soil is a heterogeneous mass and it acts as a microhabitat. Soils contain an intricate network of plants and microbes in a heterogeneous solid medium in which chemical and physical conditions vary at the scale of the molecule and the cell. Soil represents the largest carbon pool on the Earth's surface (2157–2293 Pg), the amount of this element being twice as high in soil as in the atmosphere and two or three times larger than the amount in all living matter (Bajtes 1996; Prentice et al. 2001). Because of the large quantity of C stored in soils, small modifications in soil C status may have a significant effect on the global C balance and therefore on climate change (Gonzalez-Perez et al. 2004). The living population inhabiting soil includes macrofauna, mesofauna, microfauna and microflora. Soil comprises a variety of microhabitats with different physicochemical gradients and discontinuous environmental conditions. Microorganisms adapt to microhabitats and live together in consortia with more or less sharp boundaries, interacting with each other and with other parts of the soil biota. A number of investigations emphasize the impact of soil structure and spatial isolation on microbial diversity and community structure (Tiedje et al. 2001; Sessitsch et al. 2001; Ranjard and Richaume 2001). Analysis of the spatial distribution of bacteria at microhabitat levels showed that more than 80% of the bacteria were located in micropores of stable soil microaggregates (2–20 μm) (Ranjard and Richaume 2001). Such microhabitats offer the most favorable conditions for microbial growth with respect to water and substrate availability, gas diffusion and protection against predation.

In their role as "engineer" of soil ecosystem processes, soil organisms perform a number of vital functions. Out of those functions, most of the activities are beneficial to plants and in turn to humans as ecosystem services. Decomposition of organic sources with high C/N ratio, availability of plant nutrients, biological N_2 fixation, plant growth promotion, biocontrol and biodegradation are the few beneficial functions of microorganisms. Some of the important interactions that take place in this ecosystem are suppressing soil-borne pathogen through antagonism, synthesizing enzymes, vitamins, hormones, vital chelators, and allelochemicals that regulate population and processes, direct interaction with plants through mutualism, commensalisms, competition, and pathogenesis.

10.3 Diversity of Microbes

Several studies have investigated microbial communities under organic and conventional systems. Overall, reports on differences in bacterial communities between organic and conventional systems are not so limited (Foissner 1992; Wander et al. 1995; Yeates et al. 1997; Shannon et al. 2002; Girvan et al. 2003; Hole et al. 2005; van Diepeningen et al. 2006), but differences in fungal communities are scanty (Shannon et al. 2002; Sekiguchi et al. 2007). However, there is evidence of a general trend towards elevated bacterial (Fraser et al. 1988; Scow et al. 1994; Mader et al. 1995; Bossio et al. 1998; Gunapala and Scow 1998; Widmer et al. 2006; Melero et al. 2006; Marinari et al. 2006; Elfstrand et al. 2007; Stark et al. 2007) and fungal (Fraser et al. 1988; Yeates et al. 1997; Shannon et al. 2002; Elfstrand et al. 2007) range and abundance under organic farming systems. In a meta-analysis, Bengtsson et al. (2005) reported 30% higher species richness in organic farming. Peacock et al. (2001) reported 30–42% increase in gram-negative bacteria Phospholipid fatty acid (PLFA) biomarkers under organic management practices than conventional. Amendment with carbon rich manures was cited as key factor (Fraser et al. 1988; Gunapala and Scow 1998; Bossio et al. 1998; Peacock et al. 2001; Gomez et al. 2006) along with versatile crop rotations, reduced applications of nutrients, and the ban on pesticides helps in improving biological activity under organic systems (Hansen et al. 2001). Furthermore, addition of farmyard manure for 130 years induces in microbial community towards more bacteria dominated community in specifically coarse sand fraction (Poll et al. 2003). The organically managed soils contained higher numbers of copiotrophic and oligotrophic bacteria, and had a higher diversity in both the eubacteria (van Diepeningen et al. 2006).

Bacterial community was cited too diverse to evaluate the difference, whereas fungal community was suitable for comparing the effect of management practice (Sekiguchi et al. 2007). Furthermore, the fungal community was considered a more suitable indicator of changes due to management practices especially in organic farming as it is responsible for the decomposition of organic matter. Shift in fungal community structure was reported due to organic management practices (Fraser et al. 1988; Yeates et al. 1997; Shannon et al. 2002; Elfstrand et al. 2007; Sekiguchi et al. 2007). Stark et al. (2007) in a recent study concluded that microbial community structure was strongly influenced by the presence or lack of substrate, while the type of amendment (organic or mineral) had an effect on microbial biomass size and activity.

Arbuscular mycorrhizal fungi (AMF) play a crucial role in nutrient acquisition and soil fertility. Studies related to AMF root colonization under organic management practice has been investigated in detail (Cavagnaro et al. 2006; Douds et al. 1997; Galvez et al. 2001; Gryndler et al. 2006; Harinikumar and Bagyaraj 1989; Mader et al. 2000; Oehl et al. 2004).

It was found that the percentage of root length colonized by AMF was 30–60% higher in low-input farming systems than in conventionally farmed soils. Variation of AMF root colonization was explained by chemical properties of the soils especially the effect of soluble soil P being most pronounced (Mader et al. 2000). In another study in Central Europe it was found that AMF spore abundance and species diversity was significantly higher in the organic than in the conventional systems (Oehl et al. 2004). Mineral fertilizer can have a profound negative effect on AMF, as reported by Galvez et al. (2001), who found less spore in mineral-fertilized soil than in organic soil. Gryndler et al. (2006) found that mineral fertilization reduced the growth of AMF, as estimated, using both measurements of hyphal length and the signature fatty acid 16:1ω5, whereas manuring alone increased the growth of AMF. Some species of AMF may even be severely depressed by conventional management (Oehl et al. 2004). On the other hand organic management increased sporulation (Douds et al. 1997) or propogule density in the soil (Harinikumar and Bagyaraj 1989). Studies concluded that AMF species present in natural ecosystems are maintained under organic farming but severely depressed under conventional farming, indicating a potentially severe loss of ecosystem function under conventional farming.

Nematodes play a major role in decomposition and nutrient cycling in soil food webs. Due to its important role in trophic interactions, they have received attention in farming systems especially in organic farming. Although nematodes represent a relatively small amount of biomass in soil, their presence across many trophic levels in soils is vitally important in soil environments and ecosystem processes (Ingham et al. 1986).

In general, higher nematode populations were reported in organic farming than in conventional systems (Foissner 1992; Yeates et al. 1997; Neher 1999; Bulluck and Ristaino 2001; Bulluck et al. 2002; van Diepeningen et al. 2006; Griffiths et al. 2007). Griffiths et al. (2007) reported that application of poultry manure altered the types of nematode present and favored bacterial feeders and rhabditids in particular within a short term as compared to farmyard manure. Diversity of population based on its specific functions were known to be more influential in a soil ecosystem and variations were cited in organic farming practices (Neher 1999; Neher and Olson 1999; Berkelmans et al. 2003; Mulder et al. 2003). Nematodes could be primary, secondary or tertiary consumer. Plant-parasitic nematodes are herbivores and thus primary consumers. Bacterial- and fungal-feeding nematodes are common secondary consumers. Predatory and omnivorous nematodes are tertiary consumers (Beare et al. 1992). Organic soil amendments can have large effects on plant-parasitic nematode dynamics (1996; 1997; Castagnone-Sereno and Kermarrec 1991; McSorley and Gallaher 1995, Crow et al. 1996, Neher 1999; McSorley and Frederick 1999). The plant-parasitic nematode *Meloidogyne incognita* was reduced in soils amended with different organic substrates, and the reduction was attributed to the release of ammoniacal nitrogen (Castagnone-Sereno and Kermarrec 1991; Crow et al. 1996). Reductions in nematode populations occurred when chitin was added to soil infested with plant-parasitic nematodes (Hallmann et al. 1999). Chicken manure, summer cover crops, or green manures can also suppress plant-parasitic nematodes (Abawi and Widmer 2000; McSorley et al. 1999; Viaene and Abawi 1998). In another study, members of the genus *Filenchus* were found more in organic soils than in conventional soils (van Diepeningen et al. 2006).

In general, bacterial-feeding nematodes were more abundant under organic management, whilst fungal-feeding nematodes were more abundant in conventionally managed soils (Berkelmans et al. 2003; Ettema 1993; Ferris et al. 1996; Jaffee et al. 1998; Hole et al. 2005; Neher and Olson 1999; Scow et al. 1994). Crop species influenced nematode communities to a greater extent than management systems in a comparative study of organic and conventional field soils in North Carolina (Neher 1999). Soils under organic and conventional management production in California showed little difference in bacterivore populations or total nematode populations over time, but changes in genera of bacterivores were noted (Ferris et al. 1996). Numbers of bacterivorous nematodes tend to increase after organic amendments are applied to soil since bacterial populations that provide a food base are greater after application of organic amendments (Bouwman and Zwart 1994; McSorley and Gallaher 1996; Ferris et al. 1996; McSorley et al. 1999; Bongers and Ferris 1999; McSorley and Frederick 1999). Bacterivorous nematodes were found to be soil texture specific. Bacterivorous *Acrobeloidus nanus* was found to be in organic sandy soils and *Panagrolaimus* was found in larger numbers in the organic clayey soils than in the conventional clayey soils while in the sandy soils it occurred significantly more than in the conventional soils (van Diepeningen et al. 2006).

Although studies related to nematode-trapping fungi were limited it was observed that the number of species of nematode-trapping fungi was slightly but significantly greater in organic than in conventional plots. Two species (*Arthrobotrys dactyloides* and *Nematoctonus leiosporus*) were detected more frequently in organic plots, and the population densities of *A. dactyloides* and *N. leiosporus* were greater in organic than in conventional plots. Two other species (*A. haptotyla* and *A. thaumasia*), however, tended to be more numerous in conventional than in organic plots, and the total density of nematode-trapping fungi was similar in organic and conventional plots (Jaffee et al. 1998). Additionally, fungivorous nematodes were consistently lower in soils amended with synthetic fertilizers than in soils with organic amendments (Ferris et al. 1996; Bulluck et al. 2002).

In recent past diversity indices were also calculated in order to find out the difference in the functional diversity of microbes under organic and conventional management practices (Crecchio et al. 2004; Gomez et al. 2006: Mulder et al. 2003; van Diepeningen et al. 2006) (Table 10.1). Use of descriptive indices, including the enrichment index, structure index, and channel index provided useful information about the effects of organic amendments on the structure of nematode communities (Bulluck et al. 2002). In an Italian study it was reported that H0, S, and E indices were found to be consistently higher in conventional soil than in organic farming soils and cluster analysis of Community Level Physiological Profiles indicated that the microbial communities are qualitatively much more uniform in organically managed soil (Crecchio et al. 2004). Whereas, Ros et al. (2006) reported that the Shannon diversity index (H) was similar in organic and conventional soil. In contrast, bacterial species richness (*R*) and Shannon index (H) were enhanced due to the incorporation of organic amendments compared to the unamended plots (Gomez et al. 2006). The Shannon–Wiener diversity index for the genera belonging to fungal and bacteria feeding nematodes shows remarkable differences among organic, conventional and intensive agriculture (Bulluck et al. 2002; Mulder et al. 2003).

10.4 Soil Functions

The links between microbial diversity and soil functioning are unknown because it is difficult to measure microbial diversity. In addition, we generally measure soil functions by determining the rates of microbial processes, without knowing the microbial species effectively involved in the measured process (Nannipieri et al. 2003). The central problem of the link between microbial diversity and soil function is to understand the relations between genetic diversity and community structure and between community structure and function.

Several studies have compared the different soil functions associated with organic and conventionally managed fields. Few studies, which primarily investigated the effects of organic amendments on different soil processes, were also included in this review to conclude the comparison between organic and conventional farming. We compared studies for their different soil functions under conventional and organic farming practice (Table 10.2).

With the exception of Fliessbach et al. (2007), all of the studies investigating organic and conventional farming practice recorded higher soil respiration under organic management practice (Araujo et al. 2008; Condron et al. 2000; Dilly 2001; Fliessbach et al. 2000; Gunapala and Scow 1998; Melero et al. 2006; Reganold et al. 1993; Ros et al. 2006; Wander et al. 1994). Wander et al. (1994) demonstrated that soil respiration was 50% higher in the organic animal system, compared with the

Table 10.1 Indicators of soil biological property (Modified from Franzlubbers and Haney 2006)

Indicator	Measurement method	Implications, strength and weakness	Reference
Microbial biomass carbon	Chloroform fumigation incubation	Indicates soil microbial population; various methodologies; controls nutrient cycling and biological transformation necessary for soil aggregation; dependent upon organic inputs	Rice et al. (1996)
Microbial biomass nitrogen	Chloroform fumigation extraction	Indicates biologically active fraction of soil nitrogen; various methodologies; controls nutrient cycling; dependent upon organic inputs	Rice et al. (1996)
Microbial biomass P	Chloroform fumigation extraction	Indicate biologically active fraction of soil phosphorous; control P cycle; dependent upon organic amendments	Brookes et al. (1982)
Potentially mineralizable nitrogen	Aerobic incubation for >2 weeks; 1-week anaerobic incubation	Indicates nitrogen cycling potential; determined by soil testing facility with specialized equipment following incubation in a nonstandard laboratory; relatively time-consuming; dependent upon high quality organic nutrients	Drinkwater et al. (1998)
Soil respiration (flush of CO_2)	Field chamber; Aerobic incubation for >1 week in lab	Indicates soil microbial activity; relatively simple equipment conducted in a nonstandard laboratory; can be determined in field or in laboratory; relatively time-consuming; dependent upon organic inputs	Parkin et al. (1996)
Ratio of microbial biomass to total organic carbon	Calculation from individual measures	Indicates enrichment of microbial biomass relative to total organic carbon; determined in nonstandard laboratory with specialized equipment	Rice et al. (1996)
Respiratory quotient (qCO_2)	Calculation from soil respiration divided microbial biomass carbon	Indicates activity of microbial biomass; determined in nonstandard laboratory with specialized equipment; when high, considered an indication of stress on microbial biomass	Rice et al. (1996)
Enzyme activity (urease, amidase, dehydrogenase, β-glucosidase, phosphatase, arylsulfatase, fluorescein diacetate hydrolysis)	Laboratory incubation	Indicates potential microbial activity and nutrient cycling reactions; determined in nonstandard laboratory with specialized equipment; highly spatially and temporally variable; dependent upon organic inputs	Dick et al. (1996); Parham et al. (2002)

(continued)

Table 10.1 (continued)

Indicator	Measurement method	Implications, strength and weakness	Reference
Phospholipid fatty acid (PLFA)	Methanol-KOH extraction	Indicates bacterial population structure; time-consuming; determined in nonstandard laboratory with specialized equipment; expensive equipment	Dick et al. (1996)
DNA	Extraction and quantification	Indicates total biological structure; time-consuming; expensive equipment; determined in nonstandard laboratory with specialized equipment; difficult for complete extraction	Arbeli and Fuentes (2007)
RNA	Extraction and quantification	Indicates total biological structure; expensive equipment; determined in sofisticated laboratory with specialized equipment; quantifying mRNA is still in its developmental stage	Lleo et al. (2001)
Carbon substrate utilization (BIOLOG)	Incubation of soil with substrates; color development	Indicates functional microbial diversity; determined in nonstandard laboratory with specialized equipment; produces large quantities of data; complex interpretation	Dick et al. (1996)
Nematode population	Various extraction techniques	Indicates soil food web functioning, species richness, and abundance; spatially variable; time-consuming	Blair et al. (1996)
Earthworm population	Handsorting; expulsion	Indicates soil food web functioning; spatially and seasonally variable; time-consuming	Blair et al. (1996)
Pathogen risk assessment	Soil inoculum; bioassay	Indicates potential disease abundance; determined in nonstandard laboratory with specialized equipment; host specific; time-consuming	Van Bruggen and Grünwald (1996)
Soil carbohydrate	Hydrolysis and various estimation techniques	Indicates potential energy source abundance, various technique; controls formation and stabilization of soil structure, dependent upon organic inputs	Safarik and Santruckova (1992)

Table 10.2 Summary of the effects of organic farming *vis-à-vis* conventional farming on different microbial diversity and soil functions

	References	
Parameters	Organic > conventional[a]	Organic ≡ conventional[b]
Bacterial community	Bengtsson et al. (2005); Bossio et al. (1998); Elfstrand et al. (2007); Fraser et al. (1988); Gunapala and Scow (1998); Marinari et al. (2006); Melero et al. (2006); Mader et al. (1995); Peacock et al. (2001); Scow et al. (1994); Stark et al. (2007); van Diepeningen et al. (2006); Widmer et al. (2006)	–
Fungal community	Elfstrand et al. (2007); Fraser et al. (1988); Sekiguchi et al. (2007); Shannon et al. (2002); Yeates et al. (1997)	–
Nematode community	Elfstrand et al. (2007); Fraser et al. (1988); Sekiguchi et al. (2007); Shannon et al. (2002); Yeates et al. (1997); Zaller and Kopke (2004)	–
Arbuscular micorrhizal fungi (AMF)	Cavagnaro et al. (2006); Douds et al. (1997); Galvez et al. (2001); Gryndler et al. (2006); Harinikumar and Bagyaraj (1989); Mader et al. (2000); Oehl et al. (2004)	–
Respiration	Araujo et al. (2008); Condron et al. (2000); Dilly (2001); Fliessbach et al. (2000); Gunapala and Scow (1998); Melero et al. (2006); Reganold et al. (1993); Ros et al. (2006); Wander et al. (1994)	Fliessbach et al. (2007)
N mineralization	Condron et al. (2000); Fraser et al. (1988); Monokrousos et al. (2008); Poudel et al. (2002); Pulleman et al. (2006); Reganold et al. (1993); Tu et al. (2006)	Parfitt et al. (2005); Monokrousos et al. (2008)
P mineralization	Oberson et al. (1996); Oehl et al. (2004)	Daroub et al. (2001); Green et al. (2006)
Leaching	Eltun (1995); Hansen et al. (2000, 2001); Kirchmann and Bergstrom (2001); Knudsen et al. (2006); Poudel et al. (2002); Stopes et al. (2006); Younie and Watson (1992)	Kristensen et al. (2004); Pickett and Goulding (1999); Stopes et al. (2002)
Enzymes	Chang et al. (2007); Fraser et al. (1988); Marinari et al. (2000); Melero et al. (2007); Zaller and Kopke (2004); Garcia-Ruiz et al. (2008); Mader et al. (1995); Tejada et al. (2006); Carpenter-Boggs et al. (2000); Fliessbach et al. (2007); Garcia-Ruiz et al. (2008); Marinari et al. (2006); Marschner et al. (2003); Melero et al. (2008); Saha et al. (2008a, b)	Elfstrand et al. (2007); Saha et al. (2008a)

[a] Organic better than conventional

[b] Organic similar to conventional

conventional system, 10 years after initiation of the Rodale Institute FST. Short-term enhancement of soil respiration was reported by the organic system under 6 months of organic management (Araujo et al. 2008). In contrast, Fliessbach et al. (2007) concluded that soil basal respiration did not differ between organic and conventional farming systems, but when related to microbial biomass, it was 52% higher in conventional farming system as compared to organic.

Though comparison between organic and conventional farming systems were limited in terms of mineralizable nitrogen, evidence from comparative studies indicated higher soil mineralizable nitrogen and the ratio of mineralizable N to organic carbon in the organic farm indicating a higher level of microbiological activity in this soil than in the conventionally farmed soil (Reganold et al. 1993; Condron et al. 2000; Poudel et al. 2002; Pulleman et al. 2006; Monokrousos et al. 2008). Poudel et al. (2002) reported interesting result that potentially mineralizable N was 112% more in organic soil but mineralization rate was 100% more in conventional system. In long-term study also, potentially mineralizable nitrogen was found more in organically managed soil (Fraser et al. 1988; Tu et al. 2006). Koopmans and Bokhorst (2002) validated a model to measure N mineralization under organic management system. In contrast, Parfitt et al. (2005) and Monokrousos et al. (2008) were unable to find significant difference in net nitrogen mineralization under organic farming. Whilst, in an Italian investigation it showed that increased enzymatic activities in the organically managed soil expedite mineralization and mobilization of available nutrients (Marinari et al. 2006).

Only one study investigated nitrogen immobilization under organic and conventional systems. Microbial nitrate immobilization was unexpectedly high and greater in the organic compared to the conventional soil (Burger and Jackson 2003). Moreover, the greater C availability in the organic system apparently supports a more active microbial biomass with greater N demand, thus promoting immobilization and recycling of nitrate.

Only one study specifically compared volatilization losses between organic and conventional soil. Ammonia volatilization is mainly caused by animal manure rather than by N fertilizers (Kirchmann et al. 1998).

Organic farming systems have the potential to minimize some of the negative impacts of conventional agriculture, namely, NO_3 losses to the groundwater, soil erosion, adverse effects of pesticides on non-target organisms, loss of crop genetic diversity (Tilman 1998), and often lead to improvement of soils in terms of biological and chemical properties and physical stability (Reganold et al. 1987; Mader et al. 1995; Drinkwater et al. 1998). Some comparison studies have demonstrated a higher nitrate leaching potential in conventional farming than in organic farming (Eltun 1995; Hansen et al. 2000, 2001; Kirchmann and Bergstrom 2001; Knudsen et al. 2006; Poudel et al. 2002; Stopes et al. 2006; Younie and Watson 1992) except one Danish analysis (Kristensen et al. 2004). Kristensen et al. (2004) found no significant difference in this regard. Other Danish investigations employed a modeling approach to evaluate nitrogen leaching from conventional and organic farming systems and found less leaching from an organic crop production system (Hansen et al. 2000, 2001). Redman (1992) reported that grass/

clover leys, as used on organic farms, significantly reduce the risk of nitrate leaching losses. Dalgaard et al. (2001) concluded in a study that a reduction in total N-loss from agriculture is possible by converting from conventional to organic farming but at the cost of production. Whilst, in a review, Kirchmann and Bergstrom (2001) reported that average leaching of NO_3-N from organic farming systems over a crop rotation period was somewhat lower than in conventional agriculture. But the study could not find any evidence that nitrate leaching will be reduced by the introduction of organic farming practice. In contrast, two substantive investigations indicate that nitrate pollution from organic and conventional farms were effectively identical (Pickett and Goulding 1999; Stopes et al. 2002). The export of N from manure applied soil through green house gas emissions and transport processes such as leaching, surface run off and erosion has been well documented (Adams et al. 1994; Chang and Janzen 1996; Goss and Goorahoo 1995). Migration of P from manure amended soil to ground and surface water has been linked to eutrophication of aquatic systems (Daniel et al. 1994; Sharpley et al. 1994; Heathwaite 1997).

With regard to wider issues relating to environmental quality, van der Weerden et al. (1999) compared nitrous oxide emissions from organic versus conventional farming systems after cultivation, and provided some interesting discussion on the effect of fertilizer (conventional) versus soil cultivation (organic) on the soil mineral nitrogen content and associated gaseous emissions.

Study related to P transformation in organically managed soil is very limited (Oberson et al. 1996; Oehl et al. 2004; Green et al. 2006). Only a few strictly comparative studies of organic and conventional farming and their influence on phosphorous mineralization have been carried out. Basal P mineralization was greater or equal in organic soil than conventional systems (Oehl et al. 2004). Similarly, Oberson et al. (1996) studied microbiological processes in organic P transformations in soils cultivated with conventional and biological farming systems in a long-term study. The level of phosphatase activity and mineralization of organic P indicated a higher turnover of organic substrates and in turn of organic P, in the biodynamic and bioorganic treatments. In contrast, adoption of organic management systems did not increase organic P significantly in a fractionation study (Daroub et al. 2001). Similarly, Oehl et al. (2002) reported that after 21 years, the average P input-output budget was negative for organically managed soil, whereas it was on the positive side in conventional management practice. Basal organic P mineralization was more or equal in organically managed soil than conventional soil, though basal mineralization is comparatively less important than physicochemical processes in P transformation (Oehl et al. 2004). Vermicompost was found better than farmyard manure in faster P transformation (Saha et al. 2008b). Whilst, animal manure-based organic cropping systems have been shown to have greater organic P, adenosine triphosphate, P mineralization, and P cycling and lesser water soluble P than conventional till systems (Oberson et al. 1993, 1996; Oehl et al. 2001).

Considerably fewer studies exist, comparing soil erosion pattern under organic and conventional systems. Soil erosion potential was measured using Universal Soil Loss Equation (USLE) model in 2,056 districts of Germany and it was noticed that on average, about 15% less erosion on arable land was predicted for organic management than for conventional (Auerswald et al. 2006).

Only one study related to sulfur transformation has been reported in organically managed soil. However study related to behavior of sulfur with application of organic source *vis-à-vis* conventional practice are present (Strickland et al. 1987). Knights et al. (2001) reported that S mineralization and immobilization were influenced strongly by the type of land use and long-term organic manuring, whereas annual application of sulfate-containing fertilizers for over 150 years had few effects on short-term S transformations.

There is a need to measure the activities of enzymes and to correlate these measured activities with microbial diversity in soil. It is conceptually wrong to assume a simple relationship between a single enzyme activity and microbiological activity in soil (Nannipieri et al. 2003). Most of the assays used to determine microbiological activities in soil present the same problem: measuring potential rather than real activities (Nannipieri et al. 1990). Indeed, assays are generally made at optimal pH and temperature and at saturating concentration of substrate. Furthermore, synthetic rather than natural substrates are often used, and soil is incubated as a slurry (Nannipieri et al. 1990).

Several major studies have compared soil enzymatic activities responsible for different nutrient cycling under organic and conventional systems. Overall, the result of those studies suggest that organically managed fields contain a greater enzymatic activity than conventionally managed fields (Carpenter-Boggs et al. 2000; Fliessbach et al. 2007; Garcia-Ruiz et al. 2008; Marinari et al. 2006; Marschner et al. 2003; Melero et al. 2008; Saha et al. 2008a, b). In a comparative study of 18 pairs of organic and conventional soils, it was concluded that organic management resulted in significantly higher soil enzyme activities (Garcia-Ruiz et al. 2008). Fliessbach et al. (2007) reported that relative to the organic soils at the same fertilization intensity, dehydrogenase activity was 39–42% lower in conventionally managed soils. Lupin amendment resulted in a twofold to fivefold increase in dehydrogenase activity in a 91 days incubation study (Stark et al. 2007). Significant increase in dehydrogenase, protease, and acid phosphatase in organic soil as compared to conventional soil, which may expedite mineralization and mobilization of available nutrients (Marinari et al. 2006). In a Spanish study, increased urease, protease, and alkaline phosphatase activity was observed in organically managed soil (Melero et al. 2006). Application of pig slurry compost and vermicompost in the organic soil showed higher dehydrogenase, protease, phosphatase, and β-glucosidase activities than the inorganically fertilized soil (Marinari et al. 2000; Ros et al. 2007; Saha et al. 2008a). However, similar levels of urease activity were observed in both types of soil (Ros et al. 2007).

In contrast, protease and arylsulphatase activities were found comparable to a mineral-fertilized treatment receiving no additional C, whereas acid phosphatase activity increased (Elfstrand et al. 2007). Similarly, Saha et al. (2008a) reported that β-glucosidase activity was higher in conventional soil than organic soil. Under dryland and semi-arid condition also organic fertilization improved dehydrogenase, protease, glucosidase, urease, and alkaline phosphatase activities (Melero et al.

2006, 2007). Whilst, in a greenhouse study also, dehydrogenase, cellulase, β-glucosidase, protease, urease, arylsulphatase, acid and, alkaline phosphatase activities were higher in organic management than conventional one (Chang et al. 2007).

10.5 Measurement of Microbial Diversity

Any comparison of the impacts of organic and conventional farming systems on biodiversity is likely to be problematic, largely as a result of the complexity of, and interactions between, the range of farming practices that comprise the two systems. The majority of studies seek to minimize apparently extraneous variation, unrelated to farming system with varying degrees of rigor and success. Some studies then go further, attempting to control for variation in crop-type, non-crop habitat or tillage method, either statistically or within a paired field/farm design. Others consider that such variation is part of the overall difference between regimes. The studies reviewed here comprise both extremes of this spectrum, potentially complicating any unbiased assessment. Above all, tool to measure the difference should be of high resolution so that clear-cut difference should be made.

Microbial diversity can be classified into genetic, functional and structural diversity. Soil genetic and structural diversity can be measured by various techniques. Genetic diversity of bacteria is most commonly studied by diversity of the 16S rDNA genes using Denaturing Gradient Gel Electrophoresis (PCR-DGGE) and Temperature Gradient Gel Electrophoresis (PCR-TGGE). Terminal Restriction Fragment Length Polymorphism (T-RFLP) (Liu et al. 1997) is an alternative method for examining diversity of 16S rDNA sequences of microbial communities. Structural diversity is measured by estimating PLFAs profile. The benefit of a high genetic diversity is currently under debate because it is not always correlated to functional diversity (2001, Griffiths et al. 2000).

The diversity of functions within a microbial population is important for the multiple functions of a soil. The functional diversity of microbial communities has been found to be very sensitive to environmental changes (Zak et al. 1994; Kandeler et al. 1996, 1999). However, the methods used mainly indicate the potential in vitro functionality. Functional diversity of microbial populations in soil may be determined by either expression of different enzymes (carbon utilization patterns, extracellular enzyme patterns) or diversity of nucleic acids (mRNA, rRNA) within cells, the latter also reflecting the specific enzymatic processes operating in the cells. Indicators of functional diversity are also indicators of microbial activity and thereby integrate diversity and function.

Carbon utilization patterns can be measured by the BIOLOG^{TM} assay (Garland and Mills 1991). The result of the assay is a qualitative physiological profile of the potential functions within the microbial community. The BIOLOG^{TM} assay has been shown to be more sensitive than microbial biomass and respiration measurements to impacts of soil management practices and of sewage sludge amendments to soil (Bending et al. 2000).

The enzymatic activity in soil is mainly of microbial origin, being derived from intracellular, cell-associated or free enzymes. Only enzymatic activity of ecto-enzymes and free enzymes is used for determination of the diversity of enzyme patterns in soil extracts. Enzymes are the direct mediators for biological catabolism of soil organic and mineral components. Thus, these catalysts provide a meaningful assessment of reaction rates for important soil processes. Enzyme activities can be measured as in situ substrate transformation rates or as potential rates if the focus is more qualitative. Enzyme activities are usually determined by a dye reaction followed by a spectrophotometric measurement.

Indicators of microbial activity in soil represent measurements at the ecosystem level (e.g., processes regulating decomposition of organic residues and nutrient cycling, especially nitrogen, sulfur and phosphorus). Measurements at the community level include bacterial DNA and protein synthesis. Frequency of bacteriophages is a measurement at the population level.

Synthesis of DNA is a prerequisite for bacterial cell division and, as such, an indicator of bacterial growth. DNA is unique in the way that it only participates in cell division. DNA synthesis can be determined by incorporation of ^{3}H- or ^{14}Cthymidine into bacterial DNA as thymidine is a unique nucleoside, which only participates in DNA synthesis.

Bacterial protein synthesis is directly correlated to bacterial activity and can be determined by incorporation of 3H or 14C leucine, as this amino acid is incorporated into proteins only. The method for leucine incorporation (Baath 1994) is the same as for thymidine incorporation in case of DNA synthesis and the incorporation of both precursors can be carried out in a single assay if different radiolabels are used.

The RNA molecules, ribosomal RNA (rRNA) and messenger RNA (mRNA) play key roles in the protein synthesis. The amount of RNA in individual cells or in a community may, therefore, be taken as an indicator of protein synthesis and, thus, microbial activity. The number of active cells can be detected by fluorescent in situ hybridization (FISH) (Amann et al. 1995). By this method, individual cells carrying high concentrations of rRNA, situated on ribosomes, are quantified by fluorescence microscopy. The amount of rRNA in a community can also be detected by Reverse Transcriptase Polymerase Chain Reaction (RT-PCR), where rRNA extracted from soil is detected by creating a DNA copy and separating by gel electrophoresis (Duineveld et al. 2001).

mRNA molecules are gene copies used for synthesis of specific proteins by the cell. The nucleotide sequences of mRNA molecules reflect the type of enzymes synthesized. Concentration of mRNA is correlated with the protein synthesis rate and as such with the activity of the microorganism. Therefore, the content and diversity of mRNA molecules will give very accurate pictures of the in situ function and activity of the microbial community. Detection and quantification of a specific mRNA molecule can be done by reverse transcription PCR (RT-PCR), which is a very sensitive method (Pfaffl and Hageleit 2001). A prerequisite of this technique is knowledge of the nucleic acid sequence of the mRNA for a specific gene. For certain genes, this information is available. However, the technique of quantifying mRNA is still in its developmental stage. Sensitivity of the method has though been improved by associating a magnetic capture system (Lleo et al. 2001).

PCR-based fingerprinting techniques give a higher resolution and provide information about changes in the whole community structure. These fingerprinting techniques, such as PLFA analysis, denaturant gradient gel electrophoresis (DGGE), amplified rDNA restriction analysis (ARDRA), T-RFLP and ribosomal intergenic spacer analysis (RISA), provide information on the species composition, and can be used to compare common species present in samples. However, there are some problems and biases in the PCR amplification step and, therefore, these methods cannot be used as definite indicators of species richness.

Perhaps the greatest challenge facing microbiology today is the problem of linking phylogeny and function. The methods based on 16S rRNA analysis provide extensive information about the taxa present in an environment, although they provide little insight into the functional role of each phylogenetic group. Metagenomic analysis provides some functional information through genomic sequence and expression of traits, but other methods are required to link specific functions with the group responsible for them. The concomitant quantitative and comparative analyses of expressed rRNA genes and genes for key enzymes in relation to environmental factors can be used to obtain information about the phylogeny and ecology of functional bacterial groups responsible for processes like denitrification, nitrification and methane oxidation.

All the tools have their own limitations especially in the context of functional diversity (Muyzer and Smalla 1998; Heuer et al. 2001; Nannipieri et al. 2003). Different techniques vary in their resolutions (Fig. 10.2).

Studies of sequence information from organisms in soil microhabitats and their gene expression under different management conditions will provide guidelines for designing new and improved culturing methods that resemble their natural niches.

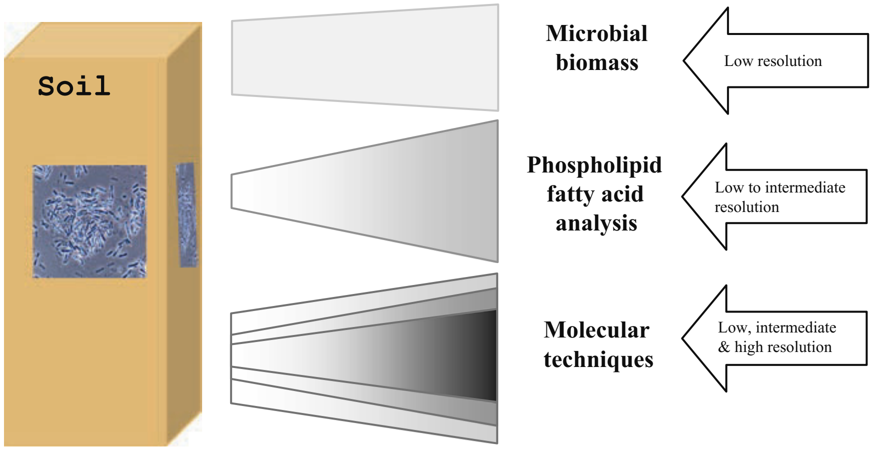

Fig. 10.2 Variability in resolution of tools of microbial analysis (Adopted from Nannipieri et al. 2003). Shades represents the resolution; darker the shade more the resolution and vice versa

New tools in bioinformatics and statistical analysis enable us to handle the huge amount of data obtained through multidimensional studies that combine growth independent molecular analyses with analyses of microbial growth, activity and physiology, and integrate measures of environmental parameters. Such polyphasic studies integrate different aspects of microbial diversity and provide a more complete picture of microbial diversity and a deeper understanding of the interactions in soil microbial ecosystems. Studies of microbial sequences, comparative genomics and microarray technology will improve our understanding of the structure/function relationships and the effects of abiotic and biotic factors on soil microbial communities. It is conceivable that with these new tools it is possible to differentiate shifts in community structure.

Few studies have been done to compare the functional diversity of microbes under organic and conventional management practices. Functional diversity of microbes in organic soil was studied using molecular tool (Stark et al. 2007; Sekiguchi et al. 2007; Postma et al. 2008). Sekiguchi et al. (2007) investigated to find out difference in fungal community structure using DGGE and found no difference between organic and conventional soil. In case of bacterial communities greater diversity was reported by Marinari et al. (2006), Melero et al. (2006) and Widmer et al. (2006). In a lupin amendment study, Stark et al. (2007) analyzed microbial community structure of actinomycetes and eubacteria using PCR-DGGE of 16S rDNA and found differed significantly between the two soils with 4 and 8 Mg ha^{-1} after long-term application not by short-term incubation. Differences between the integrated, compost and mineral soils can be attributed to the weaker and less abundant bands in PCR-DGGE (Ros et al. 2006).

Effects of fertilization on the soil community fatty acid methyl esters (FAMEs) were apparent by the second year of the study. Compost-fertilized plots were distinguishable from mineral-fertilized soil (Carpenter-Boggs et al. 2000). Bacterial PLFA were unaffected by management practices, whereas fungal PLFA were greater in organic soil than conventional (Yeates et al. 1997). PLFA profile in organically managed soil differed from other treatment (Elfstrand et al. 2007). PLFA composition of the organic and conventional soils clearly differed in their mole percentages of numerous fatty acids (Lundquist et al. 1999). Typical Gram-negative bacteria PLFA biomarkers were significantly higher than conventional treatment (Peacock et al. 2001).

10.6 Changes During Conversion

The transition from conventional to organic and low-input farming is accompanied by changes in an array of soil chemical properties and processes that affect soil fertility. Fundamental differences, both qualities and quantitative, in the flow and processing of nutrient result from the use of cover crops, manure and compost applications, and reduction or elimination of synthetic fertilizers and pesticides. These changes affect nutrient availability to crops either directly by contributing to nutrient pools or indirectly by influencing the soil chemical and physical environment.

Few studies were reported with regards to conversion from conventional to organic farming (Werner 1997; Tu et al. 2006; Melero et al. 2007; Gopinath et al. 2008). Yield reduction in organic farming due to nutrient limitation and pest incidence in the early stages of transition from conventional to organic systems is a major concern for organic farmers, and is thus a barrier to implementing the practice of organic farming. Therefore, study related to transition strategies is important for facilitating the implementation of organic practices.

Microbial biomass and respiration rate were more sensitive to changes in soil management practices than total C and N. In the first 2 years, the organic management was most effective in enhancing soil microbial biomass C and N among the transition strategies, but was accompanied with high yield losses. By the third year, soil microbial biomass C and N in the reduced-input transition strategies were statistically significantly greater than those in the conventional. Soil microbial respiration rate and net N mineralization in all transitional systems were statistically significantly higher than those in the conventional, with no differences among the various transition strategies. The study suggested that the transitional strategies that partially or gradually reduce conventional inputs can serve as alternatives that could potentially minimise economic hardships as well as benefit microbial growth during the early stages of transition to organic farming systems (Tu et al. 2006). Axelsen and Elmholt (1998) estimated that a transition to 100% organic farming in Denmark would increase microbial biomass by 77%, the population of springtails by 37% and the density of earthworms by 154% as a nationwide average. Conversion to organic farming provides opportunities to significantly increase biological activity of the soil as well (Axelsen and Elmholt 1998). During conversion from conventional to organic farming, Melero et al. (2007) reported gradual increase in dehydrogenase, protease, β-glucosidase and alkaline phosphatase. In a 2-year conversion period, most of the enzymatic activities were more in organically managed soils than mineral-fertilized soils (Gopinath et al. 2008).

10.7 Conclusion

The relation between microbial diversity and soil functions is poorly understood because we cannot measure easily the microbial diversity, even if we can detect unculturable microorganisms by molecular techniques (Nannipieri et al. 2003). In addition, the present assays for measuring microbial functions determine the overall rate of entire metabolic processes, such as respiration, or specific enzyme activities, without identifying the active microbial species involved. The recent advances in RNA extraction from soil might permit us to determine active species in soil (Griffiths et al. 2000; Hurt et al. 2001). Further advances in understanding require us to determine the composition of microbial communities and microbial functions in microhabitats.

Organic management currently provides a clear advantage over conventional farming as a whole with respect to microbial diversity. This review indicates that organic farming has the potential to help in achieving the conservation of soil biodiversity. Despite the pressing need for long-term, system-level studies of the biodiversity response to organic management at the landscape scale, the available evidence indicates that organic farming could play a significant role in increasing biodiversity. At the same time, continued growth in the organic farming sector is dependent on sustained consumer and legislative support, which in turn will depend largely on the outcome of the debate over the balance between environmental benefits and resource performance. Though the continuing debate on the issue of adoption of organic farming has not come out with clear-cut resolution in many parts of the world, the biodiversity aspect in turn soil functions will be on the positive side for the foreseeable future.

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Chapter 11
Indigenous Soil Knowledge for Sustainable Agriculture

Iin P. Handayani and Priyono Prawito

Abstract Indigenous soil knowledge, a foundation of traditional farming systems, plays an important role in developing agricultural and environmental sustainability, especially in developing countries where most farmers have limited access to soil analysis and extension services. Recently, indigenous soil knowledge has been recognized as a vital source for most scientists to be used to change and improve natural resource management without neglecting the social and cultural values of the local environment. However, the transfer of the knowledge from generation to generation, farmer to farmer, farmers to scientists, and scientists to farmers is critical for a better understanding of soil processes, which is a major part in developing sustainable agriculture. This chapter reviews indigenous soil knowledge and its application and how scientists respond to the value of indigenous soil knowledge and integrating it into agricultural activities. Case studies from various countries in Africa, America, Asia, and Europe revealed that there is a diversity of local or traditional knowledge and practices in soil management. These include plant species selection, landscape management, succession or fallow management, ways to observe soil degradation, and practices of responding to ecological problems in soils (i.e., fertility, acidity, erosion, biodiversity). Farmers' experiences illustrate the benefits of using indigenous soil knowledge and the incorporation of it into scientific soil knowledge to nurture and conserve natural resources. Combining both of the knowledge seems to be the best approach to support sustainable farming systems grounded in local environments and cultural values. For future, a more complete understanding of soil processes needs to be developed, not only based on local observations, but also in terms of philosophies and methodologies of transferring the knowledge. Farmers should be familiar with soil process concepts from

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I.P. Handayani (✉)
School of Agriculture, Murray State University, S 213 Oakley Applied Science Building,
Murray, KY, 42071, USA
e-mail: iin.handayani@murraystate.edu

P. Prawito
College of Agriculture, University of Bengkulu, Jalan Raya Kandang Limun, Bengkulu,
38371, Sumatra, Indonesia

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both knowledge to achieve better and more sustainable relationship with their land, and to respond to the global opportunities and challenges.

Keywords Farming system • Indigenous soil knowledge • Scientific soil knowledge • Soil characteristics • Soil degradation • Soil restoration Sustainable agriculture • Traditional soil knowledge

11.1 Introduction

Indigenous or folk knowledge refers to local people's knowledge (Bellon and Taylor 1993). It is crucial for agricultural and environmental sustainability, especially in developing countries where most farmers have limited access to soil analysis and extension services (Smalling and Braun 1996; Handayani et al. 2006). Farmers usually derive their knowledge from their long interaction with local agroecosystems (Altieri 1990; Barrios et al. 1994). The transfer of indigenous knowledge from generation to generation becomes critical for a better understanding of soil processes, which is a major part in agriculture ecosystems.

Interest in indigenous knowledge has been growing in recent years due to greater recognition in biodiversity conservation (Gadgil et al. 1993), protection of watersheds (Johannes 1993), management of agroecosystems (Handayani et al. 2006), greenhouse gas mitigation (Winklerprins 1999), and improved resource use in a sustainable way (Schmink et al. 1992). Scientists, biologists, ecologists, ecological anthropologists, and sociologists all share an interest in indigenous knowledge for scientific, social, or economic reasons (Norton et al. 1998).

According to Warren and Rajasekaran (1993), indigenous knowledge is considered a valuable part of national resource management because (1) it provides concepts to facilitate communication among various people, such as researchers and extension workers, (2) it helps to assure that the users of specific agricultural development projects are involved in developing technology appropriate to their needs, (3) it can be used as the basis for decision making and provides the foundation for local innovations and experimentations, (4) it is relatively cost-effective, because it builds on local development efforts, thus enhancing sustainability and capacity building, and (5) it can facilitate a dialogue between rural populations and development workers.

Being the basis of agricultural development, soil knowledge plays an important role in managing crop yields. Indigenous soil knowledge has now been recognized and accepted as a vital source due to the growing awareness of locally generated information that can be used to change and improve agriculture and natural resource management (Chimaraoke et al. 2003; Handayani et al. 2006).

The study of indigenous soil knowledge began with soil observation and classification (ethnopedology), and proceeded to considerations of local communities' understanding of soil processes and their relationships with agriculture production and the environment (Talawar and Rhoades 1998). Most indigenous soil knowledge analyses have components of local observation toward natural resources and environmental phenomena, local knowledge and practice, and beliefs regarding how people fit into or relate to the ecosystem (Murage et al. 2000; Winklerprins 1999). Therefore, indigenous soil knowledge is a knowledge – practice – belief complex (Sandor and Furbee 1996; Steiner 1998).

Indigenous soil knowledge can be seen as adaptive and holistic in outlook. It is commonly gathered by observers through generations because their lives depended on this information (Ingram 2008; Handayani and Prawito 2008). It is often collected incrementally, examined by trial and error for many years, and passed on to future generations orally or during practical experiences (Ohmagari and Berkes 1997). Not all practices from it are considered to be ecologically wise because of the changing conditions (Dwyer 1994; Roberts et al. 1995). For example, farmers in Sumatra, Indonesia use *Chromolaena odorata* (Fig. 11.1) or *Austroeupotarium* spp. to improve soil fertility in cocoa and cinnamon agroforests and deforested areas (Burgers and Williams 2000; Handayani et al. 2006). In fact, some households spread more seeds to ensure thick growth (Burgers and William 2000). Ecologically, this practice is not wise because the species is considered an invasive plant. Farmers in Chiapas, Mexico, justify that earthworms have a positive impact on soil quality (Grossman 2003). Earthworms are beneficial to soil because they can produce casts (Fragoso et al. 1997), increase the number of macropores and improve water infiltration (Francis and Fraser 1998), and influence decomposition process (Subler et al. 1998). However, farmers in the southern highlands of Papua New Guinea observed that earthworm population caused a decrease in sweet potato yield (Sillitoe 1995).

Despite some inherent contradictions, growing interest in indigenous soil knowledge for creating sustainable ecosystems indicates that we need to seek further insights into the ecologically wise practices generated from it, which is the objective of this chapter. We provide a diversity of indigenous soil knowledge systems and discuss the their usefulness as complements to scientific information.

Fig. 11.1 *Chromolaena odorata* has invaded *Imperata cylindrica* grassland in Sumatra, Indonesia

The synthesis is partly based on the findings from various studies exploring farmers' or local communities' knowledge linked to ecosystem management. With such knowledge it will be possible to predict whether a particular indigenous soil knowledge can be used to design agroecosystems that have the best chance to be sustainable.

In this chapter, we will focus on the role of indigenous soil knowledge as a foundation for sustainable agriculture. Indigenous soil knowledge from different regions is exemplified to illustrate how agricultural ecosystems and sustainable crop productions are maintained to secure a flow of natural resources and ecological services on which people depend.

11.2 Indigenous Soil Knowledge and Sustainable Agriculture

11.2.1 What Is Indigenous Soil Knowledge?

Indigenous soil knowledge is considered an important part of traditional ecological knowledge. Traditional ecological knowledge refers to the knowledge, practice, and belief concerning the relationship of living beings to one another and to the physical environment, which is held by people in relatively nontechnological societies with a direct dependence on local resources (Berkes 1993). It has equal status to scientific knowledge (UNEP 1998) and has been named as "the intellectual twin to science" (Deloria 1995). Gadgil et al. (1993) stated that modern scientific knowledge accompanied by the human view on the natural world has been successful for better understanding and manipulating the simple systems. However, neither the human view nor scientific knowledge has been particularly successful when facing complex ecological systems. This context shows that traditional ecological knowledge is significant regarding ecosystem management.

Indigenous soil knowledge is recognized as ideas, beliefs, values, norms, and rituals about soils, which are native and embedded in the minds of people and considered to be local knowledge (Warren et al. 1995; Akullo et al. 2007; Handayani et al. 2006). It derives from the physical, biological, and spiritual environment that is part of daily life (Deloria 1992). To a given culture or society, indigenous soil knowledge is unique and dynamic because it changes through creativity and experiment, as well as through interaction with other local and national or international influences (Warren et al. 1995). Its systems are often integrated and adapted to local culture and environmental conditions and linked to the needs of local people and the available resources (Akullo et al. 2007). As a tool, indigenous soil knowledge can create better understanding and can predict the environmental changes to soil upon which the livelihood or even individual survival depends (Berkes 1993; Deloria 1996; Stevenson 1996; Handayani et al. 2006).

Indigenous soil knowledge can be a source of new insights to soil management and potential design for land conservation, rehabilitation, and sustainable development. It has practical significance to contemporary sciences, such as agriculture, ecology, forestry, wildlife management, and environmental science. In addition, it has high potential for incorporating the science of ecological restoration (Martinez 1994; Kimmer 2000). For example, farmers in the forest margins of Sumatra, Indonesia, use soil color of yellowish red or light brown to indicate planting times for coffee following vegetable cropping during shifting cultivation sequence (Handayani and Prawito 2008). Native farmers justify that vegetable cropping for 3 years changes the soil color where upon the soil cannot provide enough nutrients for vegetables, but can provide for coffee trees. In addition, they observe that coffee trees can help restore the soil via litter accumulation and decomposition over time.

The World Conservation Union (IUCN 1986) recognizes that indigenous soil knowledge gives benefits to the environmental applications, new biological insights, environmental assessment, commodity development, sustainable agriculture, natural resource management, development and planning, and environmental education. It also plays an important role in monitoring ecological changes by providing early warning signs of change. The collection of it will bring wisdom to sustainable development (Handayani et al. 2006; Handayani and Prawito 2008; Williams and Baines 1993).

Most of indigenous soil knowledge has much in common with scientific soil knowledge (Handayani et al. 2006). This is not surprising because both types of knowledge derive from a similar source, that is, structured observations of nature. Both the knowledge systems provide information on natural phenomena and interaction among the components in the ecosystems (Mauro and Hardison 2000). However, indigenous soil knowledge differs from scientific soil knowledge in several ways (Handayani et al. 2006; Handayani and Prawito 2008). The observations tend to be qualitative and have data base from a single local site over a long period. Also, the observers tend to be the resource users themselves, for example, farmers, fishers, hunters, and gatherers, who successfully maintain the quality and reliability of their land. On the other hand, scientific observations made by groups of scientists or professionals are quantitative and often represent simultaneous observations from a wide range of sites (Corbeels et al. 2000; Habarurema and Steiner 1997).

Scientific soil knowledge is performed by academia in which nature is objectively viewed (Pierotti and Wildcat 2000). Indigenous soil knowledge is woven into and cannot be separated from the contexts of social, spiritual, and cultural practices. There is a competition between indigenous soil knowledge and scientific soil knowledge as a body of empirical information. However, indigenous soil knowledge may often hold more explanatory power beyond what scientific information can have, in terms of social and cultural values. Values are usually associated with indigenous soil knowledge, while scientific knowledge relies on data which is "value-free" (Berkes 1993). Respect, ethics, and obligations between human and nonhuman in the ecosystems are considered values in indigenous soil knowledge. Combination between indigenous and scientific soil knowledge offers not only important soil insights, but also a cultural framework for soil problem solving, which involves human values (Handayani et al. 2006).

11.2.2 Importance of Indigenous Soil Knowledge in Developing Sustainable Agriculture

The farming system is a foundation in agriculture. A sustainable farming system is recognized as a system that maintains the resource base upon which it depends, relies on minimum of synthetic inputs, manages pests and diseases through internal regulating processes, and can recover from the human disturbance caused by agricultural practices, i.e., cultivation and harvest (Edwards et al. 1990; Altieri 1995). Sustainable agriculture is farming systems that are maintaining their productivity and benefit to society indefinitely (Appleby 2005; Lichtfouse et al. 2009).

Gleissman (2001) describes that the components of sustainable agriculture begin with two types of existing systems: natural ecosystems and traditional farming systems (Table 11.1). Both have a test of time to maintain land productivity and provide a different kind of knowledge. Natural ecosystems offer a reference point for better understanding of the ecological process of sustainability; while traditional farming systems provide various practices to support the social systems, culture, politics, and economy in order to be fit into the sustainability formula. The knowledge resulting from these systems can help agricultural research to create principles, practices, and designs that can be applied to unsustainable farming systems thereby transforming them into sustainable systems.

Altieri (1990) provides standard characteristics of traditional farming systems that make them sustainable. Sustainable farming systems commonly do not rely on external, synthetic inputs, but use locally available resources, such as local crop varieties, wild plants, and animals, which promote nutrient cycling, minimize negative impacts on environment, and maintain spatial and temporal variability. Sustainable systems are tolerant to local conditions, adapted to microclimate variation within the cropping system, farm, and region, and able to maximize yield to meet local needs first without sacrificing the long-term productivity. In addition, sustainable farming systems are built with indigenous or local knowledge (Handayani

Table 11.1 Characteristics of natural ecosystems, sustainable farming systems and unsustainable farming systems (Gleissman 2001)

Characteristics	Natural ecosystems	Sustainable farming systems	Unsustainable farming systems
Production	Low	Low/medium	High
Species diversity	High	Medium	Low
Resilience	High	Medium	Low
Flexibility	High	Medium	Low
Output stability	Medium	Low/medium	High
Human displacement of ecological processes	Low	Medium	High
Reliance on external inputs	Low	Medium	High
Internal nutrient cycling	High	Medium/high	Low
Sustainability	High	High	Low

et al. 2006; Handayani and Prawito 2008). The last statement supports the idea that indigenous knowledge is the foundation for developing sustainable agriculture. Indigenous knowledge can be related to plant varieties, soil, agricultural practices and tools, land conservation, land restoration and biological diversity. A sustainable farming system does not need to have all the characteristics above, but it must be planned in order to have all functions of these characteristics (Gleissman 2001).

Further, Gleissman (2001), Odum (1984), Conway (1985), and Altieri (1995) observed differences between two types of farming systems and one natural ecosystem. Table 11.1 shows that sustainable farming systems have high diversity, resilience, and the autonomy of natural ecosystems, while unsustainable farming systems or conventional agroecosystems provide relatively lower and more variable crop production. Lower crop production is usually caused by reduction in external inputs and adverse environmental impacts.

The characteristics of sustainable and traditional farming systems offer important lessons about the role of local society in sustainability. For farming systems to be sustainable, the culture and the economy of the local people must support and utilize practices that are ecologically sound (Gleissman 2001). In this case, the farmer has to make a decision to maintain the continuity of farm stability. For example, fallow periods have to be extended to restore the soil fertility, so that the farmers do not have to put more manure on the ground (Handayani et al. 2006). Traditional farming systems tend to use the concept of ecological knowledge, which is the beginning step in developing sustainable agriculture (Gleissman 2001; Altieri 1995; Appleby 2005).

Lessons from indigenous soil knowledge offer not only a host of innovative agroecological insights, but also opportunities for cross-validation of scientific findings (Handayani et al. 2006; Grossman 2003). It provides observations from concrete evidence for contemporary interpretations of soil patterns in nature. Previous research shows that oral traditions in many ethnic groups in the world deliver accurate information on past natural events and disasters, such as volcanoes, tsunamis, floods, drought, and degraded lands, which can validate scientific hypotheses. There are well-documented examples that indigenous soil knowledge brings significant predictions toward the pattern of soil fertility, agriculture productivity, rainfall, and plant adaptation well in advance of scientific information (Norton et al. 1998; Ali 2003; Ryder 2003; Handayani et al. 2006; Handayani and Prawito 2008; Ingram 2008).

Incorporating indigenous into scientific soil knowledge provides better approaches during the process of maintaining sustainable agriculture. Considering indigenous soil knowledge in daily practices in agriculture brings deeper awareness for ecologically sound farming systems. Ryder (2003) reported that empirical farmer evaluations can be used to verify theoretical scientific prediction of site suitability. Local farmers bring invaluable insight into historical changes in land cover and soil management practices that have had an impact on local soils. For example, in the Dominican Republic, surveyors and local farmers combine the criteria they use for soil identification and classification (including soil color, texture, structure, aroma, moisture, taste, stoniness, depth, and horizons). Integrating indigenous soil knowledge into soil surveys facilitates the exchange of empirical farmer knowledge and theoretical surveyor knowledge, thus enhancing rural development projects.

Table 11.2 Indigenous knowledge of soil degradation in Asia (Ali 2003; Handayani et al. 2006)

Soil degradation type	Controlling factors
Intensive cultivation	Population pressures
Overgrazing	Limited grazing land
Deforestation	Population pressure and firewood, and furniture demand
Soil erosion	Too much plowing/tilling, no cover crops
Stoniness	High soil erosion
Flood	Heavy rainfall, soil has poor drainage system
Drought	Not enough rainfall, too much sand in soil
Low soil fertility	No fallow practices, no crop rotation, no manure application, over-plowing

Table 11.3 Indigenous knowledge of soil characteristics and method of determination in Asia (Ali 2003; Handayani et al. 2006; Handayani and Prawito 2008)

Soil characteristics	Method of determination
Density	Soil compactness, heavy soil weight
Texture	The feeling of presence of sand, silt, and clay while tilling
Organic matter	The presence of earthworms, plant residues, roots, and darker soil color
Acidity	Visual perception of poor vegetative plant growth and root, soil has orange, reddish, or purple color with iron or manganese spots, some farmers can taste the acidity, dense growth of *Melastoma malabathricum*
Salinity	Tasting the soil and observe the salt layer in the soil surface
Drainage	The presence of clay or sand, more clay means poor drainage
Fertility	High crop yield, dense growth of *Chromolaena odorata*, no *Imperata cylindrica* and no *Saccharum spontaneum* in the field, high organic matter, dark soil color

Table 11.2 shows that the farmers in Bangladesh and Indonesia have profound and deep knowledge of the local soil typology, soil degradation, and management problems (Ali 2003; Handayani et al. 2006; Handayani and Prawito 2008). The farmers have limited knowledge about soil genesis and chemistry, but they are highly knowledgeable in different soil properties that affect crop production (Table 11.3). In this case, the diversity of indigenous knowledge in these countries contributes to the national agricultural development planning, which has an objective to sustain higher crop yield without destroying the environment. By incorporating indigenous soil knowledge into the program, the farmers and scientists can contribute equally to rural development, and their knowledge of soils is complementary to each other.

In Tanzania, farmers have knowledge on rainwater harvesting based on their knowledge of soil properties and soil typology (Mbilinyi et al. 2005). The indigenous knowledge on potential sites for rain water harvesting are the following:

1. Areas with high moisture content indicate shallow water table and thus become the best areas for water storage reservoirs.
2. Heavy and stable soils are suitable areas for routing canals.
3. Clay soils have high water-holding capacity, and therefore will work the best for water storage reservoirs.

4. Best areas for charco dams are those where warthogs dig their ponds in search of water.
5. Flat areas adjacent to a gentle slope are the best for charco dams.

In recognition of the potential of rainwater harvesting technology to improve water availability and land productivity, the government of Tanzania considered it to improve agriculture development. Finally, rain water harvesting technology is becoming a key element of the Agricultural Sector Development Strategy in semi-arid areas.

In addition, the concept of *Mashamba ya mbuga* was also developed by farmers in Tanzania (Mbilinyi et al. 2005). In this concept, farmers grow high water demanding crops in low land, so that the crops can receive rainwater from the surrounding high land. The rainwater harvesting systems developed by local farmers have been sustainable for many years, because they are compatible with local lifestyles, institutional patterns, and social-economic systems (Gowing et al. 1999).

Pawluk (1995) described that Zuni farmers in New Mexico, USA have indigenous soil knowledge, such as *he'bik'yaye*, a sticky clay area with poor infiltration, *so:lana*, a coarse alluvial sediment, which can capture water and is considered fertile soil, and *danaya so:we*, an organic soil located below upland forest trees. They have soil terms to show surface soil condition with regard to infiltration, farming practices, and transport of parent material. Further, solutions to land degradation in Zuni Indian Reservation, New Mexico were built based on indigenous knowledge. The agroecology research supports community action by valuing and recognizing local agricultural systems and combining them with scientific soil knowledge to combat desertification (Norton et al. 1998). Incorporating Zuni-developed knowledge into research design increases respect and communication among local people, researchers, and planners, and therefore empowers the local farming community to develop agriculture and conserve resources on their own terms.

Scientific knowledge depends considerably on indigenous knowledge for interpretation, especially at the level of local farm implementation (Ingram 2008). Agriculture practices require highly skilled operations using technical and scientific knowledge, but this knowledge needs to be integrated with local knowledge of soil and weather conditions to be more effective. Research proves that farmers have more understanding toward nutrient budgeting and are more confident in land management when they combine both indigenous and scientific knowledge during the process of cultivation (Ingram and Morris 2007).

In England, farmers are technically well informed about agriculture, but they often have limited understanding of scientific knowledge of more complex systems, such as calculating the nutrient value of manure. Most farmers have a good knowledge of soil but they may have limited skill or knowledge about soil management. The research concluded that although farmers' knowledge about soil and sustainable agriculture is good, some areas need to be enhanced by policy and further research efforts (Ingram 2008).

In Chiapas, Mexico, organic coffee farmers have a dual soil knowledge system built upon experiences and phenomena that they can visualize and apply (Grossman 2003).

However, the implementation of agricultural practices depends upon socioeconomic factors. Farmers have excellent knowledge about the transformation of leaf material to soil (decomposition) over time, but their knowledge of various factors affecting decomposition is not well understood. They know about the root nodules, but not the role of legumes in nitrogen fixation. About 50% of the farmers interviewed thought that compost addition can improve coffee plant growth and soil fertility. Results show that farmers still possess knowledge gaps regarding unseen phenomena and more training is needed to address the unobservable ecosystem processes.

In Mongolia, herders rely considerably on soil conditions and vegetation cover when assessing pasture (Fernadez-Gimenez 2000). Severely damaged pastures are referred to as weedy or waste lands (*khog hazar*), black or bald pasture (*khar* or *khadsgay belcher*), or areas where the "soil has died" (*khurs ukhsen gazar*). *Artemisia glauca* and *A. adamsii* in the mountain steppe were the most widely recognized indicator species for overgrazed pasture. Ungrazed mountain pastures are considered to be poor forage by herders because the heavy thatch of litter limits the growth of coarse, tall grasses.

In Indonesia, farmers recognize various fallow species that are used as indicators of soil fertility during the process of shifting cultivation. For example, *C. odorata* (Fig. 11.1) and *Wedelia trilobata* (Fig. 11.2) are considered indicator of better soil fertility compared to *Saccharum spontaneum* (Fig. 11.3) and *Imperata cylindrica* (Fig. 11.4) (Handayani et al. 2006). Ants are also used as indicators to show that the soil is unfertile, however, earthworms are an indicator of good soil for farming. Clay soil is considered good for cultivating paddy rice, and organic soil provides the ideal growth medium for oil palm trees (Handayani and Prawito 2008).

Fig. 11.2 *Wedelia trilobata* has invaded *Imperata cylindrica* grassland after 3 years with an improvement in overall soil fertility (Handayani et al. 2006)

Fig. 11.3 *Saccharum spontaneum* has invaded degraded land in Sumatra, Indonesia

Fig. 11.4 *Imperata cylindrica* grassland in Sumatra, Indonesia

The above-mentioned facts show that indigenous soil knowledge provides the basis for sustainable agriculture; however, there are some obstacles to using it. Akullo et al. (2007) describe these obstacles as follows:

1. Modern agriculture training has often biased people's attitudes toward using indigenous soil knowledge.
2. Some farmers feel that it is time-consuming to involve indigenous soil knowledge into farming activities.
3. Ineffective for large-scale production.

4. Some religious beliefs forbid traditional beliefs and technologies regarded as demonic or superstitious.
5. Lack of standardization and limited documentation of indigenous technologies and practices.
6. High variation in guidelines, which sometimes cause confusion.
7. Some people cannot effectively relay the knowledge to others.

11.3 Discussion

As noted above, indigenous soil knowledge made a demonstrable difference in research projects and agriculture management, but it has not been accepted by the broader or scientific audience. The common reasons are that most managers, planners, and researchers are unfamiliar with the social and anthropology contexts. They often do not prepare to use social approaches to gain information. In addition, they seem hesitant and uncomfortable in cross-cultural interactions (Berkes 1993; Agrawal 1995). The users of indigenous soil knowledge are often reluctant to share information, and issues of ownership of it sometimes arise (Akullo et al. 2007). Mbilinyi et al. (2005) mention that more planners, policy makers, extension workers, development practitioners, and researchers have realized the potential of indigenous soil knowledge, but it remains a neglected resource. A key reason for this is due to limited source of guidelines for recording and applying it, particularly over wider geographic areas. This creates an implicit danger that indigenous soil knowledge may become extinct. All the constraints above cause a more complex problem than a simple lack of recognition of the merit of indigenous soil knowledge.

Facts show that some farmers are well equipped to conduct sustainable agriculture practices. However, in some areas the farmers have to be encouraged to use indigenous soil knowledge, and the practices have to be standardized to meet new challenges, especially for the improvement of the "know-why" and the "know-how" (Defra 2005). Actually, indigenous soil knowledge itself is linked to long consequences of society or community action and environmental changes and therefore, it is always able to modify the practices for sustainability and respond if environmental and socioeconomic conditions allow. The changes in local conditions over time will create new information and findings, which eventually influence the spatial orientation of indigenous soil knowledge (Deloria 1992). The spatial and temporal orientations will lead people to recognize the new knowledge and experiences in the community and transmission of indigenous soil knowledge by oral traditions will allow farmers to be more adaptive in response to the world's change.

In conclusion, with respect to cultural diversity and sustainability of the agroecosystems, indigenous soil knowledge can be used as a complement to scientific knowledge. Both are fundamental to establishing strategies and practices to maintain sustainable agriculture, as well as for cultural survival and a healthy ecosystem. In addition, better biodiversity usually occurs on or adjacent to traditional ecosystems as compared to nontraditional ecosystems, and it will only be protected if the relationship between culture and ecosystems is maintained (Nabhan 1997). Thus, valuing local agricultural knowledge strengthens culture (Kloppenburg 1991). In this case, experiences, which emerge from local areas, are the basis of both scientific and indigenous soil knowledge. Kloppenburg (1991) stated that the integration of local knowledge into scientific knowledge is important for the development of sustainability. Since local knowledge is "preadapted to its physical and human ecology," its elaboration and improvement are more likely to be sustainable in the long term.

11.4 Conclusion

The development of indigenous soil knowledge systems has been a matter of survival to the farmers who generated these systems. It offers alternative knowledge based on local practices of land resource use. In most developing countries, indigenous soil knowledge has been used as a source to provide solutions to ecological dilemmas, especially for restoration of degraded lands and creating wisdom in farming. Facts from various countries illustrate that recognition and application of indigenous soil knowledge into farming activities in the local environments provide avenues for farmers to develop sustainable agricultural practices worldwide. Study cases also describe that local farmers have full participation and collaboration for integrating indigenous soil knowledge into agricultural management decision making in ethical and effective ways. However, a more complete understanding of soil processes and knowledge transfer need to be developed, especially in terms of detailed local observations, philosophies, and methods of communication. In addition, indigenous soil knowledge must be incorporated with scientific knowledge to enable farmers achieve better understanding of soil process concepts and more sustainable relationship with their land, as well as compete and respond to global opportunities and challenges.

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Chapter 12
Composting to Recycle Biowaste

György Füleky and Szilveszter Benedek

Abstract If agriculture is to be made sustainable, few activities like composting are very important. Composting not only allows organic waste of agricultural origin to be recycled and returned to the soil, but also provides a solution for managing much of the waste, which is currently a major problem. If urban organic waste is selectively collected and composted, it no longer represents a problem for the city, and, if wisely applied, will enrich the soil, thus promoting the preservation or improvement of the organic matter reserves of the soil, an important component in the soil protection strategy of the EU. This review paper considers up-to-date aspects of our knowledge on composting, presenting a discussion of materials suitable for composting, the composting process itself, and the biochemical and microbiological aspects of this process. Special attention has been given to the question of maturity, marking the end of the composting process, and to the quality of the end-product. Although it is not part of the composing process, information is also provided on the related field of anaerobic digestion. The use of municipal solid waste (MSW) compost in agriculture has many benefits to soil, crops, and environment. If the fermentation is correctly managed, pathogens are killed during the heat period. Compost can reduce the incidence of variant plant diseases. A very important parameter for the composting material is the C/N ratio, the optimal value is 25-30. Composting recycles organic household, yard waste, and manure into useful humus-like end-product, the compost. There are two major approaches to composting. In active (hot) composting there is high temperature and the end-product has high quality, while passive composting is slower and is more common in the garden composting. Composting is a microbiological process, done by aerobic bacteria. The microbes can be classified to the metabolic types on the carbon and energy sources utilized by the cell. Compost is used in the agriculture as organic fertilizer;

G. Füleky (✉) and S. Benedek
Department of Soil Science and Agricultural Chemistry, Szent István University,
Institute of Environmental Sciences, Páter Károly utca 1, H-2103, Gödöllő, Hungary
e-mail: fuleky.gyorgy@mkk.szie.hu

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there is organic matter input to the soil and also reduces P fixation. Maturity means in what stage, of the composting process the material has progressed, and in the mature compost the biological activity has slowed. The maturity can be estimated by the C/N ratio, oxygen uptake, and germination test. The parameters for the assured compost quality label are the potentially toxic element content, the organic pollutants, and the hygienic requirements. In the European Union, composting the recycling of biowaste, becomes one solution of sustainable agriculture. It plays an important role in the developing countries also. Although it is not part of the composing process, information is also provided on the related field of anaerobic digestion: it is an alternative way of recycling biowaste producing biogas.

Keywords Agronomic value of composting • Anaerobic digestion • Biowaste • Compost quality • Composting process • Maturity

12.1 Introduction

The loss of soil fertility, the high mineral fertilizer prices, the decrease of soil organic matter, and the insufficient nutrient supply in plant production in the developing countries declare the need for alternative fertilizers. The high amount of household waste both in developed and developing countries is an actual problem. Composting allows organic waste to be recycled and returned to the soil as fertilizer and provides a solution for managing much of waste. Besides, compost can be used in landscaping, horticulture, and agriculture as a soil conditioner. It is also useful for erosion control, land and stream reclamation, wetland construction, and as landfill cover. Compost application is a very actual task considering the EU soil protection priorities, where one of the most important priorities is the improvement of organic matter content of soil. Compost serves as a growing medium: a porous, absorbent material that holds moisture and soluble minerals, providing support and nutrients in which most plants will flourish. To maximize the fertilizer effect of compost it can be useful to dilute compost with soil or peat to reduce salinity or to add neutralizers to bring the pH closer to 7, or additional nutrients like fertilizers or manure, wetting agents, and materials to improve drainage and aeration, such as sand, grit, bark chips, vermiculite, perlite, or clay granulates. Composting of municipal solid waste (MSW) and its subsequent application to agricultural land is gaining popularity because of the environmental concerns associated with the disposal of these materials in landfills. Several studies have shown that the use of MSW compost in agriculture has many benefits to soil, crops, and environment (Hortenstine and Rothwell 1973; Maynard 1995; Hicklenton et al. 2001; Rodd et al. 2002). Compost influences plant growth and health indirectly via the grooving conditions, by providing nutrients, especially micronutrients and by improving soil conditions and water retention capacity. Composts are not inert materials; they are carriers of living organisms. If the fermentation is correctly managed, pathogens are killed during the heat period (Bollen 1993; Engeli et al. 1993). At the same time, antagonists develop during maturation of the compost. Therefore, composts can reduce the incidence of variant plant diseases (Fuchs 1995, 2002; Hoitink et al. 1997).

Composting has a long history in connection with the animal manure management, but the modern composting originates in the organic farming in the early twentieth century. In organic farming, the mineral fertilizers are not allowed to use, but compost as an organic fertilizer has high importance. However, the more recent application of composting is the large-scale waste reduction. Because of the European Landfill Directive from 1999 the countries of the European Union have to meet specified targets for landfill reduction, principally by establishing alternate disposal and treatment of organic materials. Today, composting has three important aspects: (i) mechanical-biological treatment of biowaste, (ii) management of animal manure and plant residues, and (iii) home composting.

Recycling is the reprocessing of materials into new products. It prevents generally the waste of potentially useful materials, reduces the consumption of raw materials and reduces energy usage, and hence greenhouse gas emissions, compared to virgin production. Recycling is a key concept of modern waste management and is the third component of waste hierarchy. Recyclable materials may originate from a wide range of sources including the home and industry. They include glass, paper, aluminum, asphalt, iron, textiles, and plastics. Biodegradable waste, such as food waste or garden waste, is also recyclable with the assistance of microorganisms through composting or anaerobic digestion. Recyclates are sorted and separated into material types. Contamination of the recyclates with other materials must be prevented to increase the recyclates' value and facility. This sorting can be performed either by the producer of the waste or within semi-or-fully-automated materials recovery facilities. Recycling is beneficial in two ways: it reduces the inputs (energy and raw materials) to a production system and reduces the amount of waste produced for disposal. For economic, agricultural, and environmental reasons, composting is frequently used for organic waste recycling (Lemunier et al. 2005).

Biodegradable waste is a type of waste, typically originating from plant or animal sources, which may be broken down by other living organisms. Waste that cannot be broken down by other living organisms may be called nonbiodegradable. Biodegradable waste can be commonly found in municipal solid waste as green waste, food waste, and biodegradable plastics. Through proper waste management, it can be converted into valuable products by composting or energy by waste-to-energy processes, such as anaerobic digestion and incineration. Composting converts biodegradable waste into compost. Anaerobic digestion converts it into several products, including biogas and soil amendment (digestate). Incineration as well as biogas can be used to generate electricity and/or heat. Biodegradable waste can be recycled into useful materials by biological decomposition. There are two mechanisms by which this can occur: The most common mechanism of recycling of household organic waste is household composting or municipal curbside collection of green wastes sent to large-scale composting plants. Alternatively organic waste can be converted into biogas and soil improver using anaerobic digestion. Here organic wastes are broken down by anaerobic microorganisms in biogas plants. Biogas can be converted into renewable electricity or burnt for environment-friendly heating. Advanced technologies, such as mechanical biological treatment, are able to sort the not-recyclable elements of the waste out before biological treatment by composting, anaerobic digestion, or biodrying.

The collected and treated amounts of organic material differ much in the European Union (EU) countries. Around 35% of the estimated 49 million tons biowaste is presently collected separately (ECN 2008). In Germany, 30% of the household waste insists of biowaste and between 1990 and 2004 the highest increase is also documented for biowaste: from two million tons in 1990 to around eight million tons in 2004. The German Federal Compost Quality Assurance Organisation (BGK) assumes the amount in 2007 to 9–10 million tons, but in this year alone six million tons biowastes were delivered to composting plans connected to the BGK.

There are three disposal ways of the biowastes:

- Composting and digestion
- Incineration or mechanical-biological treatment with the aim to landfilling
- Landfilling of untreated biowastes

In Germany, 60–70% of the biowastes are collected separately and recycled by composting or digestion, but in the EU-15 countries only 6% and 22% are incinerated, and 72% is landfilled (Kehres 2008). For composting the selective collection of waste is important because of the separation of biowaste.

12.2 Composting Materials

The major categories of substrates potentially suitable for composting are the following:

- Municipal biosolids
- Industrial sludges
- Manures
- Yard wastes
- Septage
- Food and agricultural wastes
- Special wastes

Many different materials are suitable for composting organisms. The most important parameter for composting is the C/N ratio (Table 12.1). Some materials contain high amounts of carbon in the form of cellulose, which is required by the bacteria for their energy and other materials contain nitrogen in the form of protein, which provide nutrients energy exchanges. Suitable ingredients with relatively high carbon content include:

Table 12.1 C/N ratio of some raw compost materials (in: Periurban Vegetable Project: http://puvep.xu.edu.ph/composting.htm)

Nitrogen-rich waste	C/N ratio	Carbon-rich waste	C/N ratio
Liquid manure	2–3	Leaves	40–60
Chicken dung	10	Fruit	35
Grass cuttings	12	Legume straw	40–50
Kitchen waste	13–23	Corn cobs/rice straw	80–100
Cow/pig/horse dung	20–25	Sawdust	100–500
Feathers hair	30	Paper/cardboard	200–500

- Dry, straw-type material, such as cereal straws
- Autumn leaves
- Sawdust and wood chips
- Paper and cardboard, such as corrugated cardboard or newsprint with soy-based inks

Ingredients with relatively high nitrogen content include:

- Green plant material (fresh or wilted), such as crop residues, hay, grass clippings, weeds
- Manure of poultry and herbivorous animals, such as horses, cows, and llamas
- Fruit and vegetable trimmings

The most efficient composting occurs by seeking to obtain an initial C/N mix of 25/30 by dry chemical weight (Haug 1993). Grass clippings have an average ratio of 10–19 to 1 and dry autumn leaves from 55–100 to 1. Mixing equal parts by volume approximates the ideal range (Haug 1993).

Poultry manure provides much nitrogen, but with a ratio to carbon that is imbalanced. If composted alone, this results in excessive N loss in the form of ammonia – and some odor. Horse manure provides a good mix of both, although in modern stables, so much bedding may be used to make the mix to carbonaceous. A light dusting of agricultural lime (not on animal manure layers) can curb excessive acidity, especially with food waste. Seaweed meal provides a ready source of trace elements. Finely pulverized rock (rock flour or rock dust) can also provide minerals, while clay and leached rock dust are poor in trace minerals. Composting in the form of bioremediation can break down petroleum hydrocarbons and a variety of toxic compounds. This is the bacterial and some cases fungal content of the compost, which possess the enzymatic properties to de-polymerize the complex man-made molecules. Some materials are best left to high-rate, a thermophilic composting system, as they decompose slower, attract vermin, and require higher temperatures to kill pathogens than backyard composting. These materials include meat, dairy products, eggs, restaurant grease, cooking oil, manure and bedding of non-herbivores, and residual from the treatment of wastewater and drinking water. Meat and dairy products can be recycled using fermentation method. Human waste can be composted by industrial, high-heat methods and also by composting toilets, even though most composting toilets do not allow the thermophilic decomposition that is believed to be necessary for rapid killing of pathogens.

12.3 Composting Process

12.3.1 Generalized Composting Process

Composting is the aerobic decomposition of biodegradable organic matter, producing compost. The decomposition is performed primarily by facultative and obligate aerobic bacteria, yeasts, and fungi, and also helped in the cooler initial and ending phases by a number of larger organisms, such as ants, nematodes, and oligochaete worms. Composting recycles organic household and yard waste and manures into a useful humus-like, soil end-product called compost. Ultimately, this permits the return of needed organic matter and nutrients into the foodchain. Composting can significantly reduce the amount of biowaste going into burgeoning landfills. The decomposition process is a result of raised temperatures. The elevated heat results from exothermic processes, and the heat in turn reduces the generational time of microorganisms and thereby speeds the energy and nutrient exchanges taking place.

Although it would be very difficult to find a universally accepted definition of composting, Haug (1993) gives a practical definition, which very well summarizes the main points of the composting process: Composting is the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens, and plant seeds, and can be beneficially applied to land. Thus, composting is a form of waste stabilization, but one that requires special conditions of moisture and aeration to produce thermophilic temperature. The latter are generally considered to be above about 45°C. Maintenance of thermophilic temperatures is the primary mechanism for pathogen inactivation and seed destruction (Fig. 12.1).

The generalized diagram of the composting process is shown in Fig. 12.2. There are two major approaches to composting: active and passive (in Haug 1993): *Active (hot) composting* is defined as composting at close to ideal conditions, allowing aerobic bacteria to thrive. Aerobic bacteria break down material faster and produce less odor and fewer pathogens and destructive greenhouse gases than anaerobic bacteria. Commercial-grade composting operations actively control the composting conditions, such as the C/N ratio. When the temperature exceeds 55°C for several days only some highly resistant pathogenic bacteria like *Clostridium* can survive. To achieve the elevated temperatures, the compost bin must be kept warm, insulated, and damp. From the chemical point of view as it produces ultimately only energy in the form of waste heat and CO_2 and H_2O is *aerated composting* an efficient form of composting. With aerated composting, fresh air (i.e., oxygen) is introduced throughout the mix of materials using any appropriate mechanism. The air stimulates the microorganisms that are already in the mix, and their by-product is heat. In a properly operated compost system, pile temperatures are sufficient to stabilize the raw material, and the oxygen-rich conditions within the core of the pile eliminate offensive odors. High temperatures also destroy fly larvae and weed seeds, yielding a safe, high-quality finished product.

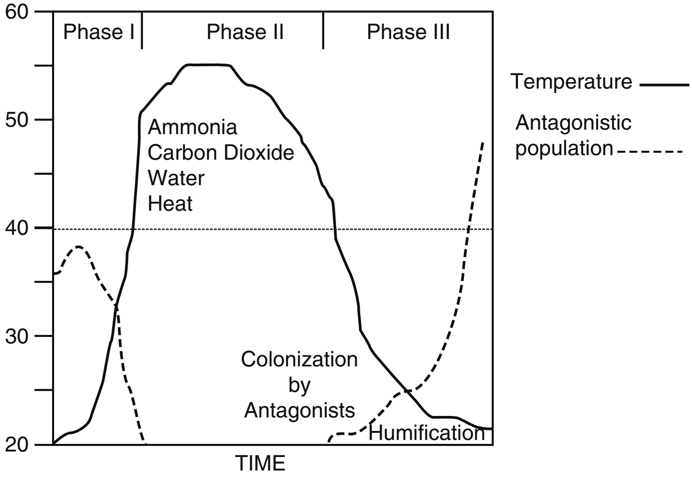

Fig. 12.1 Composting process. During phase I the initial heating takes place and readily soluble components are degraded. During Phase II, cellulose and hemicellulose are degraded under high temperature (thermophilic) conditions. This is accompanied by the release of water, carbon dioxide, ammonia and heat. Finally, during Phase III, curing and stabilization are accompanied by a drop in temperatures and increased humification of the material. Recolonization of the compost by mesophilic microorganisms occurs during Phase III. Included in these microbial communities are populations of antagonists (in: Smith 1992)

Finally, aeration expedites the composting process through the mechanism of heating insofar as the elevated heat will drive biochemical processes faster, so that a finished product can be rendered in 60–120 days. Aerated compost is an excellent source of macro- and micronutrients as well as stable organic matter, which support healthy plant growth. In addition, the microorganisms in compost aid in the suppression of plant pathogens. Compost retains water extremely well resulting in improved drought resistance, a longer growing season, and reduced soil erosion. *Passive composting* is composting in which the level of physical intervention is kept to a minimum, and often as a result the temperatures never reach much above 30°C. It is slower but is the more common type of composting in most domestic garden compost bins. Such composting systems may be either enclosed (home container composting, industrial in-vessel composting) or in exposed piles (industrial windrow composting). Kitchen scraps are put in the garden compost bin and left untended. This scrap bin cab has a very high water content, which reduces aeration, and so becomes odorous.

Composting systems are often divided into a *first stage*, high-rate phase and a *second stage*, curring phase. The first stage may use windrow, aerated static pile, or reactor processes. It is characterized by high oxygen uptake rates, thermophilic temperatures, high biodegradable volatile solids (BVS) reductions, and higher odor potential. The second phase is characterized by lower temperatures, reduced oxygen uptake rates, and lower odor production potential. The curing phase provides the time required for (i) degradation of the more refractory organics, (ii)

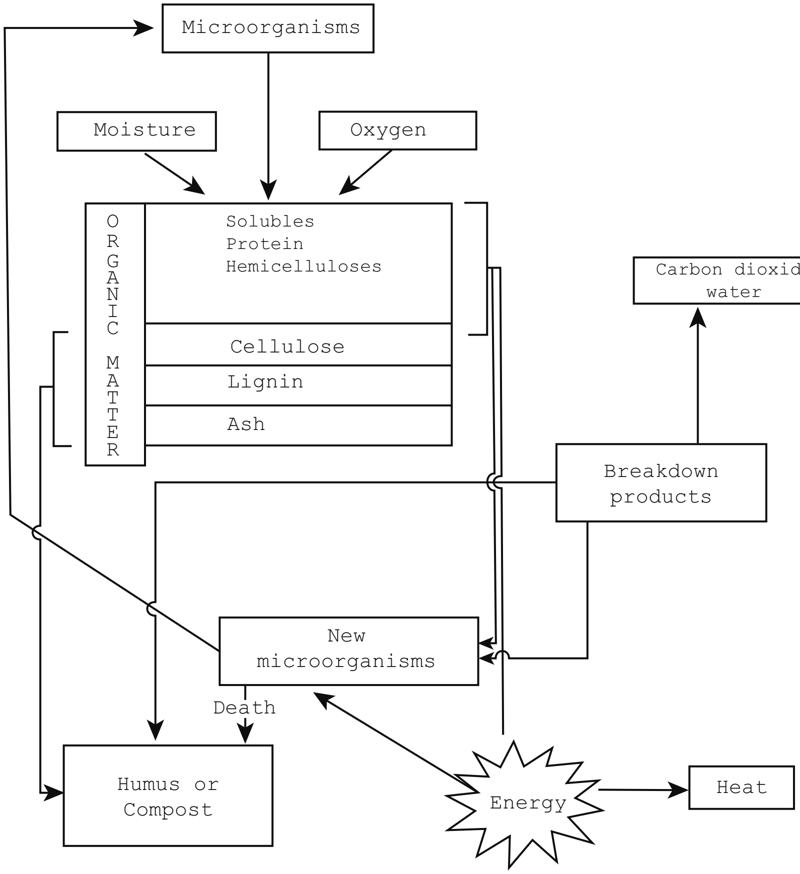

Fig. 12.2 Generalized diagram for composting (in: Gray and Biddlestone 1981)

overcoming the "slowing" effects imposed by kinetic rate limitations, and (iii) reestablishing lower temperature microbial populations, which may be beneficial in "maturing" the compost, metabolizing phytotoxic compounds, and suppressing plant diseases.

12.3.2 Composting Methods

The most important technical methods of composting are statistic piles, windrows, and reactor vessels (shown in Figs. 12.3 and 12.4). Composting ingredients are mixed and during the composting process aeration is indicated.

Bertoldi and Civilini (2006) carried out a composting process in two separate reactors: first, only in the thermophilic phase, with the purpose of pathogen destruction and decomposition by selected thermophilic microorganisms; second, only in the mesophilic phase, to perform the main microbial transformations with a higher

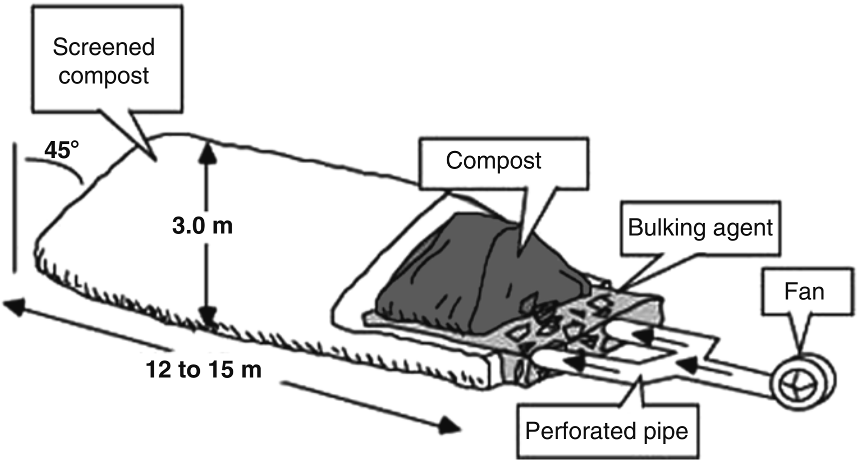

Fig. 12.3 Static piles (in: Hansen et al. 1995)

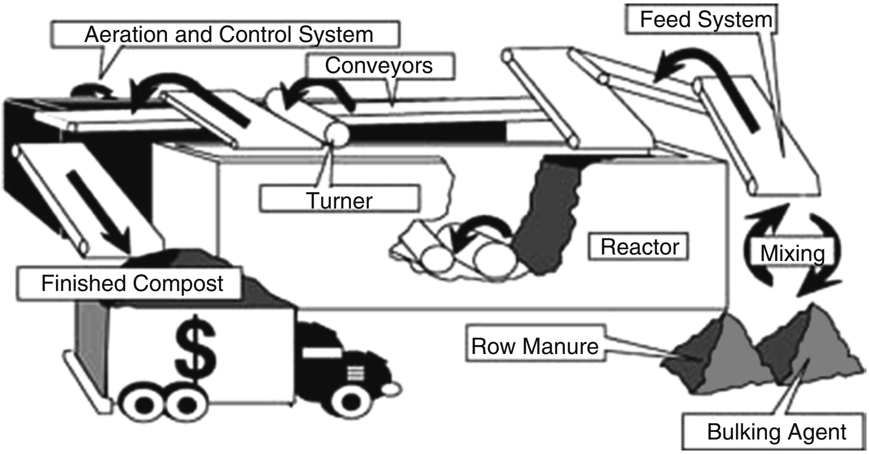

Fig. 12.4 Reactor vessels (in: Hansen et al. 1995)

rate of volatile solids destruction. The results confirmed that maintaining constant the main parameters which affect the process, the microbial activity is enhanced. In the two-phase process, the evolution of parameters like moisture, organic carbon, humified organic matter, organic N, C/N, and germination index (phytotoxicity) is more rapid relative to the single phase process. Also pathogen destruction is improved with the complete elimination of Faecal coliforms and Enterobacteriaceae and with a stronger reduction of Faecal streptococci. Any expert appraisal of municipal solid waste composting plants requires the evaluation of each piece of equipment in the processing sequence. Hence rotating drum-pilot plants are used for composting (Aboulam et al. 2006).

12.3.3 Biochemical Aspects of Composting

The composting mass is at ambient temperature, but a rapid rise occurs as the microorganism multiply. When the temperature moves above 40°C, the mesophilic stage is replaced by the thermophilic stage. The time required to reach the thermophilic stage varies, but it is frequently achieved in 2 or 3 days (Olds 1968). The temperature stabilizes around 70°C, followed by a gradual cooling to ambient temperature. This temperature pattern has been observed by many investigators for typical garden compost as well as for municipal compost (Webley 1947; Kortleven 1951; Eastwood 1952; Chang and Hudson 1967; Kochtitzky et al. 1969). The temperature gradient from the center outward lessens as the pile size increases. Since heat loss is proportional to surface area and heat generation is proportional to volume, the larger pile, having a smaller surface area to volume ratio loses relatively less heat. In large compost piles, the temperature increases steadily 70°C with time, in smaller piles there is usually a pause or leveling at 40°C while the transition from mesophilic to thermophilic microorganisms occurs (in: Anonymus 1953). Decomposition of organic matter is fastest in the thermophilic stage. The optimal temperature, based on oxidation of organic matter into CO_2 and H_2O has to be 60°C (Waksman et al. 1939; Wiley 1957; Schulze 1961, in: Poincelot 1972). Eklind et al. (2007) reported that biowaste composting can be optimized to obtain both a high decomposition rate and low ammonia emissions by controlling the process at about 55°C in the initial, high-rate stage. To reduce ammonia emissions it seems worthwhile to reduce the temperature after an initial high-temperature stage. Grinding the materials to be composted speeds their decomposition by increasing their surface area and hence their susceptibility to microbial invasion (in: Anonymus 1953). Better initial aeration is also achieved due to increased availability of oxygen at particle surfaces. In addition, the material is more easily handled and moistened. Gray and Sherman (1969) observed that grinding might double the amount of evolved CO_2 as compared to unground material. The greater part of difference due to grinding was observed in the thermophilic temperature range (40–60°C), while little difference was seen in the mesophilic stage (Poincelot 1972). Oxygen is required by aerobic microorganisms during the decomposition process. For a mixed garbage–sewage sludge compost Schulze (1962) found that 5–9 ft^3 of air per pound of volatile matter per day was required. Windrows may be aerated by turning (outer edges mixed in with center of pile) or by thoroughly mixing by mechanical means (Poincelot 1972).

12.3.4 Microbiological Aspects of Composting

Composting is a biological process mediated by microbes belonging to the kingdom Protest, which includes bacteria, algae, fungi, protozoa, and virus particles (Table 12.2). Microbes can be classified into metabolic types based on the carbon and energy sources utilized by the cell. Autotrophs use carbon dioxide as a

Table 12.2 Microbial populations during aerobic composting (in: Poincelot 1977)

		No./Wet gram compost			
Microbe		Mesophilic initial temp. < 40°C	Thermophilic 40–70°C	Mesophilic 70°C to cooler	Number of species identified
Bacteria	Mesophlic	10^8	10^6	10^{11}	6
	Thermophlic	10^4	10^9	10^7	1
Actino-myces	Thermophlic	10^4	10^8	10^5	14
Fungi	Mesophilic	10^6	10^3	10^5	18
	Thermophlic	10^3	10^7	10^6	16

source of cell carbon, whereas heterotrophs use the carbon of organic molecules. Phototrophs obtain energy from light. Litotrophs use the energy of inorganic chemical reactions, while organotrophs use the energy of organic chemical reactions. Most bacteria and all fungi are organoheterotrophs that use organic compounds both as a source of energy and for cell carbon (Haug 1993).

Lemunier et al. (2005) resulted that biowaste compost may support long-term survival of *Salmonella* serovar Enteridits when sanitation has been unsatisfactory during the thermophilic phase or in the case of colonization during storage of mature compost. Mature biowaste compost did not allow *L. monocytogenes* survival and also for *Escherichia coli* only a short survival time was observed. However, this study showed that management of the maturation phase is critical for limiting hazards associated with *L. monocytogenes*. The authors of the study about the potential survival of the seeded pathogens in biowaste composts conclude that the undesirable long-term survival of *E. coli* and *L. monocytogenes* could be prevented by proper management of the maturing phase. No risk of survival during compost storage should occur with *L. monocytogenes*. The survival time of *Salmonella* serrovar Enteridits was very short in composts sampled during the thermophilic phase but was longer when organisms were inoculated into mature biowaste compost. Although waste composition affected pathogen growth in sterile composts, no clear relationship between compost physicochemical parameters and pathogen survival was found. Amendments of organic waste can increase nutrient levels and promote soil health, for example, by activation of natural plant pathogen predators (Zhang et al. 1998) and improve soil physical properties such as increasing porosity and pore connectivity, and thereby, improve living conditions for the soil fauna (Giusquani et al. 1995). It has been documented that Collembola and earthworms excrete N in NH_4^+ (Sjursen and Holmstrup 2004) and hence play an important role in N mineralization. Temperature is also an important selective factor for the development of *Actinobacteria* populations in composts, and they constitute a substantial part of the community in the different compost stages (Streger et al. 2007). Microbial biomass C correlates strongly with microbial activity but is even strongly correlated with the pH (Gattinger et al. 2004).

The cited papers in the field of biochemistry and microbiology can contribute to find better composing technology to reach higher decomposition rate using optimal temperature, time, and grinding the materials that help to reduce the survival of pathogens and ammonia loss.

12.4 Composting Products and Maturity

12.4.1 Agronomic Value of Composting Products

Compost contains high portions of the humus-C, the portion of carbon that contributes to the humus reproduction. It accounts for 51% of the total organic carbon and is therewith higher than in any other humus fertilizer. Compared with compost, straw and liquid manure contain 21% carbon and green-fertilizers contain only 14%. The effectiveness on the humus reproduction with compost is by factor 4 higher than with straw and by factor 20 higher than with liquid manure (Kehres 2008). This fact is very relevant from the view of sustainable agriculture, because agriculture cultivation is connected with losses of humus-C in the soils and the fertilization with compost could compensate it.

Organic material and their decomposition products can reduce P fixation in soils by the complexation of Al and Fe by organic acids, by the competition between organic acids and orthophosphate for adsorption sites and release of P by organic material during decomposition (Mnkeni and MacKenzie 1985; Sibanda and Young 1986; Iyamuremye et al. 1996; Kwabiah et al. 2003). Also composted organic material has been reported to reduce P fixation in soils: Ogaard (1996) studied the effect of fresh and composted cattle manure on P retention in soil and found that both reduced P fixation compared to inorganic phosphate. Buchanan and Gliesman (1990) reported that composted spent mushroom, bedding material, horse manure, and hay residue decreased P fixation in soils compared to inorganic fertilizer. Hue et al. (1994) also reported similar findings using yard-waste compost and attributed this to the release of P during the decay process and the competition between organic anions (released by compost) and P for adsorption sites in the soil complex. Guisquiani et al. (1988) reported that the addition of urban-waste compost increased soil P solubility. They postulated that the increase in soil P solubility was caused by the formation of phosphohumic complexes that minimize immobilization process, anion replacement of P by the humate ion, and coating of sesquioxide particles by humus to form protective cover. Mkhabela and Warman (2005) studied the effect of municipal solid waste (MSW) compost on soil P availability and uptake by potato and sweet corn crops. Three rates of MSW compost, one rate of chemical NPK fertilizer, and a mixture of MSW compost and chemical NPK fertilizer were used on both crops according the soil P test results. The NPK and mixture treatments produced significantly higher yields in the first year, while in the next year the yields were not significantly different for all treatments. All the MSW compost treatments had lower tissue N compared to the inorganic fertilizer and mixture treatments. The MSW compost and mixture treatments generally results equivalent concentration of Mehlich-3 extractable soil P compared to the inorganic fertilizer. In addition, the application of both inorganic fertilizer and MSW compost decreased P adsorption by the soil up to 30%. MSW compost may be a good source of P for both potatoes and sweet corn. However, the low availability of compost-N means that supplementary N in the form of inorganic fertilizer may have to be added together with compost in order to enhance N availability to crops. Alexa et al. (2004) studied the effect of compost fertilization on the NPK content of a sandy soil. Three rates of compost were used and all of them produced significantly higher contents of N_{min}, AL-P_2O_5, and AL-K_2O. The compost treatments had also a positive effect on the soil pH. Erhart et al. (2005) found that yields in treatments with compost fertilization (9, 16, and 23 t/ha/annum on average of the first 10 years) increased 8%, 7%, and 10%, respectively when compared to the unfertilized control. Yield response to the compost applications was very low in the beginning and increased slightly with the duration of the experiment. The analysis of the yield components of the cereals showed that the plants in the compost treatments were sufficiently supplied with nitrogen in the early growth stages and after pollination, but at booting, when N uptake is highest, the N supply in the compost treatments was comparable to that with mineral fertilization at up to 30 kg N/ha. Crop quality was not affected by compost fertilization, but in some cases even improved. The results suggest that on fertile soils the fertilizer effect of compost is small, but it increases with time. Chan et al. (2007) evaluated the short-term effects of selected composted soil conditioners applied in 0, 25, 50, and 100 t/ha in radish growth in a pot experiment. They found that the pot trial results indicated lack of growth response of radish at application rates up to 100 t/ha of unblended soil conditioners from garden organics. The blended soil conditioners were more variable in quality and as confirmed by pot trial results produced highly variable plant responses. Maynard (2000) showed that for optimum yield of most vegetables, a combination of compost and 10-10-10 fertilizer is preferred, although the full rate is unnecessary. Half the rate of fertilizer plus compost is sufficient for optimum yields on loamy soils and for most years on sandy soils, additional side dressings of nitrate supplying fertilizer may be required after heavy rainfalls during the growing season. Additional soil tests can determine nitrate levels during the growing season. Organic fertilizer with compost can also be used on loamy soils, but it may not provide satisfactory yields on sandy soils. This experiment demonstrated the importance of knowing soil type when using compost.

The available nitrogen of compost is predominantly dependent on the following parameters (Amlinger et al. 2003):

- C/N ratio of raw material
- Composting conditions (mainly aeration, agitation)
- Decomposition/stabilization rate, duration of composting (immature or mature compost)
- Posttreatment of compost (sieving, blending)
- Time of application (time before cropping or leaching phase)
- Compost quality parameters, such as C/N ratio, degradable amounts of C and N fractions

To evaluate the mineralization (availability) of compost N ratio to estimate the amount available for plants over a certain period several experimental and calculation methods are possible (Amlinger et al. 2003):

- Laboratory incubation tests under constant conditions (temperature, water content of the substrate with and without cultivation of crops) with or without periodical percolation of the mineralized N
- Field trials to evaluate the N efficiency in terms of comparative yield or N uptake, respectively, relative to control or mineral fertilized plots
- N-leaching tests on field scale with lysimeter or suction cups, as well as regular measurements of mineral N in the leaching horizon
- Model-based calibration of N-mineralization kinetics

For the assessment of long-term effects of compost Fuchs and Larbi (2004) applied on one half of a field each year 10 t dry weight/ha compost, while the other half was used as a control. After 5 years, soil samples were taken from the different field plots. The disease receptivity of the soils was lower in the plots with compost compared to the control plots. Elherradi et al. (2005) found that the quantities of mineralized N of the compost varied between 15% and 24% of the compost total N. Scheurell and Mahaffe (2002) reported that compost extracts could improve plant health. Larbi et al. (2006) found that green waste compost extracts protect apple plants against scab and grapevines against downy mildew under controlled conditions. The efficiency of the compost extract against scab was not affected by the compost to water ratio and extraction duration. But in many cases, different compost to water ratios have reduced the incidence or disease severity of pathogens.

Soil quality and health play an important role in sustainable agriculture: Soil quality assessment provides a basic means to evaluate the sustainability of agricultural and land management systems (Doran and Parkin 1994). Soils that are healthy have homeostatic properties, within broadly set limits (Coleman et al. 1998). The application of compost can results soil quality and health because of the organic matter content and humus-producing properties.

12.4.2 Maturity of Composting Products

The Composting Council of Canada (http://compost.org/pdf/sheet_4.PDF) defines the compost maturity as following (the guidelines for that are shown in Table 12.3): Compost maturity was chosen as one of the parameters for determining the grade of compost in Canada because it is so important to product performance. Immature compost may stunt, damage, or even kill plants, rather than enhancing their growth. Maturity is not related to quality, but to what stage in the composting process the material has progressed. Mature compost is material in which biological activity has been slowed. All of the easily degraded molecules have been broken down, leaving the complex organic material behind. It is difficult to identify the original feedstock materials. A fine texture, dark color, and a rich earthy smell often characterize mature composts. As organic material composts, large complex molecules are broken down in a series of steps. The final products are simple, stable molecules, which make up the humus-like matrix of nutrients and organic matter that we

Table 12.3 Guidelines for compost maturity (in: The Composting Council of Canada, http://www.compost.org/pdf/sheet_4.PDF)

Required tests of compost maturity	Significance
1. Two of the three following tests:	
(a) Carbon/nitrogen ratio (C/N) less than or equal to 25.	(a) As carbon is broken down through composting the C/N ratio drops. (C/N ratio starts ideally at 30, but can be higher)
(b) Oxygen uptake less than 150 mg O_2/kg organic matter/h	(b) Microbes require oxygen, so a drop in the O_2 required signals a slowing of microbial activity.
(c) Germination of cress or radish seeds in compost equal to more than 90% that of control sample, *and* plant growth rate in soil/compost mix not less than 50% that of control sample.	(c) Cress (*Lepidium sativum*) and radish (*Raphanus sativus*) are small seeds, quick to germinate and sensitive to phytotoxic (plant damaging) substances like the organic acids temporarily present in immature composts.
2. Compost must be cured for a minimum of 21 days, and must not reheat upon standing to greater than 20°C above ambient temperature.	Microbial activity produces heat. When pile is no longer heating up, the level of microbial activity has dropped.
3. Compost must be cured a minimum of 21 days and organic matter must be reduced by at least 60% by weight.	As composting progresses, water vapor and carbon dioxide are given off, resulting in a lighter, denser product.
4. Compost must be cured for a 6-month period	In the absence of other tests, 6 months under proper conditions to promote effective composting is considered sufficient to achieve maturity.

call compost. While this finished product is highly beneficial to plants, some of the intermediate stages may temporarily produce compounds, such as organic acids, that can be harmful to plant growth. This is why even compost made of high-quality materials, that is applied too soon to lawns or gardens may appear to “burn” leaves, stunt growth, or even kill sensitive plant species. Immature composts continue to break down once they are incorporated into the soil. This can affect plant health by consuming or tying up two resources that growing roots need. The high level of microbial activity in unfinished compost requires a large intake of oxygen, and the microbes may pull this from the surrounding soil, essentially suffocating the roots. The high C/N ratio of immature compost also means that, as the carbon compounds continue to break down, microorganisms will draw on soil nitrogen to assist in the process, leaving the root zone temporarily nitrogen poor. It is therefore crucial that responsible compost producers should ensure that their compost has time to fully mature before selling it to most customers, as compost that is still “hot” when applied can do serious damage to both customers’ plantings and your reputation.

Maturity is an important parameter for the nutrient management of compost: N availability in compost is closely related to the maturity reached during composting (Bernal et al. 1998; Griffin and Hutchinson 2007). Larsen et al. (2007) found that anaerobically digested and composted municipal solid waste immobilized N in the initial stage of decomposition. The N immobilization in the composted municipal solid waste indicates that it was not matured and still was metabolically active. The rate of mineral N release after the initial immobilization was similar between the anaerobically digested and composted municipal solid waste composts (MSWC). Amlinger et al. (2003) reported also similar N effects of compost amendments: an N release ranging between 5% and 15% in the first year.

The composition and the maturity of composts influence the potential for plant disease suppression, and in addition the management of the composting process, in particular the oxygen supply, seems to be the most important factor affecting compost quality (Fuchs and Larbi 2004).The three most important factors to control during fermentation are: (i) the moisture of the material, (ii) the air composition, and (iii) the temperature. At the end of the maturation, the following quality parameters have to be analyzed: (1) pH, (2) salt content, (3) ammonium, (4) nitrite, and (5) nitrate content (Fuchs and Larbi 2004). Plant test can be also very important for the quality analysis of composts, because (i) plants react to compost quality as a whole, and so hidden problems can appear, and (ii) plants react during the entire test period (about 2 weeks), thus the evolution of some parameters can be observed. This is particularly important for nitrogen availability (Fuchs and Bieri 2000). Wang et al. (2007) studied the effect of oxygen on the compost maturity and found that when C/N ratio, NO content and composting temperature were used as indexes to evaluate compost maturity, the compost matured in 35 days in the micro-aerobic treatment, compared with 45–50 days in the aerobic treatment. Biosolids compost is a good organic amendment, but immature compost can exhibit phytotoxic behavior, which can be attributed to different toxic substances (Zubillaga and Lavado 2006). The authors studied the phytotoxic behavior and found that phytotoxic effects on germinating ryegrass were mainly related to extract pH and electrical conductivity. Potentially toxic elements, volatile organic acids, phenolic compounds, and ammonia were not related to germination. Tiquia (2005) found significant correlations between the humification parameters and the microbial properties of the manure of compost. Spaccini and Piccolo (2007) studied the changes in the molecular composition of composted organic biomasses and found that the largest decrease in the molecular components occurred when compost was stabilized from 60 to 90 days, whereas its composition did not significantly vary after stabilization at 150 days. The stability and maturity of compost are highly related to the nature and content of water-soluble organic matter: fractionation of the water-extractable organic carbon showed that the ratio of hydrophobic to hydrophilic carbon increased to values greater than unity for stabilized compost (Said-Pullicino et al. 2007). The water-soluble fractions (carbon, nitrogen, carbohydrates, and phenols) show major fluctuations during the first month of composting (Castaldi et al. 2007). McEachin et al. (2007) found that measurements of mineralizable carbon and mineralization rate of composts in soil, and electrical conductivity and mineralization rate of soil and compost mixtures can be used as indicators of compost maturity. Kovács et al. (2007) analyzed the applicability of self-heating, oxygen consumption, and carbon dioxide production as measures of stability during the composting of a mixture of communal sewage sludge and wood chippings and green waste and concluded that for both types of compost the stabilization process can be described by means of the actual O_2 consumption and CO_2 production rates on the 2nd day. Compost quality, particularly maturity is linked to the composition of the microbial community structure (Steger et al. 2007).

12.5 Quality Control

A good image for compost can be built up with assured quality and a quality label. Germany, Denmark, the Netherland, and Belgium have developed a composting system which is very important for the quality assurance. Elements of the quality assurance system are quality assurance of European composting and digestion plants (in: ECN 2008):

- Raw material
- Intake control
- Limits for harmful substances
- Quality criteria for the valuable constituents in the compost
- Composting production
- External control (product and/or production)
- In-house monitoring
- Quality label for the product
- Certificate for the plant and/or for the product
- Declaration of the properties of the compost
- Recommendations for use and application
- Training and qualification of the operator
- Management and operation of plants (plant assessment)
- Annual certificates

Table 12.4 shows the status of quality assurance of European composting and digestion plants. This is very important for the classification of compost and digestion quality (Table 12.5).

Table 12.4 Status of quality assurance of European composting and digestion plants (stand: Dec. 2001) (in: ECN 2008)

Country	Plants with quality assurance	Plants with quality sign or certificate
Austria	10	2
Belgium	22	10
Luxemburg	3	3
The Netherlands	22	4
Germany	429 Composting, 16 digestion	400 Composting, 10 digestion
Sweden	2 Composting, 8 digestion	–
Denmark	Draft of quality assurance system	–
Norway	Quality assurance system exists	–
United Kingdom	Quality assurance system in introduction	–

Table 12.5 Classification of compost and digestion quality in Europe (in: ECN 2008)

Country	Type of compost/quality class
Austria	Quality Class A + (organic farming), Class A (high quality) and Class B (minimum quality/noon food production areas)
Belgium	Yard and Vegetable, Fruit and Garden VFG Compost
Denmark	Organic household waste compost with no classification up to now. No quality criteria for green/yard waste compost necessary.
Germany	Fresh and matured compost, mulch and potting soil compost solid and liquid digestion residues
The Netherlands	Compost and very good compost
Sweden	Very fresh, fresh and matured compost, digestion residues

Table 12.6 Potentially toxic element limits and allowed in the EU (mg kg^{-1} DM) (in: ECN 2008)

Country	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Austria	1	70	150	0.7	60	120	500
Belgium	1.5	70	90	1	20	120	300
Denmark	0.4	–	1,000	0.8	30	120	400
Germany	1.5	100	100	1	50	150	400
Ireland	1.5	100	100	1	50	150	350
Luxemburg	1.5	100	100	1	50	150	400
The Netherlands	1	50	60	0.3	20	100	200
Eastland	2	100	100	1	60	150	400
Sweden	1	100	100	1	50	100	300
United Kingdom	1.5	100	200	1	50	150	400

The quality criteria for the classification are the following (in: ECN 2008):

- Potentially toxic element content (Table 12.6)
- Organic pollutants
- Hygienic requirements

The level of the potentially toxic elements in compost materials used in a research by Manungufala et al. (2007) was found in the following order: Fe > Mn > Cr > Ni > Zn > Cu > Co > Cd.

Although a united compost quality system of the European Union does not exist, the European Compost Network (ECN), as an initiative of the ORBIT Association developed a Quality Assurance System providing the necessary background information and documentation to build up a European Quality Assurance System (ECN-QAS). Product definitions and characterizations of this system are shown in Table 12.7.

Silva et al. (2007) characterized a municipal solid waste compost (MSWC) based on standardized European Methods (ECN) for soil improvers and growing media and found that MSWC presents a lower C/N ratio (15) than peat and composted pine bark.

The German Federal Compost Association (BGK) has defined general quality standards comparing the following elements (Siebert 2008):

Table 12.7 Product definitions and characterizations (in: ECN 2006)

	Characterization	Purpose of use	Area of application	Remarks
Fresh Compost	Sanitized decomposed material (from aerobic treatment), Rate of degradation: low	Soil improvement, Fertilization	Agriculture, Recultivation	Declaration: no application on soils with new sowing or growing crops
Mature Compost	Sanitized decomposed material (from aerobic treatment), Rate of degradation: high	Soil improvement, Fertilization	Agriculture, Landscaping, Horticulture, Hobby gardening	
Compost as mixing component for growing media	Sanitized decomposed material (from aerobic treatment), Rate of degradation: very high	As constituent for growing media production	Horticulture, Growing media production	

- External monitoring: continuous and independent control of product quality
- Internal monitoring: control and documentation of the decomposition respiratory digestion process by the plants
- Quality criteria: standardization of the product quality
- Quality label: characterization of the product quality
- Compulsory declaration: description of the essential product characteristics and constituents
- Application guidelines: information on correct application
- Furnishing proof and the documents required by the plants to show treatment according to the Biowaste and Fertilizer Ordinance to the regional competent authorities

The British Composting Association has established very recently a set of guidelines for compost, called the BSI (British Standard Institute) PAS (Publicly Available Specification) 100. There are a variety of such voluntary industry standards in Europe and worldwide, such as the German Compost Association (BGK) RAL-standard for compost developed 10 years prior to the British standard, and updated recently to include separate standards for fermented by-products (from biogas reactors) and sludge. In the USA, Procter & Gamble Company sponsored the USCC in the early 1990s to develop compost process and product standards called TMECC, still in a draft state. These standardization programs are intended to provide structure in the composting community for handling the entire composting process from raw materials and production methods, through quality control and lab testing.

Validation of treatment plants should be done with the exposition of representative test organisms, followed by the determination of the inactivating rate after the exposition time, so that the technical parameters that must be kept during the constant process control cab be defined (HACCP-concept). The validation with representative test organisms defines the technical parameters, which must be kept and help to measure the residual risk during the application of the treated material in the right areas. The monitoring of the end products can be meaningful, if for technical reasons validation is not possible by exposition of test organisms and if the organisms (e.g., *E. coli* or *enterocci*) can be found in a large number in the raw material. The monitoring of the final products on natural test organisms is easily feasible and also cheap because it is not necessary to accomplish additional installations (Philipp 2008).

Sharma et al. (2005) developed robust calibrations for some of the key parameters from the spectra or fresh phase I and II composts and found by the laboratory measurement that for phase I samples were greater than those of the phase II samples except for ash, due to a higher degree of heterogeneity in the substrate.

12.6 Biowaste in the European Union

The importance of the composting as biowaste recycling for the sustainable development in Europe can be summarized in the following two points:

- Increasing of soil organic matter through the use of compost
- Compost as fertilizer in the agricultural production

One, from the view of the sustainability, very important consequence of the decline of soil organic matter is the release of greenhouse gases. This problem is also documented in the Impact Assessment of the Thematic Strategy on Soil Protection by the Commission of the European Communities (2006). The Kyoto Protocol committed to limit the greenhouse gas emissions: in 1997 the 15 Member States of the European Community have a combine reduction target of 8% CO_2-equivalent emissions during the period 2008–2012 compared to 1990. Soil has a very important role in this process, as a source and a sink of carbon. Soil organic matter can be maintained or increased through the promotion of organic input on arable lands (crop residues, cover crops, farm yard manure, compost, sewage sludge). Organic waste of good quality also can be used to increase soil organic matter in carbon-depleted soils (Marmo 2008).

The increase of the recent years in the biological waste treatment in Europe is reported by ECN (2008). The environmental and market requirements of the biologically treated waste are also reported. The selective biowaste collection the compost production is around 9 million Mg in the European Union.

The strategies for the management of biowaste in the European Union are summarized by Favoino (2008) as follows:

- The Landfill Directive 99/31 mandates the reduction of biodegradable solid waste to be landfilled.
- The European Climate Change Program insisting of the C sequestration, the reduced production/application of pesticides and mineral fertilizers, the improved water retention, and workability.
- The European Thematic Strategy on Soil Protection: 45% of the EU soils are poor in humus and composted biowaste could be a source of organic matter for the soils.

12.7 Anaerobic Digestion, as an Alternative Way of Recycling Biowaste

Chynoweth and Isaacson (1987) describe the process of anaerobic digestion as follows: The process begins with the separation of household waste into biodegradable and nonbiodegradable waste. The biodegradable material is shredded, slurried, and then screened and pasteurized to start the process of killing harmful pathogens. It is then pumped into the digester where bacteria break down the material and form biogas, leaving a digestate. The three main process stages in anaerobic digestion are: *hydrolysis*, *acidogenesis*, and *methanogenesis*. *Hydrolysis*: Insoluble organic polymers such as carbohydrates, cellulose, proteins, and fats are broken down and liquefied by enzymes produced by hydrolytic bacteria. Carbohydrates, proteins, and lipids are hydrolyzed to sugars which then decompose further to form carbon dioxide, hydrogen, ammonia, and organic acids. Proteins decompose to form ammonia, carboxylic acids, and carbon dioxide. During this phase gas concentrations may rise to levels of 80% carbon dioxide and 20% hydrogen. *Acidogenesis*: Organic acids formed in the hydrolysis and fermentation stage are converted by acetogenic microorganisms to acetic acid. At the end of this stage carbon dioxide and hydrogen concentrations begin to decrease.

Methanogenesis: Methane (60%) and carbon dioxide (40%) are produced from the organic acids and their derivatives are produced in the acidogenic phase. Methane is a useful fuel source and methanogenic bacteria play a further role in maintaining wider breakdown processes. Efficient mixing of the contents of the digester improves the contact between the material and the resident bacteria. Mixing of the waste slurry in the digester is important in maintaining a high rate of anaerobic biodegradation and a high production level of gas. The mixing process disperses the incoming waste within the digesting sludge, improving contact with the microorganisms. Monitoring the acidity within the digester is necessary to provide optimum conditions for the balanced growth of bacteria. Monitoring takes place in the reactor using probes. The concentration of volatile fatty acids is an important parameter for monitoring as this can be the first indicator that digestion is not progressing normally.

Biogas plants have two products: biogas and digestate. Digestate is regarded as an organic fertilizer. The main issue in the Swedish regulations for organic fertilizer is coverage of the storage; field application is prohibited during winter months and also during early spring and late autumn in coastal areas, maximum 110 kg P/ha during a 5-year period for a single application (Palm 2008).The waste status of the outputs of anaerobic digestion has been identified as a key barrier to the development of the industry to treat waste in the UK. Because of that a standard for anaerobic digestion outputs should be developed with a certification scheme and quality protocol insisting of the clarity of the regulators and regulated, the confidence in a product delivered to the right market, and removing a barrier and allowing development of the industry (Verma 2008). The soil improvement challenges with digestate are opportunities to improve source separation and the digestate quality and the threat is lack of lignin or wood (Pires 2008). Dry digestion (specifically developed for the anaerobic digestion of organics derived from household waste) becomes particularly attractive when the production of excess wastewater can be avoided by particular stream digestion or by drying the digestate with waste heat coming from the biogas engines. Dry digestion is more easily integrated on existing composting sites and can be used to expand the capacity on the site with the use of limited amount of surface area (Baere 2008). Wet digestion systems are operated at a lower solid concentration compared to dry digestion systems. Taking into account all areas in which the biogas technology is used worldwide the wet technology is the most prevailed biogas technology (Korz 2008). In composting plants based on the percolation technique the waste is first percolated to deliver easily accessible organic matter to the methane reactor. This ensures the existence of two different microbial communities, which are totally dependent on each other. When the percolate from the module becomes low in organic matter the composting of the energy-poor waste in the module is started (Bloch 2008). The biogas potential of kitchen waste is because of the high fat and carbohydrates content, so with a partial stream digestion the waste is to be divided into a stream perfect for both anaerobic digestion and composting (Mayer 2008). Cuhls (2008) determined gaseous emissions from different types of large-scale treatment plants for biowaste in Germany and found that CO_2-equivalent (methane and nitrous oxide) from biological treatment of biowaste is in the waste gas ~30–40 kg/Mg and in the clean gas after biofilter ~70–80 kg/Mg. The estimated emissions for methane and ammonia are overvalued so far, specific contingent of composting or digestion is rather low (<0.5% of total national emission). Anaerobic digestion is increasing. The importance of compost suppressing plant diseases is growing. Results of public RFP (province Utrecht, 2007) granted on price and CO_2 performance indicate results in savings on greenhouse gases up to 160 kton $CO_{2\text{-eq}}$/ton of biowaste to be realized in 2009 (Elsinga 2008). Through co-fermentation, i.e., through the joint treatment of biogenic wastes (co-substrates) in the digesters of the wastewater treatment plant, the digester gas production cab has to be increased considerably (Reipa and Schmelz 2008). Some authors have concluded that there is a need for the cost-effective solutions in the integrations of the anaerobic digestion plant technologies (Hogg 2008; Kajan et al. 2008; Persson 2008; Santen and Fricke 2008; Turk and Kern 2008; Vasconcellos 2008). In comparison with other biotreatment methods biogas production is more expensive. The environmental degradation effects are not sufficient, economically tested and they are not compared with the investments planned for biogas production (Bendere 2008). Uriate (2008) and Siebert (2008) have concluded that the product quality is a very important aspect and because of that quality standards are needed. The highly developed European techniques of anaerobic digestion having a standard quality have good chances in the developing countries, and also in the agricultural production through composting and the use in aqua culture of the residues from the anaerobic digestion (Bildlingmaier 2008).

Biomass (including organic residues and biowaste) represents a continuously renewable potential source of methane and thus offers a partial solution to the eventual prospect of fossil fuel depletion. Processes for conservation of biomass to methane may be classified into two categories: thermal and biological. Thermal processes have the ability to effect total conservation of organic matter at rapid rates. The biological gasification, better known as anaerobic digestion, is a low-temperature process that can process wet or dry feeds (with added water) economically at a variety of scales. The process is based on methane fermentation. The product gas is composed primarily of methane and carbon dioxide with traces of hydrogen sulfide. The major limitation of this process is that conservation is usually not complete, often leaving as much as 50% or more of organic material unconverted.

12.8 Conclusion

Composting biowaste and the application of compost play an important role in sustainable agriculture. Composting allows organic waste to be recycled and returned to the soil and provides a solution for managing much of the waste, which is currently a major problem. If urban organic waste is selectively collected and composted, it no longer represents a problem. Composting provides an excellent way to manage the huge volume of organic waste and convert it into a useful soil amendment. This approach could have practical significance in reducing the use of chemical fertilizers for sustainable agriculture and the environment. The application of enriched compost with N increased the aggregate stability of the soil (Ahmad et al. 2008). The impact of organic amendments and compost extracts in organic vegetable production systems improves soil health (Ghorbani et al. 2008). Hachicha et al. (2006) reports that the compost made of poultry manure and olive mill by-products appears as a promising ecological alternative material to classical fertilizers. Compost will enrich the soil, thus promoting the preservation or improvement of the organic matter reserves of the soil, which is an important component of the soil protection strategy of the EU.

Composting is a complex chemical and biochemical process, during which a series of chemical transformations takes place in organic (bio- or green) wastes. In the course of composting, the decomposition of organic matter takes place in the presence of oxygen with the aid of various microorganisms and invertebrates. The majority of the biological transformations take place via enzyme-catalyzed reactions. From the soil biology point of view, composting is equivalent to rotting, the process whereby organic matter is mineralized, or in come cases humified, with the help of aerobic microorganisms. The end-product of this process is compost, a mixture of stabilized organic matter, mineral nutrients, and microbial products. This end-product should be of a quality that requires no further treatment prior to storage or utilization, and can be used in agriculture or horticulture without any danger to the environment.

In the course of composting the organic matter is stabilized with the help of microorganisms, leading to changes that are beneficial for soil fertility: the use of compost improves the biological activity and nutrient-adsorbing ability of the soil, the acids and microorganisms evolving during humus decomposition make largely insoluble mineral nutrients available to plants, hormone-like compounds stimulate plant growth, and the plants become more resistant to pathogens and pests.

However, if the raw materials are contaminated or the composting process is incomplete, unfavorable effects must be expected. Heavy metals may be introduced into the compost with communal waste. To ensure that these do not enter the food chain, authorised limit values must be strictly adhered to. The same is true of organic contaminants (particularly polyaromatic or chlorinated hydrocarbons), the effect of which is extremely complex. If the fermentation process is not satisfactory, putrefaction will occur, the by-products of which (SO_2, NH_3, NO_2, organic acids, cadaveric alkaloids, etc.) inhibit plant growth and attract pests.

The composting process is an excellent means of recycling, as it reduces the mass and volume of the waste, while inactivating or destroying pathogenic microorganisms, viruses, and parasites, and improving the smell of the waste. The compost thus produced is a valuable form of fertilizer, which increases the organic matter content of the soil, stimulates biological activity, and improves soil texture. The recycling process is complete, as biological waste arises from plant biomass, which extracts nutrients from the soil, while these are returned to the soil when compost is applied as fertilizer.

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Chapter 13
Nematodes as Biocontrol Agents

Tarique Hassan Askary

Abstract The high cost of chemical pesticides, their adverse effects on the environment and development of pest resistance demand an alternative approach for crop pests management, which should be ecofriendly and cost-effective. Entomopathogenic nematodes belonging to genera *Steinernema* and *Heterorhabditis* together with their symbiotic bacteria *Xenorhabdus* and *Photorhabdus*, respectively, and slug-parasitic nematodes *Phasmarhabditis* with its symbiotic bacteria *Moraxella* have been considered as promising biocontrol agents for the management of crop insect pests and slugs. These nematodes have short life cycle, wide host range, and can resist under unfavourable conditions and environmental extremes. Survival and pathogenicity of these nematodes vary from 5 to 35 0ºC. Nematodes can be mass produced under both *in vivo* and *in vitro* conditions. With the realization of these attributes among these bioagents there is a need to search out an ideal formulation and proper application technology to include them in pest management programme.

Keywords Bioagent • Entomopathogenic nematode • Heterorhabditis • In-vitro • In-vivo • Moraxella • Phasmarhabditis • Photorhabdus • Slug-parasitic • Steinernema • Xenorhabdus

13.1 Introduction

The use of nematodes as a biocontrol agent has been developed in the past 2 decades. Proper use of these bioagents on experimental scale has proved superbly successful in both short- and long-term pest suppressions. Crop insect pests are one

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T.H. Askary (✉)
Plant Protection, KVK, Shuhama, Veterinary College Campus, SKUAST-K, Alastang, Srinagar, 190006, Jammu and Kashmir, India
e-mail: tariq_askary@rediffmail.com

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of the major limiting factors in sustaining the agriculture productivity and the indiscriminate use of chemical pesticides for its management has affected humans and their environment. Hence, the biological control of crop pests is an ideal alternative to reduce the overall use of chemical pesticides. Entomopathogenic nematodes belonging to the families Steinernematidae and Heterorhabditidae and slug-parasitic nematodes, *Phasmarhabditis* spp. are considered lethal parasites of crop insect pests and slugs, respectively, and have a high biocontrol potential, safe for humans, other non-target organisms and virtually posing no hazardous effect on the environment. These nematodes harbour symbiotic bacteria in their intestine, which are released after entering into the host. The bacteria produce a toxic substance that ultimately leads to killing of the host (Woodring and Kaya 1988). The focus of this chapter lies upon three nematodes, viz., *Steinernema, Heterorhabditis* and *Phasmarhabditis* important from biological control of view, limitations in their use and ideas to overcome the problem in the present context.

13.2 Historical Background

Nematodes from more than 30 families are known to be associated with insects and other invertebrates (Poinar 1979, 1990; Kaya and Stock 1997). However, only a few have established their potentialities as host enemies, while majority of them are more associated either for transport and dissemination or for sharing the same habitat (Sundarababu and Sankaranarayanan 1998). The nematodes from seven families, viz., Mermithidae, Allantonematidae, Sphaerularidae, Tetradonematidae, Phaenopsitylenchidae, Steinernematidae and Heterorhabditidae are important from biological control of view (Kaya and Stock 1997). Steinernematidae and Heterorhabditidae are of much interest and drew lot of attention on the part of research workers and practitioners (Lacey et al. 2001). These nematodes possess many attributes of parasitoids and pathogens. They are analogous to parasitoids because they have chemoreceptors and can actively search for their hosts (Kaya and Gaugler 1993; Gaugler et al. 1997). Their similarity to pathogens is due to their association with mutualistic bacteria, viz., *Xenorhabdus* and *Photorhabdus* for steinernematids and heterorhabditids, respectively. The nematode–bacterial complex is highly virulent, killing its host within 48 h through the action of mutualistic bacteria, can be cultured in vitro, have a high reproductive potential (Kaya and Gaugler 1993), have wide range of hosts, yet pose no threat to plants, vertebrates and many invertebrates (Akhurst 1990; Kaya and Gaugler 1993).

Steinernematidae comprises two genera: *Steinernema* and *Neosteinernema*. *Steinernema* has more than 50 species (Ganguly 2006), whereas *Neosteinernema* has only one species (Nguyen and Smart 1994). The family Heterorhabditidae has one genus *Heterorhabditis* with eight reported species (Adams and Nguyen 2002). However, these figures have increased as in the last few years a number of new species belonging to *Steinernema* and *Heterorhabditis* have been described from different parts of the world. Phan et al. (2005) described *Steinernema robustispiculum* from Vietnam. *S. seemae* and *S. masoodi* were described from India (Ali et al.

2005a), *S. khoisanae* from South Africa (Nguyen et al. 2006a), *S. leizhouense* from southern China (Nguyen et al. 2006b), *S. hebeiense* from northern China (Chen-ShuLong et al. 2006), *S. ashiuense* from Japan (Phan et al. 2006), *S. sichuanense* from east Tibetan mountains, China (Mracek et al. 2006), *S. cholashanensen* from Sichuan province of China (Nguyen et al. 2008a), *S. weiseri* from Turkey (Unlu et al. 2007), *S. costaricense* and *S. puntauvense* from Costa Rica (Uribe-Lorio et al. 2007), *Heterorhabditis safricana* from western cape province of South Africa (Malan et al. 2008) and *H. georgiana* from Georgia, USA (Nguyen et al., 2008b).

The first entomopathogenic nematode, *Aplectana kraussie* was reported by Steiner (1923), which was later named as *S. kraussie* by Travassos (1927). However, biocontrol potential of entomopathogenic nematode under field condition was recognized when Glaser (1932) reported the suppression of Japanese beetle with the application of *Neoaplectana glaseri*. Application of the nematode to 73 field plots in New Jersey resulted in 0.3–81% pest suppression and its persistence was noticed for 8.5 years after treatment (Glaser 1932; Glaser and Farrell 1935; Glaser et al. 1940). Schneider (1859) described the association of a nematode with the slug *Arion ater*. Maupas (1900) established culture of a nematode, *Phasmarhabditis hermaphrodita* (which he called *Rhabditis causenelli*) on rotting flesh and the dauer larvae used for this purpose was found in the intestine of *A. ater*. However, *Pp. hermaphrodita* was first described as a potential biocontrol agent by Wilson et al. (1993a). In 1994, the commercial product of this nematode was released for use by home gardeners under the trade name Nemaslug® (Glen et al. 1994, 1996). This nematode has now been on sale in several European countries (Ester and Wilson 2005).

13.3 Steinernematids and Heterorhabditids

13.3.1 Ecology and Distribution

After the baiting technique developed by Bedding and Akhurst (1975), random soil surveys were conducted globally in order to find entomopathogenic nematode in temperate, sub-tropical and tropical countries. These nematodes were common in both cultivated and uncultivated soils and their distribution was found to be worldwide (Hominick et al. 1996; Hominick 2002). Steinernematids were much more biologically diversified than Heterorhabditids. The most widely distributed species were *S. carpocapsae,* which has been isolated from Europe, Australia, New Zealand, India and America followed by *S. feltiae* from Europe, Australia and New Zealand (Poinar 1990). *S. carpocapsae* and *S. feltiae* were widely distributed in the temperate region, whereas *H. bacteriophora* in the continental Mediterranean climate and *H. indica* throughout the tropics and sub-tropics (Hominick 2002). Among the most thinly distributed species were *S. anomali*, which was recovered only from Russia, *S. rara* from Brazil, *S. kushidai* from Japan and *S. scapterisci* from Uruguay. The most prevalent species in the UK was *S. feltiae*, whereas in Northern Europe it was *S. affini* (Poinar 1990). The factors affecting the local distribution of entomopathogenic nematodes are soil texture, vegetation and availability of suitable hosts (Griffin et al. 2005). *S. affini* was found largely in arable lands and grasslands but absent in forests, whereas *S. kraussie* was common in forests (Hominick 2002). *H. megidis* and *H. indica* were extensively found in sandy soils, resulting in a mainly coastal distribution (Griffin et al. 1994, 2000). The distribution of *H. indica* has also been reported from the soil samples collected from three sites in the date palm growing region in the eastern province of Saudi Arabia (Saleh et al. 2001). Uribe-Lorio et al. (2005) conducted a survey in north Pacific and southeast Caribbean regions of Costa Rica. Out of a total of 41 soil samples, five were positive for entomopathogenic nematodes, with three containing *Steinernema* and two containing *Heterorhabditis* isolates. Campos-Herrera et al. (2007) studied the distribution of entomopathogenic nematodes in natural areas and crop field edges in La Rioja, Northern Spain. Five hundred soil samples from 100 sites were assayed for the presence of entomopathogenic nematodes. There was no statistical difference in the abundance of entomopathogenic nematodes to environmental and physical-chemical variables, although, there were statistical differences in the altitude, annual mean air temperature and rainfall, potential vegetation series and moisture percentage recovery frequencies. Twenty isolates were identified upto species level and 15 strains were selected of which 11 were *S. feltiae*, two *S. carpocapsae* and two *S. kraussie*. *S. kraussie* was isolated from humid soils of cool and high altitude habitats and *S. carpocapsae* was found to occur in heavy soils of dry and temperate habitats. *S. feltiae* was the most common species with a wide range of altitude, temperature, rainfall, pH and soil moisture, although this species preferred sandy soils.

In course of evolution, entomopathogenic nematode like other terrestrial organisms have adopted unique survival mechanism to resist unfavourable condition and environmental extremes including absence of water, extreme temperature, lack of oxygen and osmotic stress. Survival and pathogenicity of *S. carpocapsae* has been found greater at lower temperature (5–25°C) than at higher temperature (35°C), whereas survival and pathogenicity of *S. glaseri* has been found greater at higher temperature (15–35°C) than at the lower temperature (5°C) (Kung and Gaugler 1991). The optimum temperature and moisture requirement for infectivity and survival vary with nematode species as has been reported in case of *S. abbasi*, *S. tami*, *S. carpocapsae*, *S. feltiae*, *S. glaseri* and *S. thermophilum* (Karunakar et al. 1999; Ganguly and Singh 2001; Ganguly and Gavas 2004). Cooler temperature has not been found detrimental to nematode survival (Kaya 1990) but exposure to nematode at 35°C or above have proved detrimental to infective juveniles (Schmiege 1963). Hazir et al. (2001) studied the effect of temperature on the infectivity, time of death, development and reproduction of *S. feltiae*. Five isolates of *S. feltiae* were used in the experiment: SN from southern France, Rafaela from Argentina, Monterey from California, MG-14 from Hawaii and Sinop from Turkey. The result indicated that all isolates caused 100% mortality of greater wax moth, *Galleria mellonella* larvae and developed and produced progenies between 8°C and 25°C. At 28°C none of the isolates produced progeny, and the nematodes developed to the first generation adults were unable to proceed to the next generation. In all isolates, penetration efficiency was highest at 15°C and 20°C and emergence time was fastest at 20°C and 25°C. Bhatnagar and Bareth (2003) conducted an experiment to study the survival of *H. bacteriophora* in sandy loam soil at four moisture levels representing 25%, 50%, 75% and 100% of the field capacity. In saturated soils, 70% of the infective juveniles survived for 75 days. Nematode mortality reached 40% within 15 days in soil with 50% field capacity moisture level and within 5 days in soil with moisture level at 25% field capacity. Jothi and Mehta (2007) investigated the impact of different temperatures on the infectivity and productivity of four entomopathogenic nematodes, viz., *H. indica, H. bacteriophoa, H. zealandica* and *S. glaseri* on *G. mellonella*. All the species of entomopathogenic nematodes caused 100% mortality at a temperature ranging between 30°C and 40°C at 24 h after inoculation. At 48 h after inoculation *H. indica* and *H. bacteriophora* caused 100% mortality between 20°C and 27.5°C, whereas *H. zealandica* was effective at temperature between 22.5°C and 27.5°C. *S. glaseri* was found to be virulent even at 15°C and continued upto 27.5°C at 48 h after inoculation by causing 100% mortality.

13.3.2 Life Cycle

Life cycle of entomopathogenic nematode includes the egg, four juvenile stages and adult. The third stage is a free-living infective juvenile (dauer stage). The infective juveniles of both steinernematids and heterorhabditids carry in its gut bacteria of the genus *Xenorhabdus* and *Photorhabdus*, respectively (Boemare et al. 1993). The infective juvenile enters the host through mouth, anus or spiracles or penetrate through the intersegmental membranes of the insect cuticle as in case of *Heterorhabditis* sp. (Bedding and Molyneux 1982; Peters and Ehlers 1994) and reaches the haemocoel. In the haemocoel, infective juvenile releases cells of bacterial symbiont from its intestine. The nutrient-rich haemolymph of insect helps in the rapid multiplication of bacteria and ultimately results in killing the host within 48 h (Woodring and Kaya 1988). The infective juvenile then becomes feeding juvenile or functional third-stage juvenile and feed on the multiplying bacteria and degrading host tissues. The nematodes moult to fourth stage and finally develop into adult .The life cycle of steinernematids from infection to emergence of infective juveniles ranges from 7 to 10 days and for heterorhabditids ranges from 12 to 15 days (Sundarababu and Sankaranarayanan 1998). The number of generations may be more than one within the host cadaver depending upon the available resources.

Infective juveniles of Steinernematids develop into amphimictic females and males and never develop into hermaphrodites, whereas Heterorhabditids always develop into hermaphrodites in the first generation. Subsequent generation of heterorhabditids produces males, females and hermaphrodites (Dix et al. 1992). First-generation adults of steinernematids are termed as giant adults due to their larger size. This condition is believed to be due to the abundant available nutrition. The progeny of next generation, in most cases, find gradually depleting food supply due to regular progeny development. A full third-generation progeny may be observed when the food supply is in plenty (Adams and Nguyen 2002). Juveniles developing with adequate food supply mature to adults, while those developing in crowded conditions with limited food resources results in infective juveniles. Under suitable condition infective juveniles exit the cadaver to seek new hosts.

The eggs are initially laid into the host medium but in older female or hermaphrodite, eggs hatch in the uterus, and the developing juveniles consume the parental tissues. This process is known as *endotokia matricida* (Johnigk and Ehlers 1999), i.e. intrauterine birth causing maternal death. The infective juveniles are provided with two layers of external membrane, the cuticle of the third and second stages, due to superimposed first and second moults. The sheath of *Heterorhabditis* spp. in particular helps in protection against desiccation, freezing and fungal pathogens (Timper and Kaya 1989; Campbell and Gaugler 1991a; Wharton and Surrey 1994). This tight-fitting sheath of heterorhabditids do not lose easily, whereas the loose-fitting sheath of steinernematids is soon lost, as the nematode moves through the soil (Campbell and Gaugler 1991b; Dempsey and Griffin 2003). The physiology of infective juveniles may also bestow resistance or hardiness. In addition, oral and anal openings of infective juveniles remain closed in soil, thus preventing entry by microbial antagonists and toxic chemicals.

13.3.3 Nematode–Bacteria Symbiosis

The symbiotic association between entomopathogenic nematode and its bacteria have been reported by several workers (Kaya 1990; Kaya and Gaugler 1993; Tanada and Kaya 1993; Sicard et al. 2005; Somavanshi et al. 2006; Wang et al. 2007a). Infective juveniles of entomopathogenic nematode carry the bacteria *Xenorhabdus* (in case of steinernematids) or *Photorhabdus* (in case of heterorhabditids) belonging to Enterobacteriaceae (Forst et al. 1997; Nagesh et al. 2002). These bacteria are Gram-negative, anaerobes, nonspore former and do not have resistant stage. Infective juveniles of *Steinernema* sp. harbour *Xenorhabdus* sp. in a special intestinal vesicle, whereas those of *Heterorhabditis* sp. carry *Photorhabdus* sp. in the anterior two third part of the intestine (Forst and Clarke 2002).

Entomopathogenic nematodes, *Steinernema* and *Heterorhabditis*, belonging to different species harbour different species of bacteria (Table 13.1). The life cycle of nematode–bacteria association is composed of two stages: (i) a free stage in the soil, where the infective juveniles carry bacteria in their guts and search for new insect host, and (ii) a parasitic stage, where the infective juveniles infect insect, release their bacterial symbionts and reproduce in order to produce new infective juveniles (Emelianoff et al. 2007). Both partners benefit from the association. The bacteria provide a nutritive medium for the growth and reproduction of nematodes. These bacteria are also useful in other two ways: (i) largely responsible for the rapid death of the host, as well as (ii) suppressing other competing organisms by the production of antibiotics. On the other hand, nematode protects the bacteria from the external environment, carries them into the insect haemocoel and in some cases inhibits the insect immune response. Martens et al. (2003) suggested that

Table 13.1 Entomopathogenic nematodes and their symbiotically associated bacteria (Reproduced from Ganguly 2006)

Entomopathogenic nematode	Bacterium
Steinernema kraussei	*Xenorhabdus bovienii*
S. carpocapsae	*X. nematophila*
S. feltiae	*X. bovienii*
S. glaseri	*X. poinarii*
S. kushidai	*X. japonica*
S. intermedium	*X. bovienii*
S. affine	*X. bovienii*
S. cubanum	*X. poinarii*
S. bicornutum	*X. budapestensis*
S. longicaudatum	*X. beddingii*
S. rarum	*X. szentirmaii*
S. scapterisci	*X. innexi*
S. serratum	*X. ehlersii*
S. thermophilum	*X. indica*
Heterorhabditis bacteriophora subgroup Brecon	*Photorhabdus luminescens luminescens*
H. bacteriophora subgroup HP88	*Pp. luminescens laumondii*
H. bacteriophora subgroup NC	*Pp. temperata*
H. megidis Nearctic group (Ohio, Wisconsin)	*Pp. temperata*
H. megidis Palaearctic group	*Pp. temperata temperata*
H. indica	*Pp. luminescens akhurstii*
H. zealandica	*Pp. temperata*

Xenorhabdus nematophila initiates infective juvenile colonization of *S. carpocapsae* by competing for limited colonization sites or resources within the nematode intestine. Mahar et al. (2008) isolated the bacterial cells and metabolites of entomopathogenic bacterium *Pseudomonas luminescens* from *H. bacteriophora* and compared their effectiveness to the larvae of diamondback moth, *Plutella xylostella*. All different instars of diamondback moth were susceptible to lethal effect of bacterium and its metabolites. However, bacterial cells of *Pp. luminescens* suspended in broth were slightly more lethal to diamondback moth larvae. Jan et al. (2008) in an experiment found that cells of the bacterial symbiont *X. nematophila* isolated from *S. carpocapsae* are lethal to the pupae of greater wax moth, *G. mellonella,* beet armyworm, *Spodoptera exigua*, diamondback moth, *Pp. xylostella* and blackvine weevil, *Otiorhynchus sulcatus* in the absence of nematode vectors. The cells of *X. nematophila* were found to enter the haemocoel of the pupae.

13.3.4 Host Range and Effects

Steinernematid and Heterorhabditid nematodes attack a far wide spectrum of insects and are being exploited worldwide to manage crop insect pests. The host range of these nematodes varies with the species (Table 13.2) and it has been observed to

Table 13.2 Host suitability of some *Steinernema* sp. against various insect pests

Steinernema sp.	Host insect
S. seemae, S. masoodi, S. thermophilum, S. glaseri, S. carpocapsae	Greater wax moth (*Galleria mellonella*)
S. carpocapsae, S. seemae, S. thermophilum, S. glaseri, S. masoodi	Rice moth (*Corcyra cephalonica*)
S. carpocapsae	Black cutworm (*Agrotis ipsilon*)
S. carpocapsae, S. feltiae, S. abbasi, Heterorhabditis indica	Tobacco caterpillar (*Spodoptera litura*)
S. glaseri, S. carpocapsae	White grub (*Holotrichia consanguinea*)
S. carpocapsae	Leaf minor (*Liriomyza trifolii*)
S. masoodi, S. seemae, S. carpocapsae, S. thermophilum	Gram pod borer (*Helicoverpa armigera*)
S. carpocapsae	Diamondback moth (*Plutella xylostella*)
S. seemae, S. masoodi	Legume pod borer (*Maruca vitrata*)
S. masoodi, S. seemae, S. carpocapsae	Blue butterfly (*Lampides boeticus*)
S. seemae, S. masoodi, S. carpocapsae	Bruchid (*Callosobruchus* sp.)
S. seemae, S. masoodi	Wheat flour beetle (*Tribolium castaneum*)
S. masoodi, S. seemae, S. carpocapsae	Grey weevil (*Myllocerus* sp.)
S. masoodi, S. seemae, S. carpocapsae	Bihar hairy caterpillar (*Diacrisia obliqua*)
S. masoodi, S. carpocapsae	Mealybug (*Centrococcus* sp.)

infect over 200 species of insects belonging to different orders (Woodring and Kaya 1988). *S. carpocapsae* has been found to parasitize more than 250 insect species from over 75 families in 11 orders (Poinar 1975). The host range of nematodes largely depends on foraging strategy varying from cruising to ambusher (Campbell and Gaugler 1997). Cruisers have an active searching strategy, moves through the soil and are more effective against those insects, which are less mobile (Lewis et al. 1993; Campbell and Gaugler 1997). The cruise foraging species are *Heterorhabditis* sp. and *S. glaseri* (Lewis 2002). Ambushers nictate during foraging by raising nearly all of their bodies off the substrate. *S. carpocapsae* and *S. scapterisci* are the extreme ambushers and may nictate for hours at a time (Campbell and Gaugler 1993). Heterorhabditids have a better host-finding ability than the Steinernematids (Choo et al. 1989). Motility and attraction are also responsible for host-finding ability of nematodes. There is a third type having intermediate foraging strategy whereby nematodes raise themselves on substrate for a short while, and has been reported in some species like *S. riobrave* and *S. feltiae* (Griffin et al. 2005). Susurluk (2008) compared the vertical movement of Turkish isolates of *S. feltiae* (TUR-S3) and *H. bacteriophora* (TUR-H2) at different temperatures in the presence and absence of larvae of the host insects, *G. mellonella*. It was observed that nematodes of both species moved faster towards the bottom of the column when an insect was placed there. *S. feltiae* showed greater vertical dispersal ability than *H. bacteriophora*. The vertical movement of both species increased as the temperature increased and lower temperature depressed the movement of *H. bacteriophora* more than *S. feltiae*. The nematodes that had migrated different distances were compared for their infectivity to *G. mellonella* and the positive correlation between the distance travelled and infectivity indicated that there was a link between host-searching behaviour and infection behaviour in *S. feltiae* and to a lesser extent, also in *H. bacteriophora*.

The insects killed by nematodes are flaccid and do not undergo putrefaction because the mutualistic bacteria produce antibiotics, which prevent the growth of secondary micro-organisms. Also the cadaver differs in colour. Insects killed by steinernematids turn ochre, yellow brown or black, whereas those killed by heterorhabditids turn red, brick- red, purple, orange or sometimes green (Sundarababu and Sankaranarayanan 1998). The insect infected with heterorhabditids, luminesce in the dark and this is due to the symbiotic bacteria *Photorhabdus luminescens* present in the intestine of the nematodes. The internal tissues of the killed insects become gummy or sticky.

Cannayane et al. (2007) conducted a laboratory experiment to test the pathogenic potential of *H. indica* and *S. glaseri* on cardamom root grub, *Basilepta fulvicorne*. After mortality the cadaver of *B. fluvicorni* exhibited brick red to brown colour when infested with *H. indica* and also luminescent under ultraviolet, whereas, yellow and flaccid nature was due to *S. glaseri* infestation.

The efficacy of Steinernematids and Heterorhabditids in the management of crop insect pests has been worked out by several workers in the past. Kumar et al. (2003) studied the efficacy of Heterorhabditids against *S. litura* collected from castor bean. The insect mortality was significant within 48 h of exposure when infective juveniles of *Heterorhabditis* were released against the larva of *S. litura* at the rate of 50, 75, 100, 125 and 150 infective juveniles per 100 g of soil. Narayanan and Gopalakrishnan (2003) reported that mustard sawfly, *Athalia lugens proxima* was highly susceptible to *S. feltiae* on radish under field condition. Toledo et al. (2006) for the first time demonstrated the infectivity of *H. bacteriophora* on third instar of tropical fruit fly, *Anastrepha serpentina* under laboratory conditions. Adjei et al. (2006) reported that *S. scapterisci* applied in stripe to a 10 ha bahia grass pasture reduced populations of mole crickets, *Scapteriscus* spp. by 79.2% over a period of 3 years. Infection on *Tipula paludosa*, a turf grass pest on golf courses was studied under laboratory condition against *Heterorhabditis* and *Steinernema* and it was observed that these nematodes were virulent against *T. paludosa* (Simard et al. 2006). Shapiro-Ilan and Cottrell (2006) also reported the susceptibility of lesser peach tree borer, *Synanthedon pictipes* against *S. carpocapsae* and *S. feltiae*. Cuthbertson et al. (2007) tested the efficacy of *S. feltiae* under both laboratory and glass house condition against sweet potato white fly, *Bemisia tabaci*. They observed 90% mortality in second instar of *B. tabaci* under laboratory condition and 80% under glass house condition. Ramos-Rodriguez et al. (2007) reported that under laboratory bioassay *S. riobrave* significantly reduced survival of larva, pupae and adults of a store grain pest red flour beetle, *Tribolium castaneum*. In an experiment, *S. thermophilum* when applied at 3000 infective juveniles per millilitre caused 46% mortality of diamondback moth infesting cabbage, whereas, mortality at 2,000 infective juveniles per millilitre was 40.5% (Somavanshi et al. 2006). Elawad et al. (2007) assessed the pathogenicity of *H. indicus* a local isolate of UAE against red palm weevil, *Rhynchophorus ferrugineus*. The result indicated that nematode was effective in declining the population of *R. ferrugineus* under both laboratory and field conditions. However, a higher concentration of *H. indicus* was required for field application. Khan et al. (2007) tested the pathogenicity of *S. masoodi* against final instars of six insect pests, i.e. *G. mellonella, Pp. xylostella, Pieres brassicae, Corcyra cephalonica, Helicoverpa armigera* and *A. proxima*. Six concentrations of the nematode were used, i.e. 25, 50, 75, 100, 125 and 150 infective juveniles per larvae. The nematode was found to be pathogenic to all the six insects with a considerable degree of variability in pathogenicity. Koppenhofer et al. (2008) conducted a series of laboratory and green house experiments to evaluate the comparative effectiveness of *S. scarabaei*, *H. bacteriophora* and *H. zealandica* for the control of second and third instar of cranberry white grub, *Phyllophaga georgiana* in cranberries. The result indicated that *S. scarabaei* was the most effective species causing 76–100% mortality of *Pp. georgiana* under green house condition. However, under laboratory condition *S. scarabaei* was more effective against third instar than second instar of *Pp. georgiana*. In an experiment under laboratory condition, Entonem and Larvanem, the two commercial products of *S. feltiae* and *H. bacteriophora*, respectively, were evaluated against *Parahypopta caestrum*, the major insect pest of *Asparagus officinalis* in Greece. *S. feltiae* caused insect mortality within 24 h, however, the highest level of mortality was observed at 48 h. In contrast, *H. bacteriophora* required 96 h to achieve the highest level of mortality. However, under field condition the two nematodes provided equal insect suppression (Salpiggidis et al. 2008).

13.3.5 Mass Production

The two different techniques for mass production of entomopathogenic nematodes are (i) in vivo, and (ii) in vitro. Production of entomopathogenic nematodes depend upon the area to be applied as well as the type of nematode species used. If a small plot is to be applied as for research purpose, the in vivo production technique would be appropriate, otherwise for fields in vitro methods are used.

13.3.5.1 In Vivo Production

White trap (White 1927) is one of the most common methods to produce entomopathogenic nematodes. Insects are inoculated with entomopathogenic nematodes on a petridish lined with filter paper. After 2–5 days, the infected insects are transferred to the White trap. The White trap consist of an inverted watch glass placed in a petridish on which Whatman paper of appropriate size is placed and moistened with sterilized distilled water. Adequate amount of distilled water is also maintained on and around the watch glass. As the infective juveniles emerge from the cadaver they migrate to the surrounding water and get trapped. The nematodes are harvested from the White trap and collected in a beaker. The concentration of nematodes can be accomplished by

Fig. 13.1 Entomopathogenic nematode *Steinernema masoodi* multiplying over the body of *Galleria mellonella* larva (Reproduced from Ali et al. 2005b)

gravity settling (Dutky et al. 1964) and/or vacuum filtration (Lindergen et al. 1993). Entomopathogenic nematodes produced in vivo are highly virulent and infective. The last instar of the greater wax moth, *G. mellonella*, is generally used for in vivo production of entomopathogenic nematodes as this insect is highly susceptible, easily available and produces high yields (Fig. 13.1) (Woodring and Kaya 1988).

Other Lepidopterans and Coleopterans have also been used for in vivo production of nematodes (Shapiro-Ilan and Gaugler 2002). Nematode yield depends upon the insect host size. In general yield of nematode is proportional to the size of the insect host (Blinova and Ivanova 1987; Flanders et al. 1996), however, yield per milligram insect (within host species) and susceptibility to infection is inversely proportional to size or age of host (Dutky et al. 1964; Shapiro-Ilan et al. 1999). The major drawback of in vivo technique is cost of production, which tilts towards the higher side, as two different organisms, host insect and entomopathogenic nematode are to be cultured simultaneously. But such limitation has not restricted the production technology to sustain itself as a cottage industry (Gaugler et al. 2000; Gaugler and Han 2002). In vivo production of entomopathogenic nematodes is likely to continue as small ventures for niche markets or in those countries where labour cost is low. The production and application of entomopathogenic nematodes in infected host cadaver is also an alternative to encourage this technology (Shapiro-Ilan et al. 2001, 2003).

13.3.5.2 In Vitro Production

Bedding (1984) developed a technique whereby huge number of infective juveniles may be economically produced using a chicken, duck or turkey offal medium on a porous polyurethane foam substrate. The rearing container used in this method is a glass flask or autoclaved plastic bags aerated with aquarium pumps and inoculated with approximately 2,000 infective juveniles per gram medium. This method can be used to produce on an average one billion infective juveniles per bag of flask of 500 ml capacity (100 g medium). Currently, some companies, viz., Andermatt (Switzerland), Bionema (Sweden), Oviplant (Poland) and Biologic (USA) are using this technology of nematode production (Ehlers and Shapiro-Ilan 2005). This technique involves the following steps.

Preparation of Rearing Flasks/Bags

Small foam pieces are impregnated with chicken, duck or turkey offal homogenate at the rate of 12.5 parts medium to one part foam by weight. A wide mouthed Erlenmeyer flask of 500 ml capacity is filled with this foam homogenate mixture to the 250–300 ml mark (about 100 g). The mouth of the flask is wiped, plugged with cotton, wrapped with cheese muslin cloth and autoclaved at 121°C for 20 min.

Inoculation with Bacteria

Appropriate *Xenorhabdus* or *Photorhabdus* bacterial cells are aseptically transferred to 5 ml of nutrient broth in a test tube and kept overnight on a shaker. The flasks containing autoclaved material are inoculated with the bacterial culture by pouring the contents of one culture tube. The flask is shaken well and stored for 2–3 days at 25°C to allow multiplication of the bacteria.

Inoculation with Nematodes

Each flask colonized with the bacteria is inoculated with surface sterilized 500–1,000 infective juveniles of an appropriate species in 5 ml sterilize distilled water and are incubated at 25°C. The flask after inoculation should not be shaken vigorously to enable better feeding and reproduction of the nematode.

Harvesting

The nematodes can be harvested from the flask in about 15 days. A 20 mesh sieve is taken and foam pieces are piled 5 cm deep on it. The sieve is then placed in a pan and brought near water tap with water level adjusted so that the foam pieces are just submerged. It is left for 2 h. During this period infective juveniles will migrate into the water. The nematodes may be sedimented and rinsed to remove particulate matter and inactive or dead juveniles. The infective juveniles thus obtained should be rinsed with specialized distilled water for several times to make the suspension clear. Various other synthetic media tested to mass culture of entomopathogenic nematodes have been enlisted (Table 13.3).

Table 13.3 Different media recommended for production of entomopathogenic nematodes

Synthetic medium	Nematode species	Incubation period	Temperature	Nematode harvested	Reference
Beef extract, peptone, corn meal, water on sponge	*Steinernema feltiae*	–	–	–	Li (1984)
Dogfood agar medium	*S. feltiae*	–	–	10^5/g medium	Hara et al. (1981)
Kidney/fat homogenate	*S. feltiae*	2–3 weeks	25°C	3.8×10^7/30 flasks	Bedding (1981)
	S. bibionis			2.9×10^7/73 flasks	
	S. glaseri			8×10^6/11 flasks	
	Heterorhabditis bacteriophora			3.6×10^7/10 flasks	
	H. heliothidis			3.2×10^7/15 flasks	
3% Soyapeptone + 3% yeast extract + 10% chick embryo extract medium	*S. glaseri*	–	–	10^4/week for 93 days	Tarakanov (1980)
Nutrient broth yeast extract vegetable oil, flour coated on sponge	*H. heliothidis*	4 weeks	25°C	10^7/250 ml flask	Wouts (1981)
Wheat bran+ salad oil	*S. feltiae*	3 weeks	25°C	10^7/g medium	Abe (1987)
Wheat bran	*S. feltiae*	3 weeks	25°C	10^4/g medium	Abe (1987)

13.3.6 Formulation, Storage and Quality

The important aspects, which are to be kept in mind for commercialization of entomopathogenic nematodes as biocontrol agent are formulation, storage and quality control. Formulation refers to the preparation of a product from an ingredient by the addition of certain active (functional) and non-active (inert) substances. It provides means to improve the activity, delivery, ease to use, storage stability and field efficacy of the nematodes. Entomopathogenic nematode species have differential requirement for temperature, moisture and oxygen (Glazer 2002). These requirements may dictate the conditions for formulation and storage. As a result of varied nematode species, differential survival requirements and formulation types, an array of products can be developed for management of different insect pests. Entomopathogenic nematodes are live organisms and regardless of how they are formulated, their quality declines with time. Furthermore, all formulations are susceptible to temperature extremes, ultraviolet light, anoxic conditions and contamination (Lewis and Perez 2004). Infective juveniles of entomopathogenic nematode can be stored in water for several months in refrigerated bubbled tanks, however, high cost as well as quality maintenance are somewhat difficult through this method. Tolerance and activity of the nematodes at extreme environmental conditions can limit the shelf life, quality and field performance of the products (Ehlers et al. 2005). Till now no entomopathogenic nematode formulation has met the 2-year shelf life requirement of a standard chemical pesticide (Table 13.4).

The target in developing an ideal formulation is (i) maintenance of quality, (ii) increased storage stability, (iii) low transport cost, and (iv) enhancement of nematode survival during and after application. These can be achieved when absorbents, adsorbents, anticaking agents, antimicrobial agents, antioxidants, surfactants, carriers, preservatives, ultra violet protectants, etc. may be added to the formulation depending upon the need. Formulation of nematodes for storage and transport are generally done by two ways.

1. The nematodes are placed in inert carriers such as sponge and vermiculite that allow free gas exchange and movement of nematodes.
2. Addition of functional ingredients, which reduces nematode activity and metabolism.

It has been observed that sometimes nematodes escape from the inert carriers and dry out (Grewal and Peters 2005), therefore in formulations mobility/metabolism of nematodes is minimized through physical trapping, inclusion of metabolic inhibitors or through the induction of partial anhydrobiosis. Nematode metabolism is temperature driven and a warm temperature between 20°C and 30°C accelerates metabolic activities, thereby reducing nematode viability (Georgis 1990a). Formulations prepared in carriers such as alginate, clay, polyacrylamide gels, vermiculite, activated charcoal, etc. can be stored for at least 3 months under refrigeration or at room temperature. Temperature requirement during storage, however,

Table 13.4 Expected shelf life of different entomopathogenic nematode formulations

Formulation	Nematode species	Strain	Shelf life (months)	
			22–25°C	2–10°C
Sponge	*Steinernema carpocapsae*	All	0.03–0.01	2.0–3.0
	Heterorhabditis bacteriophora	HP88	0	1.0–2.0
		Hybrid	0	0.75–1.5
	H. indica	LN2	0.25	0
	H. marelata	Oregon	0	1.0–2.0
Vermiculite	*S. carpocapsae*	All	0.1–0.2	5.0–6.0
	S. feltiae	SN	0.03–0.1	4.0–5.0
Liquid concentrate	*S. carpocapsae*	All	0.16–0.2	0.4–0.5
	S. riobrave	RGV	0.1–0.13	0.23–0.3
Wettable powder	*S. carpocapsae*	All	2.0–3.5	6.0–8.0
	S. feltiae	UK	2.5–3.0	5.0–6.0
		ENO2	0.5–1.0	3.0–4.0
	S. glaseri	NJ43	0.03–0.06	1.0–1.5
	S. scapterisci	Uruguay	1.0–1.5	3.0–4.0
	H. bacteriophora	ENO1	0.5–1.0	2.0–3.0
	H. indica	LN2	0.25–0.50	0
	H. megidis	UK	2.0–3.0	4.0–5.0
	H. zealandica	X1	1.0–2.0	0
Water-dispersible granule	*S. carpocapsae*	All	4.0–5.0	9.0–12.0
	S. feltiae	SN	1.5–2.0	5.0–7.0
	S. riobrave	RGV	2.0–3.0	4.0–5.0
Alignate gel	*S. carpocapsae*	All	3.0–4.0	6.0–9.0
	S. feltiae	SN	0.5	4.0–5.0
Flowable gel	*S. carpocapsae*	All	1.0–1.5	3.0–4.0
	S. glaseri	NJ43	0.16–0.2	0.4–0.5
	S. scapterisci	Colon	0.1–0.13	0.23–0.3

varies with entomopathogenic nematode species. General range of storage temperature for steinernematids is 5–10°C, whereas for heterorhabditis it is 10–15°C (Georgis 1990b). In another approach functional ingredients such as alginate and flowable gel formulations are used to trap nematodes physically in order to reduce their movement. Also with the induction of partial anhydrobiosis, nematode activity and metabolism can be reduced. Grewal (2002) reported the storage of *S. carpocapsae* for 3–4 months at 25°C and *S. feltiae* for 2–4 weeks in alginate gel formulation. Bedding (1988) described a formulation whereby nematodes were mixed in clay for removing excess surface moisture and inducing partial anhydrobiosis. The formulation called ‘sandwich’ consisted a layer of nematode between two layers of clay.

Water-dispersible granule formulation is considered to be the first commercial formulation enabling storage of *S. carpocapsae* for 6 months at 25°C at a concentration of over 300,000 infective juveniles per gram (Grewal 2000). When stored at

Table 13.5 Formulations of *Steinernema* and *Heterorhabditis* developed by different countries

Nematode	Product	Country
Steinernema carpocapsae	Ortho biosafe	United States of America
	Bio vector	United States of America
	Exhibit	United States of America
	Sanoplant	Switzerland
	Boden nutzlinge	Germany
	Helix	Canada
S. feltiae	Manget	United States of America
	Nemasys	United Kingdom
	Stealth	United Kingdom
S. riobrave	Vector MG	United States of America
S. scapterisci	Proactant Sc	United States of America
S. kushidai	SDS biotech	Japan
Heterorhabditis megidis	Nemasys	United kingdom
H. bacteriophora	Otinem	United States of America
	E- Nema Gmbh	Germany

room temperature, water-dispersible granule formulations were found prone to microbial contamination. Therefore, antimicrobial and antifungal agents are often added to suppress the growth of these microbes.

Application of nematodes in infected insect cadavers have also been described by some workers (Shapiro-Ilan et al. 2001, 2003), which enables the slow release of nematode and therefore considered effective for small-scale application. Coating the cadavers with starch and clay mixture helps in preventing rupture during storage and shipping (Shapiro-Ilan et al. 2001).

Quality is measured in terms of degree of excellence of a product and quality control is a system of maintaining standards in manufactured products. According to Grewal and Peters (2005) quality of entomopathogenic nematode involves correct identity of species, total number of live nematodes, ratio of live and dead nematodes, matching of host finding behaviour to the target pest, pathogenicity and reproduction ability of nematodes in the target pest, age of the nematodes used, storability, heat tolerance and cold or warm temperature activity. Size and packaging, reliable instructions for the consumers, ease at transportation, absence of contaminants, product cost, availability and field efficacy are the other parameters required for the product quality (Grewal and Peters 2005). Some commercial products of entomopathogenic nematodes prepared in different countries are enlisted (Table 13.5).

13.3.7 Application Technology

Application technology aims at minimum loss during transfer of active ingredient, i.e. entomopathogenic nematodes from the mixing tank to the target insect. Several factors affect the ability to deliver infective juveniles in close proximity to the target insect for achieving optimal results at the minimal possible cost. Since formulations of entomopathogenic nematodes have live, delicate and tiny organisms, a careful handling is required during its application so that the adverse effects of the surrounding are minimized in order to achieve the desired activity and efficiency. Survival of nematodes during and after application is also an important aspect to be considered. Application of nematodes is mostly targeted to the soil and cryptic habitats of insects (Hussaini 2001). The choice of application equipment, and manner in which the nematodes are applied, can have substantial impact on pest control efficacy (Shapiro-Ilan et al. 2006).While selecting an application system, some points, which need special attention are volume of the sprayer, agitation system, pressure, recycling time, environmental conditions and spray distribution pattern (Shetlar 1999). A high- or low-volume sprayer can be used to dispose the nematodes, but care should be taken that the pressure in the spray tank should not be too high (300 psi or 2,070 kPa); otherwise, it will prove detrimental to the nematodes. Repeated recirculation of the tank mix also decrease viability as the mechanical stress from the pump and nozzles may lead to the rise of temperature in the liquid (Nilsson and Gripwall 1999). Therefore, the best way is to maintain the temperature below 30°C within the pump, tank and nozzles (Grewal 2002) and this can be done by the use of lower-capacity pumps, such as diaphragm or roller pump. When applied in aqueous suspension the water should neither be too hot nor heavily chlorinated. At higher temperature, the solubility of oxygen decreases ultimately making the nematodes inactive. Another important issue is settling or sedimentation. When the density of infective juveniles to be used is 1.05 g/cm^2, it becomes heavier than the water and settles in spray tank (Wright et al. 2005). Infective juveniles larger in size settle faster than the smaller one. Sedimentation results in unequal distribution of nematodes particularly when used under irrigation system. Increasing the viscosity of water by adding carboxymethyl cellulose may reduce the sedimentation speed (Peters and Backes 2003). Above all, the right choice of nematode species or strain for a particular target insect pest is also very important (Shapiro-Ilan et al. 2008).

For soil application, larger capacity hydraulic nozzle is usually recommended. Nozzles with largest orifice create relatively the lowest shear stress on nematodes. Any obstacle such as smaller particles in the spray suspension may partly block the nozzle orifice, leading to a reduction in viability of the nematodes passing through the nozzle (Gwynn et al. 1999). When entomopathogenic nematode is to be applied in soil, pre- and post-application irrigation is usually recommended. This will help in going down the nematode deeper in soil and work efficiently against the target insect. Also the nematodes remain protected from the environmental extremities (Ali et al. 2005b).

Foliar application is also an interesting option, which requires careful handling of the nematodes as well as equipment to be used. Droplet size and spray distribution system are the other two important considerations for foliar application of entomopathogenic nematodes (Grewal 2002). Solid cone nozzle and flat fan nozzle deposit greater number of entomopathogenic nematode on leaves and give higher mortality of target insect (Lello et al. 1996). Addition of adjuvant to spray solution can also help in increasing the deposition of entomopathogenic nematode on foliage. However, surface application on foliage faces hindrance as entomopathogenic nematodes cannot tolerate the effect of extreme temperature and ultraviolet radiation. Use of antidesiccant to retard evaporation of the nematode suspension on foliage and to prevent desiccation of nematodes has led to a great chance of success (Glazer and Novan 1990). Glycerine 10% has proved to be a more effective adjuvant for increasing survival and activity of nematodes on foliage (Nash and Fox 1969). But high cost of glycerine and risk of phytotoxicity at higher temperature limit its application. A better alternative for an effective protection against these external factors can be achieved by addition of fluorescent brightener and application during the period of moderate temperature and high humidity or late in the evening (Ali et al. 2005b). With some exceptions foliar applications have been less successful than soil applications due to nematode susceptibility to desiccation and ultraviolet rays, however, frequent low-rate applications of nematodes to foliage can result in substantial suppression of green house pests such as thrips (Shapiro-Ilan et al. 2006).

13.3.8 Compatibility with Pesticides

Entomopathogenic nematodes are compatible with many agrochemicals including herbicides, fungicides, acaricides, insecticides and fertilizers, as well as soil amendments (Rovesti and Deseo 1990; Gupta 2003). Infective Juveniles are tolerant to short-term exposures and therefore, can be tank mixed for applying together. Thus, entomopathogenic nematodes can also be included in the integrated pest mvanagement programme. But in several cases, nematode activity and its survival is reduced due to addition of some pesticides (Grewal et al. 1998) and sometimes chemicals used as inert ingredients or adjuvants used in formulation can prove toxic to nematodes (Krishnayya and Grewal 2002). Therefore, compatibility of each formulation with the specific nematode species should be evaluated before final application. There are various pesticides, which act synergistically with entomopathogenic nematodes and improve their efficacy in inundative applications. Easwaramoorthy and Sankaranarayanan (2003) have found that *S. glaseri* is compatible with carbofuran, phorate, quinalphos and aldrin. Compatibility of *S. carpocapsae* with dimethoate, endosulfan, malathion, mancozeb and zineb at recommended dosages have also been reported (Das and Divakar 1987). Gitanjalidevi (2007) conducted an experiment to test the effect on the viability and infectivity of freshly emerged infective juveniles of *Steinernema* sp. and *H. indica* on different formulations of formaldehyde, charcoal and alginate capsule. The result indicated that there was no significant difference in viability in the two nematode species in water + 0.1% formaldehyde + charcoal and water + 0.1% formaldehyde + alginate capsule treatment. The survival of the infective juveniles was highest in the formulation containing 0.1% formaldehyde + alginate capsule, followed by 0.1% formaldehyde + charcoal, for *H. indica and Steinernema* sp. Wang et al. (2007b) evaluated the combined efficacy of chemical pesticides, chlorpyriphos, imidacloprid and entomopathogenic nematode, *S. carpocapsae* against

Rhabdoscelus lineaticollis, a pest of palm and sugarcane. It was found that the mortality of *R. lineaticollis* was highest (88.89%) in the combined treatment of chlorpyriphos, imidacloprid and *S. carpocapsae* as compared to individual application of chlorpyriphos (72%), imidacloprid (25%) and *S. carpocapsae* (27.7–52.6%). Composted manure and urea do not influence *S. carpocapsae* but fresh manure may affect virulence (Shapiro-Ilan et al. 1997). Mahmoud (2007) conducted a laboratory bioassay to determine the potential of combination between *S. feltiae* and botanical insecticides, neem seed kernel extract, NeemAzal T (5%) and Neemix (4.5%) against the third-instar larvae of peach fruit fly, *Bactrocera zonata*. Of 25 treatment combinations between neem seed kernel extract and *S. feltiae,* 18 gave synergistic response, four were additive, none antagonistic and three without any response. Shapiro-Ilan et al. (2004) has reported antagonistic relationship between the fungi *Paecilomyces fumosoroseus* and *H. indica* or *S.carpocapsae*. Rumbos et al. (2007) investigated the effect of PL251, a strain of nematophagous fungi, *Pp. lilacinus* on the survival and virulence of *S. feltiae, H. bacteriophora* and *H. megidis* under controlled conditions. The survival and pathogenicity of all the three nematode species were not affected by PL251 application. In an experiment, *S. carpocapsae* when combined with nucleopolyhedrovirus against the beet armyworm *S. exigua*, caused additive mortality of sp. *exigua* larvae without causing any affect on reproduction of *S. carpocapsae* (Gothama et al. 1995, 1996). *Pasteuria penetrans*, a bacterial pathogen of plant parasitic nematodes did not infect *Steinernema* sp. under laboratory condition (Mohotti et al. 1998; Somasekhar and Mehta 2000). *Heterorhabditis* spp. and *S. glaseri* were also found not causing any infection on earthworm *Eudrilus eugeniae* (Prabhuraj et al. 2000).

13.4 Phasmarhabditis Hermaphrodita

Among the several slug-parasitic nematode species, *Pp. hermaphrodita* is considered to be the most successful capable of killing several slug species, the widespread pest of many agricultural and horticultural crops. In the recent years *Pp. hermaphrodita* has also been exploited as biocontrol agent. Schneider (1859) was the first to describe this nematode associated with the slug *A. ater*. Maupas (1900) established culture of *Pp. hermaphrodita* and maintained it on rotting flesh. Wilson et al. (1993c) patented the use of *Phasmarhabditis* as biological mulluscides on the basis that this nematode is capable of parasitizing and killing a wide range of agricultural and horticultural pest slug species.

13.4.1 Life Cycle

Till now not much extensive studies on *Phasmarhabditis* has been done, however, whatever the little information available indicates that life cycle of this nematode is dependent upon the slug species it encounters. Researchers have described three distinct life cycles of *Phasmarhaditis* sp.

1. Saprobolic – Where the nematodes have been reared on rotting flesh (Maupas 1900), on slug faeces (Tan and Grewal 2001) or on a wide range of bacteria (Wilson et al. 1995). Tan and Grewal (2001a) have the opinion that this nematode can be exploited for long-term inoculative slug control as it can persist in the environment without the living hosts. Recently, Rae et al. (2006) in an experiment found that *Pp. hermaphrodita* strongly attracted to dead slug *Deroceras reticulatum* than the live one, which adds weight to the hypothesis that this nematode is a facultative parasite capable of growing and reproducing on decaying plant and animal materials present in soil.
2. Necromenic – The infective juveniles of *Phasmarhabditis* get entrance into a slug, remain there without further development till the slug dies (Mengert 1953). After this infective juveniles feed on the slug cadaver, develop and reproduce. When the food starts depleting the formation of new infective juveniles takes place. These infective juveniles can be found in the mantle cavity, the general body cavity or the digestive tract of slugs. However, the entrance of nematode into slug and completion of life cycle there is parasitic or necromenic is still not fully understood (Wilson and Grewal 2005).
3. Parasitic life cycle: The infective juveniles enter into slug through the dorsal integumental pouch, through a short canal and reaches into the slug's shell cavity below the mantle (Wilson et al. 1993b; Tan and Grewal 2001). The development and reproduction of nematode takes place inside the slug. The infection in slug causes swelling of the rear half of the mantle where the nematodes reproduce. On an average 250–300 offspring of nematode is produced and once the second generation is produced these offspring spread throughout the slug's body and develop. The slug dies and third-generation nematodes are produced, which feeds on slug cadaver. When the food supply begins to deplete formation of infective juveniles takes place. Although the death of host generally occurs between 4 and 21 days, from the very time after infection the slug feeding is stopped (Glen et al. 2000; Grewal et al. 2001, Grewal et al. 2003).

13.4.2 Nematode–Bacteria Association

The research on the association of slug-parasitic nematode, *Pp. hermaphrodita* with bacteria has not been carried out extensively as like entomopathogenic nematodes; therefore, a meagre information is available on this aspect. Tan and Grewal (2001b) on the basis of an experiment reported that *Pp. hermaphrodita* acts as a vector to transport the bacteria *Moraxella osloensis* into the shell cavity of the grey garden slug, *Derocerus reticulatum*. The infective juveniles of the nematode move through the soil, locate and infect the slug by penetrating through a natural opening at the backside of the mantle. Once inside the body of the host the infective juveniles release bacterial cells, start feeding on multiplying bacteria and develop into self-fertilizing hermaphrodites. This nematode–bacterial complex can cause the death of slug within 7–21 days after infection. Wilson (2002) reported association of

Pp. hermaphrodita with several bacterial isolates. In an experiment highest yield of *Pp. hermaphrodita* was obtained when cultured with the bacteria, *Providencia rettgeri, M. osloensis* (Wilson et al. 1995a) and two isolates of *Pp. fluorescens*. When a bioassay was conducted with these nematode–bacterial isolates against the slug *D. reticulatum* only, *M. osloensis* and *Pp. flourescens* were found to be pathogenic (Wilson et al. 1995b). However, no highly specific mutualistic association of *Pp. hermaphrodita* with bacteria has been found. Wilson and Grewal (2005) is of the opinion that lack of bacterial specificity as a food source as well as lack of a rigid cuticle in slugs indicate that more or less there is a general association of bacteria with *Pp. hermaphrodita*. It has been observed by researchers that the bacteria *M. osloensis* kill slugs only when they are carried by infective juveniles of nematodes (Tan and Grewal 2001b). New infective juveniles carry more viable cells of *M. osloensis* than the older one (Tan and Grewal 2001b). Tan and Grewal (2002) reported that *M. osloensis* produces a heat-stable endotoxin, which consists of a lipopolysaccharide lethal to slugs.

13.4.3 Host Range and Effects

The parasitic behaviour of *Pp. hermaphrodita* against different slug species have been studied by several workers (Wilson et al. 2000; Grewal et al. 2003). A single high dose of nematode, applied to slugs under soil condition caused significant mortality to three different pest families of slugs, i.e. *D. reticulatum*, *D. panormitanum, A. silvaticus, A. distinctus, A. intermedius, A. ater, Tandonia budapestensis* and *T. sowerbyi* (Wilson et al. 1993a). Coupland (1995) reported rapid killing of snails belonging to four species (*Theba pisana, Cernuella virgata, Cochlicella acuta* and *C. barbara*), when exposed to 300 infective juveniles per snail. Wilson et al. (2004) prepared a model to optimize biological control of slug *D. reticulatum* by using the nematode *Pp. hermaphrodita*. In this method the application rate of *Pp. hermaphrodita* was based on slug number per unit area. The accurate estimate of slug population density together with predictive modelling of slug population dynamics exploit the full potential of the model for optimizing the use of *Pp. hermaphrodita* for slug control. Hapca et al. (2007) investigated the response of *Pp. hermaphrodita* to the presence of slug mucus and finally concluded that nematodes exhibit both chemotactic and chemokinetic responses to a signal emanating from slug mucus.

13.4.4 Production and Formulation

Pp. hermaprodita has been grown successfully in xenic culture using solid foam culture and also in deep liquid culture on a flask shaker (Wilson et al. 1993b). An yield of 1 lakh infective juveniles per millilitre has also been achieved as reported by Wilson et al. (1995a). Once maximum yield of infective juveniles are obtained they are concentrated by centrifugation before formulation (Young et al. 2002).

Since 1994, the nematodes are being sold as commercial product under the trade name Nemaslug® (Glen et al. 1994, 1996) prepared by MicroBio Ltd. (now Becker Underwood) and now the sale of this biological molluscicide has increased to many other European countries like France, Germany, Switzerland, the Netherlands, Italy and Ireland. However, the shelf life of this product is very less when compared to other entomopathogenic nematodes such as *Steinernema* sp. or *Heterorhabditis* sp. (Ester and Wilson 2005).

13.4.5 Application Technology

The protocol used for applying slug-parasitic nematodes is more or less the same as for entomopathogenic nematodes such as application of nematodes in the early evening to avoid the ill effects of ultraviolet rays, a light irrigation in the soil immediately after application to save the nematodes from desiccation or application of nematodes in moist or damp soil (if condition prevails) or cultivating the soil immediately after application (Wilson et al. 1996; Hass et al. 1999) in order to remove the nematodes from surface, thus preventing the nematodes from desiccation and ultraviolet rays. The equipments used for application are watering can, knapsack sprayer and tractor-mounted sprayer (Ester and Wilson 2005). Uniform application of nematodes in soil as well as in narrow bands centred on the crop rows in row crops has also been reported (Hass et al. 1999). *Pp. hermaphrodita* can also be applied in combination with metaldehyde bait pallets, even at a very high concentration, thus showing its compatibility with chemical mulluscicide (Wilson et al. 2000).

13.4.6 Effects on Other Organisms

Pp. hermophrodita is considered as a lethal parasite for slugs, however, its affect on non-target organisms has not been extensively studied. Whatever, the information available makes the evidence clear that this nematode is safe for non-target snails, beneficial predators and earthworms. Under laboratory condition, the exposure of two snails, *Cepaea hortensis* and *Monancha cantiana*, to *Pp. hermaphrodita* showed susceptibility in snails, but no effect was found under field condition (Wilson et al. 2000). Morley and Morritt (2006) studied the effect of *Pp. hermaphrodita* upon the two fresh water snails *Lymnaea stagnalis* and *Physa fontialis* at ‘spray tank’ concentration and a 50% diluted ‘spray tank’ concentration over a period of 14 days. A significant mortality in *L. stagnalis* was found at both application levels, however, *Pp. fontialis* was unaffected. When bioassay of *Pp. hermaphrodita* was conducted against tenebrionid beetles *Zophoba morio* and *Tenebrio molitor* it was found that the nematodes do not infect either of the two organisms (Wilson et al. 1994). In another experiment under laboratory condition, adults of *Pterostichus melanarius*, the beneficial predatory carabid beetle was not killed when exposed at a high dose of *Pp. hermaphrodita* (Wilson et al. 1993d). The effect of a commercial formulation of *Pp. hermaphrodita* on the earthworm *Eisenia fetida* was tested. Adults of *E. fetida* were exposed in 1-l glass beakers to *Pp. hermaphrodita* at three different concentrations (1×, 10× and 50× of the field-recommended rate of 3×10^9 billion nematodes/hectare) during a 14-day period in an artificial soil substrate. Also in this experiment injured earthworms with posterior ends removed were exposed to the 10× field-recommended rate of the nematode formulation. The results showed that neither intact nor injured *E. fetida* was susceptible to the nematodes during the 14 days of exposure even at a higher concentration, i.e. 10 and 50 times greater than the label dose (De-Nardo et al. 2004).

13.5 Constraints

The entomopathogenic nematodes, *Steinernema* and *Heterorhabditis*, as well as slug-parasitic nematodes, *Phasmarhabditis* offer the most promise for its commercial development as biocontrol agent. During the past 20 years a significant progress has been made in the development of nematode formulations, however, post-application survival is still a debatable issue. High product cost, limited product availability, lack of suitable production technology for different nematode species, low shelf life in comparison to traditional chemical pesticides and lack of proper technique (how to use) among the users are some hindrance coming in the way, which have still kept nematodes under-utilized in pest management programmes. Also, these beneficial nematodes always need a low temperature (whether formulated or not), which adds an additional expense for producers ultimately making the final cost high. Limited production capacity, poor shelf life and seasonal nature of demand further aggravate the problem.

13.6 Conclusions

In the present context the two basic elements necessary for entomopathogenic nematodes to be successful are (i) a suitable nematode for the target pest, and (ii) favourable economics for its commercialization. For sustainable agriculture an integrated approach of all the methods are required to obtain maximum effect without interfering with the effectiveness of other practices. Since entomopathogenic nematodes can interact synergistically with several chemicals and bioagents a combination of multiple tactics should be prepared to achieve a satisfactory result. In the recent years some progress has been made in developing application technologies, however, further improvements are still needed to make entomopathogenic nematodes compete with other insecticides. Increase in shelf life of nematodes, improvement in transport logistic and marketing will substitute insecticides and contribute to stabilize agriculture environments and crop yields.

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Chapter 14
Allelopathy and Organic Farming

Jana Kalinova

Abstract Allelopathy is a biological process including interactions between two plants through the production of chemical compounds (allelochemicals) that are released by leaching, volatilization, decomposition, or root exudation. Hence, allelopathy together with competition is a promising environment-friendly tool for weed management. However, detailed knowledge of this phenomenon is necessary for its successful application due to still limited available knowledge. Suitable use of allelopathic crops in agriculture could reduce the pesticide application and thereby reduce the environmental and food pollution, decrease costs in agriculture, improve food security in poor regions and soil productivity, and increase biodiversity and sustainability in the agro-ecosystem. Weed management in organic agriculture is one of the most difficult aspects of organic farming and uses especially preventive methods that include ways such as cover crops, mulches, green manure, intercropping in which allelopathy could play an important role. Therefore, this review focuses on the possibilities of the allelopathy application in organic agriculture. Roots of allelopathic plants as cover crops, intercrops, green manure, or so-called smothering crops or decomposing residues release compounds in the soil that are toxic to weeds. The weed-suppressive effect is influenced by species, planting date, seeding rate and method, weather, and other factors. Decomposition time of plant residues and amounts of biomass are important factors of weed control by mulching. Annual, biennial, or perennial herbaceous plants in a pure or mixed stand can be grown for these purposes. Biofumigation is the name for one type of allelopathy that includes effects of the chemicals, i.e., highly toxic isothiocyanates, produced by Brassica green manure. The balance in the crop rotation is necessary due to possible autotoxicity. A allelopathic plants as catch crops or trap crops found utilization in plant protection of tropical regions against parasite weeds, because they can reduce the parasite seed bank by 72%. Other applications of allelopathy for weed control include the use of plant residues as an herbicide agent, e.g., water

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J. Kalinova (✉)
Faculty of Agriculture, University of South Bohemia,
Ceske Budejovice, Czech Republic
e-mail: janak@zf.jcu.cz

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extracts, pellets, flours, by-products of crop processing, etc. Sorgaab, an extract of sorghum, is produced commercially as a natural herbicide. Allelopathic compounds act as repellents for herbivorous pests, so the same strategy used in weed control could be effective against pests and pathogens, e.g., push–pull strategy. All possible applications of allelopathy need to combine with other methods of plant protection. Newly investigated pollen allelopathy could reduce reproductive ability of wind pollination annual weeds. Pollen of allelopathic species would be artificially dusted on the stigmatic surface of other plants. This phenomenon is yet to be studied and field tested. The new crop varieties with elevated allelopathic activity could be a great chance not only for organic farming. Hybridization could be the promising method. However, allelopathic activity was identified as a quantitative trait and therefore this characteristic is affected by both genetic effects and environmental conditions.

Keywords Allelopathy • Cover crops • Crop residues • Intercropping • Mulching • Organic farming • Weeds

14.1 Introduction

Intensive farming practices in agriculture during the last 50 years in Europe caused a considerable decline in both the range and abundance of many species associated with farmland and the incurred agricultural homogeneity has had a negative impact on farmland biota (Hole et al. 2005). Organic farming has a great potential to overcome these losses. Organic agriculture is based on living ecological systems, biological processes, and cycles; works with them, emulates them, and helps sustain them (IFOAM 2005). This management should attain ecological balance and maintain genetic and agricultural biodiversity due to the restriction on the use of inorganic fertilizers and pesticides. Organic sustainable systems also have the capability to reduce greenhouse gas emissions, lower nutrient losses, and achieve resilience to drought (Tangerman 2003).

During recent years, the area of organic agriculture has still increased. In 2006, approximately 1.8 million hectares were newly certified as organic. The total area of organically grown crops is estimated at 30.4 million hectares (at the end of 2006). The greatest share of global organic area is in Oceania/Australia (42%), followed by Europe (24%) (IFOAM 2008).

Weeds constitute one of the major problems in agriculture. They are an important constraint on yield in most crops across the world. These days, growers spend much money on weed control. About 6 million ton of herbicides was sold in the world in 2006 and herbicides are the most used pesticides; they form approximately 38% of the total amount of pesticides (FAO 2006). Nowadays, an effort to tighten rules for authorization and application of pesticides, research and develop products that are target-specific, degrade quickly and do not accumulate in the food chain, exists in order to protect human health and the environment from dangerous or excessive use of pesticides in agriculture. Therefore some EU countries have specific reduction programs concerning the quantities of pesticides applied or sold (CEC 2006). Pesticides inflict a range of sublethal effects. Certain pesticides are known to elicit their adverse effects by mimicking or antagonizing natural hormones in the body and their long-term, low-dose exposure are increasingly linked to human health effects such as immunosuppression, hormone disruption, diminished intelligence, reproductive abnormalities, and cancer (Crisp et al. 1998).

The economic impact of pesticides in nontarget species (including humans) has been estimated at approximately $8 billion annually in developing countries (Wadhwani and Lall 1972). For developing countries, it is imperative to use pesticides, as no one would prefer famine or hunger but the prices of pesticides are high and therefore allelopathy is cheap and environmental friendly solution.

Utilization of allelopathic and suppressive effects of crops against weeds is one of the hopeful basis for integrated and ecological systems of production. Higher biodiversity in agro-ecosystem leads as well to indirect decrease of pests and diseases. Weed control in organic systems focuses on preventive methods of weed regulation and on the production of vigorous competitive crops. The organic farmer is not interested in total elimination of all weeds but needs to keep the weeds at an economical threshold. Hence, allelopathy is a promising environment-friendly tool for weed management and it has a great potential for use in organic rotation and organic weed control strategies. However, detailed knowledge of this phenomenon is necessary for its successful application.

14.2 Allelopathy

Allelopathy is defined as biochemical interactions between one plant or microorganism (alga, bacteria, or virus) and another plant through the production of chemical compounds – secondary metabolites (allelochemicals), which influence, direct or indirect, harmful or beneficial, plant growth and development (Rice 1984). Allelochemicals are present in almost all plants and in many tissues, like leaves, stems, flowers, fruits, seeds, roots, or pollen and may be released from plants into the environment by volatilization, leaching, root exudation, and decomposition of plant residues (Chou 1990).

Allelochemicals include terpenoids, phenolic compounds, phenylpropane derivatives, flavonoids, organic cyanides, long-chain fatty acids, and others. Potential allelopathic plants are most often connected with the total phenol content (Ben-Hammouda et al. 2001; Lee et al. 2004). For example, cereal residues release 2,4-dihydroxy-1,4(2H)-benzoxazin-3-one (DIBOA) and a breakdown product 2(3H)-benzoxazalinone (BOA) that both strongly inhibit the growth and germination especially of dicotyledonous plants (Tabaglio et al. 2008). Therefore BOA was suggested as a potential herbicide (Durtn-Serantes et al. 2002). Sorgoleone, benzoquinone isolated from sorghum is another example of a strong allelopathic inhibitor.

Effects and presence of many other compounds in different crops was described by a lot of researchers, e.g., by Birkett et al. (2001).

The released chemicals are usually a mixture of many organic compounds and may exert toxicities in a synergistic manner. According to Hegde and Miller (1992), mixtures of five or more phenolic acids were more phytotoxic than their individual components except in the case of trans-cinnamic acid. Strong synergistic effects were observed among the identified allelochemics in vulpia (*Vulpia* spp.) residues (An et al. 1998). Sometimes small amount of an ingredient can enhance allelopathic effect dramatically. Shiming (2005) reported that Precoene I and Precoene II are the two major allelochemicals in *Ageratum conyzoides* L. but their mixture did not have the synergistic effect. On the other hand, bisabolene, caryophyllene, and fenchylacelate are not very important in allelopathy of this crop, but they caused enhancement of effects if they were mixed with Precoene II individually or all together.

The visible allelopathic effects include inhibition of germination; reduced growth; swelling or necrosis of roots; root curling; discoloration, lack of root hairs; increased number of seminal roots; reduced dry weight accumulation and decreased reproductive capacity (Rice 1984). The allelochemicals affect a large number of physiological functions and biochemical reactions: enzyme activities, cell division and ultrastructure, cell elongation, membrane permeability, and ion uptake. Some allelochemicals isolated from higher plants inhibit photosynthesis and respiration, e.g., juglone (a toxic compound present in black walnut (*Juglans nigra* L.), and increase oxidative stress (Terzi et al. 2003). Gniazdowska and Bugatek (2005) recorded individual physiological effects of different allelochemicals. The same compound can act as an allelochemical and in other case can share another role. Allelochemicals are probably directly transferred to target plants by cell–cell contact and the physical contact of roots with an allelochemical is more important than uptake of this compound (Inderjit 2003). Their toxicity is depended on concentration. Most of the isolated allelochemicals exhibit bioactivity at concentrations from 10^{-5} to 10^{-10} M (Macias et al. 2001). Lower concentrations can have stimulative effects. Plant survival in allelopathy stress depends on resistant mechanisms leading to detoxication.

Allelopathic potential of plants is affected by many factors. An increase of allelopathic effects was observed by the water deficit, high temperature, high irradiance, pathogen, insect and herbivore damages, or nutrients deficiency (Hura et al. 2006). In other case, the concentrations of the allelochemicals released from the allelopathic rice seedlings in soil increased dramatically (3-fold higher) when they were surrounded with barnyard grass (*Echinochloa crus-galli* (L.) Beauv.) (Kong et al. 2006). Some metabolites having allelopathic potential might be newly synthesized by UV irradiation (Kim et al. 2000).

On the other hand, allelopathic effect was negatively influenced by rainfall (Shiming 2005). The inhibition process was mitigated by shading and consequent moisture conservation (Muller 1966). Allelopathic activity can vary as well with photoperiod (Peng et al. 2004). Harder et al. (1998) found out that an increasing availability of nutrients decreased the concentration of allelopathic effective phenolic compounds in the plants of two winter wheat varieties. In soil, allelochemicals can be adsorbed by soil particles, decomposed by microorganisms and move with water.

Phenolic acids can be allelopathic but their presence in soil is ephemeral due to rapid degradation and/or sorption by soil particles (Inderjit 2004). Sorption of benzoic acid onto soil particles increased with concentration and it may explain the reason for the limited allelopathic effect of benzoic acid at concentrations often recorded in natural soil (Inderjit 2004). Microorganisms help to generate allelochemicals, but they may also modify toxic compounds into nontoxic compounds (Khanh et al. 2005). Allelochemicals are changed in composition and quantity during the residue decomposition. Allelopathy plays an important function in nutrient recycling (Rice 1984).

The production and active release of allelochemicals from donor plants depends not only upon external environmental conditions but also upon the relative developmental stages of crops, plant tissues, and genetic disposition (Batish et al. 2001; Peng et al. 2004). Zuo et al. (2007) described the highest allelopathic potential in the tillering stage and the weakest in the seed filling stage of wheat. From plant tissues, leaves are usually the richest in the allelochemical content (Kalinova 2008). Significant varietal differences in allelopathic potential were established among winter wheat accessions (Zuo et al. 2007) and other crops (see Chapter: Varieties with strong allelopathic potential). The effect of allelochemicals can also depend on root absorption. According to Ferrarese et al. (2000), soya bean roots absorbed ferulic acid at greater rates when the concentrations ranged from 0.05 mM to 1.0 mM and the absorbed amount of the given compound was concentration dependent.

Allelopathic effects on a receiver plant are also affected by environmental factors. Environmental stresses affect both donor and receiver plants. They increase allelochemical production in the donor plant; on the other hand, they cause an increase in the dosage effect on the receiver plant (Shiming 2005). However, there exist genetic differences in sensitivity among accessions or species, e.g., large-seeded and deeper-seeded species are less sensitive to the allelochemicals than small-seeded and lower-seeded species (Chase et al. 1991). Small-seed species have greater absorptive surface area of roots through which allelochemicals may enter and they have fewer reserves which support seedling respiration during stress periods (Westoby et al. 2002). Ability to detoxify allelochemicals might also contribute to differences among species (Liebman and Sundberg 2006).

In nature, allelopathy forms a complex with competition for resources and both processes are very difficultly separable from each other (Kim and Shin 2003). Competition is the process in which a plant upon the habitat reduces the level of a necessary factor (radiant energy, oxygen, carbon dioxide, mineral nutrients, and water) to the detriment of another plant sharing the same habitat (either simultaneously or sequentially). Competition occurs only if the reaction involves a reduction demonstrably deleterious to another individual (Staman et al. 2001). Juvenile plants are less competitive than mature plants, e.g., deep-rooted, established alfalfa plants are better competitors for nutrients, water, and light than young seedlings. Well-established weeds may also compete with crop seedlings (Gray 1998).

Weed management in organic agriculture use preventive methods such as an appropriate crop rotation, precise soiled preparation before sowing crops, narrow seed spacing, etc. (Labrada 2003). Many of them include ways in which allelopathy (often together with competition) could play an important role (Fig. 14.1).

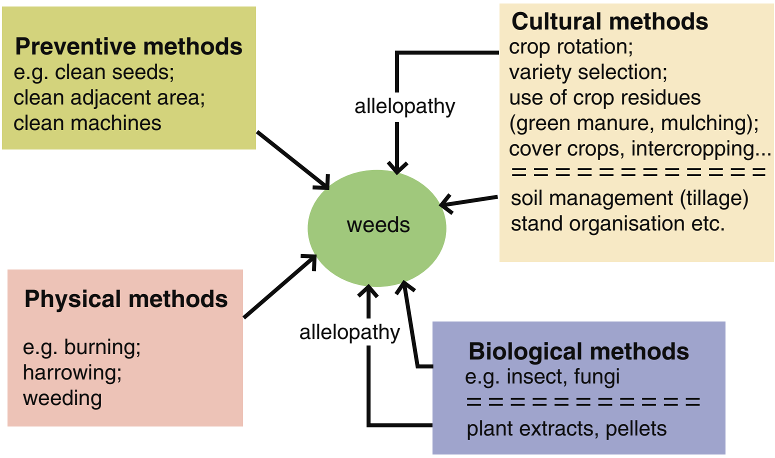

Fig. 14.1 Utilization of allelopathy in organic weed management. Weed management in organic agriculture includes four groups of different methods for weed reduction. Allelopathy plays an important role in some cultural and biological methods

Allelopathic interactions of plants can provide weed control by: (a) use of allelopathic crops as cover crops, mulches or green manure, (b) use of allelopathic plants in crop rotations, (c) crop mixtures and intercropping, (d) varieties with strong allelopathic potential, and (e) use of allelopathic crop water extracts and other agents.

However, both crops and weeds can have allelopathic effects. For example, quack grass (*Elymus repens* (L.) Gould) shoots and rhizomes reduce the emergence and growth of alfalfa, cause chlorotic and stunted growth of oats and barley and reduce root nodulation in numerous legumes (Weston and Putnam 1985). Allelopathic potential were established in such weed species as Russian knapweed (*Acroptilon repens* (L.) DC) (Alford et al. 2007), birdsfoot trefoil (*Lotus corniculatus* L.), devil's beggarticks (*Bidens frondosa* L.), mile-a-minute weed (*Polygonum perfoliatum* (L.) H. Gross), jimson weed (*Datura stramonium* L.) and *Cephalonoplos segetum* (Bunge) Kitam. (Kim et al. 1987), *Artemisia asiatica* (Pampan.) Nakai ex Kitam., Shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.), common purslane (*Portulaca oleracea* L.) and white clover (*Trifolium repens* L.) and others (Chun et al. 1988).

Hence, allelopathy alone can not be a sufficient tool for weed control. Combinations of methods that prevent weed germination and control weeds have to be used (Rasmussen 2004).

14.3 Crop Rotation with Allelopathic Crops to Control Weeds

Crop rotation is a system where different plants are grown in a defined sequence. The well-designed crop rotation is the basis of the success in organic farming. Continuous monoculture is unacceptable due to the increased pressure of weeds and pathogens and difficulties with maintaining soil fertility. Diversity of crops in the rotation is the key to a successful crop rotation program that rotate early-seeded, late-seeded and fall-seeded crops; grassy, broadleaf and legume crops; highly competitive crops with less competitive crops; use perennial phases combined with mowing or intensive grazing to control perennials; use cover crops and green manure crops that suppress weeds and disrupt weed life cycles; and provide the frequency of crop growth within a rotation (Wallace 2001). Such diversified rotations create an unstable environment for weeds. Rotation changes the growing conditions from year to year and so, it forms a situation in which only few weeds easily adapt (Sullivan 2003b). Longer rotations with more phenologically diverse crops as well help reduce seedbank populations and abundance of important weeds in organic systems (Teasdale et al. 2004).

An allelopathic crop designed in rotation sequences can suppress weeds in both cultivated and next crops (Mamolos and Kalburtji 2001) through residue decomposition or root exudates. For example, black mustard (*Brassica nigra* L.) and Indian mustard (*Brassica juncea* L. Czern.) are ideal following crops for cereals because they improve soil fertility and suppress many weed species. Allelopathic potential has been reported in numerous crops like rice (Dilday et al. 1998), wheat, oats, barley, rye, maize, common buckwheat (*Fagopyrum esculentum* Moench), millet (*Panicum* sp.), beets (*Beta vulgaris* L.), peas, lupine (*Lupinus* sp.), hairy vetch (*Vicia villosa* Roth.), sorghum, sunflower, cucumber (Rice 1984), sugarcane (Sampietro et al. 2007), chick pea (*Cicer arietinum* L.), bitter vetch (*V. ervilia* Willd.), alfalfa (*Medicago sativa* L.); velvetbean (*Mucuna pruriens* DC.), crimson clover (*Trifolium incarnatum* L.), subterranean clover (*Tr. Subterraneum* L.), sweet potato (*Ipomoea batatas* (L.) Lam.) (Batish et al. 2001), tall fescue (*Festuca arundinacea* Schreb.), creeping red fescue (*Festuca rubra* L.) and perennial ryegrass (*Lolium perenne* L.), asparagus (*Asparagus officinalis* L.), coffee (*Coffea* spp.), tea (*Camellia sinensis* (L.) Kuntze) (Khanh et al. 2005), rapeseed (*Brassica napus* L.), flax (*Linum usitatissimum* L.) and lentil (*Lens culinaris* Medik.) (Minorsky 2002), some medicinal plants and others.

If crop rotations include plants that inhibit weed germination, the balance of allelopathic crops is necessary because they can also suppress subsequent crop growth. For example, the wheat growth was depressed by grain sorghum (*Sorghum bicolor* (L.) Moench) root exudates (Ben-Hammouda et al. 1995). However, tilled sorghum residues delayed the wheat growth but did not affect the grain yield (Roth et al. 2000). In rye (*Secale cereale* L.) and maize (*Zea mays* L.) double cropping sequence, maize development was delayed and reduced (Raimbault et al. 1990). Barley (*Hordeum vulgare* L.) residues negatively influenced durum wheat (*Triticum durum* L.) and bread wheat (*Triticum aestivum* L.) (Ben-Hammouda et al. 2001). However in case of balanced allelopathic crops, crop rotation can be helpful for minimizing the toxic effects of allelochemicals on following crops (Mamolos and Kalburtji 2001). According to Conklin et al. (2002), tillage timing and system may modify soil amendment effects on weeds or crops too. When the residues are incorporated, as in strip tillage, allelopathic substances break down relatively quickly.

Allelopathic crops can inhibit the growth of the same species through the release of toxic chemicals into the environment too. This phenomenon is called autotoxicity, it is a type of intraspecific allelopathy (Rice 1984). This phenomenon probably regulates seed germination and defends against phytopathogenic agents but from an agricultural point of view it is one of the causes of "soil sickness." Therefore the knowledge of autotoxic effects would avoid unexpected harvest losses (Macías et al. 2003). Autotoxicity is common in fields where sole cropping under reduced or no-tillage system is practiced (Batish et al. 2001) e.g., in continuous monoculture rice fields and especially in fields with poor water drainage (Chou 1990), when wheat straw was retained on the soil surface (Wu et al. 2001) or by reseeding of alfalfa. This phenomenon was described in many common crops (Table 14.1) but in many weeds and other plants too. For example, autotoxic effects have been demonstrated in a tropical herb *Wedelia chinensis* Merrill (Luo et al. 1995).

The size of the autotoxic zone was about 20 cm around of the old alfalfa (*Medicago sativa* L.) plant (Jennings and Nelson 1998). Older stands caused greater inhibition than newly seeded (Peel 1998). The autotoxicity may be more severe in sandy soils, but the autotoxic factor is leached out of the root zone more easily in the sandy soils than in soils of heavier texture. Autotoxicity can be limited by proper crop rotation (Batish et al. 2001), proper soil and plant residues management, as well as microbial degrading (Yu 2001). Recommended interval for reseeding alfalfa ranges from two weeks (after ploughing or tilling) to 24 months but the most common recommendation is after rotation with a non-legume crop grown for one or more seasons (Tesar 1993). Irrigation on light-textured soils may help dilute the autotoxic chemical making it possible to shorten the rotation interval (Jennings and Nelson 1998). Autotoxicity could be overcome by selecting resistant

Table 14.1 Common crops with described autotoxicity

Crop	Reference
Soya bean (*Glycine max* Merrill L.)	Xiao et al. 2006
Maize (*Zea mays* L.)	Yakle and Cruse 1984
Asparagus (*Asparagus officinalis* L.)	Shafer and Garrison 1986
Alfalfa (*Medicago sativa* L.)	Hegde and Miller 1992; Chung and Miller 1995
Cucumber (*Cucumis sativus* L.)	Yu and Masui 1997
Rice (*Oryza sativa* L.)	Chou 1990, 1995
Barley (*Hordeum vulgare* L.)	Ben-Hammouda et al. 2001
Pearl millet (*Pennisetum glaucum* (L.) R. Br.)	Saxena et al. 1996
Sorghum (*Sorghum bicolor* (L.) Moench)	Hegde and Miller 1990
Tomato (*Lycopersicon lycopersicum* (L.) Farw.	Shiming 2005
Wheat (*Triticum aestivum* L.)	Wu et al. 2007
Watermelon (*Citrullus lanatus* (Thunb.) Mansf.)	Hao et al. 2006, 2007
Mugwort (*Artemisia vulgaris* L.)	Onen 2007
Strawberry (*Fragaria* x *ananassa* Duchesne)	Cao and Wang 2007
Tea plant (*Camellia sinensis* (L.) Kuntze)	Luo et al. 1995

Fig. 14.2 Well established stand of common buckwheat as a cover crop has great weed suppressive effects. Buckwheat emits allelochemicals, thus controlling weeds

varieties because significant varietal differences exist in tolerance to the autotoxin (Chon et al. 2002; Queslati et al. 2005). Therefore careful selection of suitable varieties is necessary in a continuous cropping system to minimize the negative impacts of autotoxicity (Wu et al. 2007).

Additional weed control may be obtained by including allelopathic plants as cover crops, green manure, or so called smothering crops (a living mulch) such as sudan grass (*Sorghum sudanense* L.) or common buckwheat (*Fagopyrum esculentum* Moench) (Fig. 14.2) and others in the crop rotation (Sullivan 2003b). For example, the allelopathic activity of buckwheat was an effective tool for inhibiting the growth and development of quack grass (*E. repens* (L.) Gould), field pennycress (*Thlaspi arvense* L.), Canada thistle (*Cirsium arvense* (L.) Scop.), ribwort plantain (*Plantago lanceolata* L.), barnyard grass (*E. crus-galli* (L.) P. Beauv.), common purslane (*Portulaca oleracea* L.) (Tominaga and Uezu 1995; Golisz et al. 2004; Kalinova 2006). The allelopathic constituents as gallic acid and their derivative, catechin, rutin, palmitic acid, long-chain fatty acids, fagomine, 4-piperidone, and 2-piperidine were identified (Iqbal et al. 2003; Kalinova et al. 2007).

14.4 Cover Crops with Allelopathic Potential

Providing weed suppression through the use of allelopathic cover crops is an important method of weed control in organic farming and it is one of the best possibilities of allelopathy application (Sullivan 2003a). Besides, growing of cover crops provide soil protection against erosion and better water infiltration, decrease nutrient losses especially nitrogen, improve soil physical and chemical characteristics, increase soil organic matter and biological diversity and reduce pressures of harmful organisms (Hartwig and Ammon 2002). However, used cover crops are necessary to rotate in the same way as crops due to protection against build-up of weed, pathogen and pest populations, and allelochemicals.

Allelopathy plays an important role in weed suppression by cover crops if other competitive factors are on the same level (Fujii 2003). Roots of the crops or decomposing residues release compounds in the soil that should be toxic to weeds. The weed-suppressive effect of the cover crops is influenced by species, planting date, seeding rate and method, weather, and other factors. There should be sufficient selectivity between the activity of cover crop toxins on weeds and on cash crops that should be relatively insensitive to allelochemicals in the environment. The relative timing and placement of residue relative to crop seeds can be manipulated to reduce the toxicity to emerging crop seedlings. According to Wuest et al. (2000), wheat residue 3 cm below the seed reduced the height and rate of wheat plant development, indicating an inhibitive effect of the wheat residue. Duration of weed suppressiveness provided by decomposing cover crop residues should be in an important consideration. Phytotoxicity of cover crops probably persists in soil from 2 weeks to 60 days (Chou and Patrick 1976; An et al. 1997; Teasdale and Pillai 2005).

Cover crops are possible to use in vineyards, orchards, and common agronomic crops, such as maize, small grains, and forages. A cover crop is a living ground cover planted with or after the main crop and usually killed before growing of the next crop. Annual, biennial, or perennial herbaceous plants in a pure or mixed stand can be grown as cover crops. For example, cool-season legumes as clovers, vetches, medics, and field peas are planted in a mix with winter cereal grains such as oats, rye, or wheat. Successfully established cover crops should develop dense canopies to interfere with the growth of weeds (Hartwig and Ammon 2002).

There are two categories of cover crops:

1. Annuals that are grown during an off-season and that are killed before planting a cash crop.
2. Living mulches are plants interplanted with the annual or perennial cash crop for all or a portion of the growing season.

Examples of highly weed suppressive cover crops are rye, buckwheat, sorghum, or alfalfa. Weed control by legumes is usually lower because nitrogen released from their residues stimulates weed emergence (Blum et al. 1997). Brassica cover crops, including canola (*Brassica napus* L.), rapeseed (*Brassica napus* L.), and mustard species (e.g., Indian mustard *B. juncea* L.; black mustard *Brassica nigra* L., white mustard *Sinapis alba* L.) are also often grown. According to Haramoto and Gallandt (2005), incorporated canola (*Brassica napus* L.), rapeseed (*Brassica napus* L.) and white mustard cover crops reduced establishment of a wide range of crop and weed bioassay species an average of 29% and the weed emergence was delayed for 1.8

days. Canola was less competitive with weeds than white mustard (*S.. alba* L.) (Daugovish et al. 2002). Brassica cover crops did not reduce the redroot pigweed growth when they were grown in mixture with green bean (*Phaseolus vulgaris* L.) (Haramoto and Gallandt 2005). On the contrary, use of winter legume cover crops mixtures resulted in more consistent overall cover crop performance, greater dry matter production, and more effective weed suppression than single cover crop species (Fisk et al. 2001; Linares et al. 2008). Examples of possible use of some cover crops in effective control of some weeds are given in the Table 14.2.

Inhibitive effects are especially influenced by amount of cover crop biomass and soil management. Weed dry matter was reduced when rye residues were greater than 3.7 Mg ha^{-1} (Crutchfield et al. 1985), and when wheat residues were greater than Mg ha^{-1} (De Almeida 1985). Fisk et al. (2001) reported that burr medic (*Medicago polymorpha* L.) and barrel medic (*M. truncatula* Gaertn.) reduced by 70% weed dry weights while weed density was not affected if were no-till seeded as winter-killed cover crops into winter wheat (*Triticum aestivum* L.) stubble.

Low-growing legumes with dense canopy such as clover and grasses are typically used for living mulches. These secondary intercropped species are often referred to smother crops; species with rapid growth suppress weeds during the critical period, i.e., the period when emerging weeds will cause a loss in the crop yield and they become senescent after this critical period (Buhler and Hartzler 2001). It is important to kill, till in, or otherwise manage the living mulch so that the living mulch does not compete with the actual crop. Kura clover (*Trifolium ambiguum* M. Bieb.) or other *Trifolium* species as *T. subterraneum* L., *T. incarnatum* L. can be managed as a living mulch in maize within 12 months without replanting (Zemenchik et al. 2000). This system is possible to combine with mechanical cultivation at about the three-leaf stage of maize. Then maize yield is not reduced and the green cover remained as soil protection till the harvest (Hartwig and Ammon 2002). Other possibility is overseeding hairy vetch (*Vicia villosa* Roth) into maize at the last cultivation or into sunflower (Teasdale and Daughtry 1993). Vetch can also be seeded into soya bean when their leaves begin to turn yellow. Buckwheat or mixture of rye and buckwheat can be interseeded with maize or sunflowers. The plants can be incorporated into the crop rows to nourish the crop (maize or sunflowers) and suppress weeds when buckwheat reaches a height of 200–300 mm (DeRosier 1998). No-till planting vegetables can be grown into subclover, sweetclover, drilled into cereals, or Italian ryegrass (*Lolium multiflorum* Lam.), or sowed into vegetables (Sullivan 2003a). Trials with the living mulch are provided with underseeding in cabbage (*Brassica oleracea* L.) and other vegetables (Bellinder et al. 1996). However, this management is difficult to establish, so it is not very acceptable to farmers. A living cover crop is capable of greater weed suppression than killed cover crop residue. The degree of effectiveness depends on factors such as the amount of residue incorporated as well as the timing of incorporation (Fisk et al. 2001).

Living mulches in perennial cropping systems are grasses or legumes planted in the alleyways between rows in orchards and vineyards. Use of the living mulch is a common practice in apple (*Malus sylvestris* L.) production. Wick and Alleweldt

Table 14.2 Examples of possible use of some cover crops in effective control of some weeds

Crop	Use	Inhibited weed	Reference
Rye (*Secale cereale* L.)	Mulch	Common millet *Panicum miliaceum* L., barnyard grass *E. crus-galli* (L.) P. Beauv., bristly foxtail *Setaria verticillata* (L.) P. Beauv., redroot pigweed *Amaranthus retroflexus* L.	Barnes and Putnam 1986; Martens et al. 2001
	Cover crop residue	Hairy crabgrass *Digitaria sanguinalis* (L.) Scop, annual ragwed *Ambrosia artemisiifolia* L., early broadleaf weeds, carpetweed *Mollugo verticillata* L., common lambsquarters *Chenopodium album* L., browntop millet *Brachiaria ramosa* (L.) Stapf	Barnes and Putnam 1983; Nagabhushana et al. 2001; Reddy 2001; Teasdale et al. 1991
	No-till cover crop	Goosegrass *Eleusine indica* (L.) Gaertn., carpetweed *Mollugo verticillata* L.	Teasdale et al. 1991
Wheat (*Triticum aestivum* L.)	Shoot residues	Giant foxtail *Setaria faberi* R. Herrm., wimmera ryegrass *Lolium rigidum* Gaud.	Schreiber 1992; Wu et al. 2001
Winter barley (*Hordeum vulgare* L.)	Mulch	Barnyard grass *E. crus-galli* (L.) P. Beauv., bristly foxtail *Setaria verticillata* (L.) P. Beauv.	Dhima et al. 2006
Buckwheat (*Fagopyrum* spp.)	Green manure	Canada thistle *Cirsium arvense* (L.) Scop., quack grass E.s repens (L.) Gould, barnyard grass *E. crus-galli* (L.) P. Beauv., monochoria *Monochoria vaginalis* (Burm. F.) C. Presl ex Kunth	Xuan and Tsuzuki 2004
Red clover (*Trifolium pratense* L.)	Green manure	Wild mustard *Sinapis arvensis* L.	Conklin et al. 2002
Yellow sweetclover (*Melilotus officinalis* (L.) Lam.)	Residues incorporated or on the soil surface	Dandelion Taraxacum officinale L. Weber, perennial sowthistle Sonchus arvensis L., kochia Kochia scoparia (L.) Schrad., flixweed Descurainia sophia (L.) Webb ex Prantl, Russian thistle Salsola iberica Sennen and Pau, downy brome Bromus tectorum L.	Blackshaw et al. 2001

Hairy vetch (*V. villosa* Roth)	Cover crop Residue or living mulch	Pigweed *Amaranthus* spp., foxtail *Setaria* spp., velvetleaf *Abutilon theophrasti* Medikus	Teasdale and Daughtry 1993
	Cover crop residues	Carpetweed *Mollugo verticillata* L., common lambsquarters *Chenopodium album* L., browntop millet *Brachiaria ramosa* (L.) Stapf , hairy crabgrass *Digitaria sanguinalis* (L.) Scop.	Reddy 2001; Teasdale et al. 1991
	Cover crop under no-till management	Goosegrass *Eleusine indica* (L.) Gaertn., stinkgrass *Eragrostis cilianensis* Vignolo ex Janch., carpetweed *Mollugo verticillata* L..	Teasdale et al. 1991
White mustard (*Sinapis alba* L.)	Green manure	Hemp sesbania *Sesbania exaltata* (Raf.) Cory, common lambsquarters *Chenopodium album* L., redroot pigweed *Amaranthus retroflexus* L., barnyard grass *E. crus-galli* (L.) P. Beauv., hairy nightshade *Solanum sarrachoides* Sendtner, Kochia Kochia scoparia (L.) Schrad. shepherd's-purse, Capsella bursa-pastoris (L.), green foxtail Setaria viridis (L.) P. Beauv.	Vaughn and Boydston 1997; Boydston and Hang 1995; Krishnan et al. 1998; Martens et al. 2001
Rapeseed (*B. napus* L.)	Green manure	Hemp sesbania *Sesbania exalta* (Raf.) Cory, hairy nightshade *Solanum sarrachoides* Sendtner), longspine sandbur *Cenchrus longispinus* (Hack.) Fern., Kochia Kochia scoparia (L.) Schrad., shepherd's-purse, Capsella bursa-pastoris (L.), green foxtail Setaria viridis (L.) P. Beauv.	Boydston and Hang 1995; Vaughn and Boydston 1997; Krishnan et al. 1998

(1983) found subterranean clover (*T. Subterraneum* L.) or white clover (*T. repens* L.) as suitable cover crops for vineyard cv. "Daliak." According to Fujii (2003), hairy vetch is the most promising cover plant for orchards, but as well vegetable and rice production in Japan.

Naturally occurring weeds could be used as the living mulch too. For example, common chickweed (*Stellaria media* L.), one of the widespread uncontrolled weeds, was tested in vineyard; grape yields were not lower and soil erosion was reduced (Hartwig and Ammon 2002). Possible influencing of the seedbed preparation for following crops, a possible source of infection to cash crops and in some cases developing a high carbon to nitrogen ratio that could reduce the yield of following crops are the main disadvantages of using cover crops (Peel 1998).

14.5 Mulching

Annual cover crops are usually killed before planting a cash crop and then either incorporated as a cover crop residue into the soil or left as a mulch on the surface of the soil. A trend towards more reduced weed growth was observed where residues were not incorporated into soil but they were retained on the soil surface (Jones et al. 1999).

Mulching of the soil surface prevents weed germination by blocking light transmission, acting as a physical barrier, decrease soil temperature, and other physical properties (Teasdale and Mohler 2000). Allelopathic chemicals in the mulch also help to suppress weed emergence. Surface residues with a large number of layers and a small amount of empty internal space will be most suppressive and can reduce weed emergence up to 90% (Teasdale 2003). From barley, canola, chickpea, field pea, mung bean, and sorghum mulch, barley residues were found to be the most inhibitive (47% of the fallow treatment) (Jones et al. 1999).

Weed suppression correlate with the amount of residues. So, cover crops that produce high amounts of biomass will enhance weed suppression by leaving high amounts of suppressive residues. For example, a mixture of hairy vetch plus crimson clover (*T. incarnatum* L.) and rye produced higher amount of biomass and suppressed weeds more than each species in monoculture (Teasdale and Abdul-Baki 1998). Decomposition time of plant residues is another important factor of weed control by mulching. Cover crop residue that decomposes slowly will extend the period of weed suppression. The hairy vetch mulch is decomposed more rapid than rye. Therefore, rye provides longer-lasting mulch that blocks weed growth longer (Teasdale and Mohler 1993).

Weed control by mulching is effective in growing seasons without high rainfall. Under high rainfall regimes, supplemental weed management practices are needed (Barker and Bhowmik 2001). Perennial and selected large-seeded annual weeds, that are able to reproduce in cover crop mulch, should become problematic by the management. The mulches can play important role especially in weed control in no-till cropping systems (Sullivan 2003a).

14.6 Green Manure

Green manure is incorporation of fresh plant biomass into the soil to improve nutritional level concerning organic matter and nitrogen, to reduce soil erosion, and it may also serve as sources of allelochemicals for suppression of weed species. Although green manures usually favor beneficial microorganisms, there can be a short-term increase in plant pathogens such as *Rhizoctonia solani* Kühn (Weinhold 1977). However some compounds as isothiocyanates can have inhibitive effects to soil-borne fungal pathogens (Sarwar et al. 1998) or reduce the occurrence of some pests. Rapeseed, sudan grass, and white mustard green manures decreased the number of Columbia root-knot nematode (*Meloidogyne chitwoodi* Golden, O'Bannon, Santo, and Finley) by up to 90% (Mojtahedi et al. 1993a, b).

Legume species and some cruciferous plants suppress weeds and simultaneously improve soil conditions (increasing of organic matter and nitrogen in the soil). Crops suitable as green manures include, e.g., *Brassica* spp., cowpeas (*Vigna* spp.), soya beans, annual sweetclover (*Melilotus* spp.), sesbania, guar (*Cyamopsis tetragonoloba* (L.) Taub.), crotalaria (*Crotalaria* spp.), velvetbeans (*Mucuna* spp.), clover (*Trifolium* spp.), jack-beans (*Canavalia* spp.), *Ipomoea* spp. (Batish et al. 2001), and buckwheat (*Fagopyrum* spp.) due to quick development and others. The genus *Crotalaria* (*C. juncea*, *C. spectabilis*, *C. pallida* Aiton), is one of the important green manure legumes spread out over several tropical and subtropical regions. These species are grown as plant antagonistics to parasitic nematodes due to the content of pyrolozidine alkaloid and they release also other substances which can be phytotoxic to some weeds too (Daimon 2006).

Mustard species as green manure crops reduced total weed biomass in soya bean by 40% four weeks after emergence and 49% six weeks after emergence (Krishnan et al. 1998). Petersen et al. (2001) noted that isothiocyanates released from winter turnip rape *Brassica rapa* L. var *rapa* ssp. *oleifera* (DC.) Metzg. biomass strongly suppressed germination of five common weed species – spiny sowthistle (*Sonchus asper* (L.) Hill), scentless mayweed (*Matricaria inodora* L.), smooth pigweed (*Amaranthus hybridus* L.), barnyard grass (*E. crusgalli* (L.) P. Beauv.) and blackgrass (*Alopecurus myosuroides* Huds.). The mechanism that suppresses germination of weeds is called biofumigation. Biofumigation is the name for one type of allelopathy that includes effects of the chemicals produced by *Brassica* green manure (Kirkegaard and Sarwar 1998). Cruciferous plants contain compounds called glucosinolates in their plant tissues. When the plant cells are damaged, glucosinolates can be hydrolyzed by myrosinase enzyme and transformed into different bioactive compounds acting as naturally produced pesticides (Gimsing et al. 2007). Same compounds are released from soil-incorporated *Brassica* tissues (Morra and Kirkegaard 2002). The biofumigant properties of cruciferous plants are just ascribed to highly toxic isothiocyanates. From the major volatiles released from chopped plants, allyl-isothiocyanates and methyl-isothiocyanates were the most inhibitive compounds, completely inhibiting the germination of all species at concentration of 1 mg kg^{-1} (Vaughn and Boydston 1997).

Glucosinolate concentrations differ in dependence on environmental conditions, species, age of the plant, health, and plant part (Brown and Morra 1996; Kirkegaard and Sarwar 1998; Sarwar et al. 1998). Roots produce different glucosinolates than shoots. The glucosinolates which are hydrolyzed to isothiocyanates were found primarily in the taproot and larger lateral roots (>2 mm), whereas younger fine roots (<2 mm diameter) had higher levels of indolyl glucosinolates (Kirkegaard and Sarwar 1999). The concentration of both glucosinolates and isothiocynates in soil was highest immediately (30 min) after incorporation of Australian canola (*Brassica napus annua* L.) and Indian mustard (*B. juncea* L.) and they could be detected for up to 8 and 12 days, respectively. The non-isothiocyanated liberating glucosinolates were found at lower concentrations but tended to persist longer in the soil (Gimsing and Kirkegaard 2006).

Selection of species that release high levels of allyl-isothiocyanates or benzyl-isothiocynates would be optimal for allelopathic activity (Vaughn and Boydston 1997). High yielding and agronomically adapted varieties of *B. napus* and *B. juncea* could be selected for higher levels of root glucosinolates as a source of natural biofumigants without compromising seed quality (Kirkegaard and Sarwar 1999). According to Petersen et al. (2001), turnip rape (*Brassica rapa* L.) produce about 0.5 g m^{-2} of isothiocyanates (about 20% of the concentration in the commercial fumigant), when 600 g m^{-2} (dw) total biomass were incorporated into the soil. Hence, using mustards as green manure could be a promising method to suppress weed germination.

Crops seeded too soon after the incorporation of a cruciferous crop can also be damaged. *Brassica* species may injure potato, spearmint, and cucumber if green manure was incorporated only a few days before planting, because the most severe inhibition by plant residues occurs at the early stages of residue decomposition. However, there is species selectivity. For example, green pea was injured by rapeseed but not by white mustard (Al-Khatib et al. 1997). According to Jaakkola (2005), white mustard appears to be more toxic to spinach and pea than to scentless mayweed (*Tripleurospermum inodorum* (L.) Sch. Bip) and other annual weeds. It could be caused by incorporation of manure infested with weeds. Krishnan et al. (1998) observed soya bean biomass and yield reduction by the incorporation of green manure crops containing weeds.

14.7 Intercropping

Another cultural method suitable for weed control strategy is intercropping (growing two or more crops together). Intercropping of clovers and grasses is widely used in pastures or for fodder production, but intercropping (cereals, grain legumes, and oil seeds) for human consumption is not so common. For example, binary grass–alfalfa mixtures for hay production are common in most subhumid to semiarid areas (Berdahl et al. 2001). Italian ryegrass (*L. multiflorum* Lam.) or oat (*Avena sativa* L.) was used as a companion crop to establish alfalfa (*M. sativa* L.) or clover stands

Fig. 14.3 One of the most common examples of intercropping – oat with red clover (*Trifolium pratense* L.). Oat provides early competition with weeds while the clover is established; the clover blocking out light to the soil; the oat also takes up excess nitrogen that would otherwise stimulate the weed growth

(Fig. 14.3) in the USA or Europe (Sulc et al. 1993). Alfalfa was the best legume to grow with smooth bromegrass (*Bromus inermis* Leyss.) (Sleugh et al. 2000). Tall fescue (*Festuca arundinacea* Schreb.) is compatible with either birdsfoot trefoil (*Lotus corniculatus* L.) or white clover (*T. repens* L.); switchgrass (*Panicum virgatum* L.), indiangrass (*Sorghastrum nutans* (L.) Nash) or sideoats grama (*Bouteloua curtipendula* (Michx. Torr.)) could be mixed with purple prairie clover (*Petalostemon purpureum* (Vent.) Rydb.), roundhead lespedeza (*Lespedeza capitata* Michx.), leadplant (*Amorpha canescens* Pursh), Illinois bundleflower (*Desmanthus illinoensis* (Michx.) MacMill. ex B.L. Rob. & Fernald), catclaw sensitive brier (*Schrankia nuttallii* (DC.) Standl.) or cicer milkvetch (*Astragalus cicer* L.) (Posler et al. 1993; Springer 1996; Springer et al. 2001). In the central USA, the grazing season for Bermuda grass (*Cynodon dactylon* (L.) Pers.) is lengthened with fall-interseeded rye (Moyer and Coffey 2000). Timothy grass (*Phleum pratense* L.) can be grown together with barley or wheat as companion crops (Jefferson et al. 2000). Interseeding red clover into small grains is one of the most common practices. Johnson et al. (1998) established successful interseeding of rye or oat (*Avena fatua* L.) into soya bean. Other successful intercrops include: oats and pulses (such as peas, lentils, or beans), flax and wheat, flax and alfalfa, wheat and lentil, flax and lentil, barley and peas, and soya and maize (Wallace 2001).

Intercropping has been an essential production method in tropical regions for hundreds of years (Vandermeer 1989). Small-scale farmers in tropical Africa grow sweetpotato (67 plants ha^{-1}) with groundnut (*Arachis villosulicarpa* Hoehne) (67 plants ha^{-1}) due to weed suppression and increased land productivity (Ossom 2007). In Philippines, mung bean (*Vigna radiata* (L.) R. Wilczek) is grown mixed with maize; the weeds smothering effect of the mung bean protects the easily infested maize. Farmers throughout Central America traditionally grow maize (*Zea mays* L.), green bean (*P. vulgaris* L.), and squash (*Cucurbita pepo* L.) together. Typical crop associations in Swaziland involve grain legumes and sweet potato (*Ipomoea batatas* (L.) Lam.), but cereals, legumes, sugarcane, maize, and grain legumes have also been intercropped (Vandermeer 1989; Ossom 2007). Intercropping of cotton (*Gossypium hirsutum* L.) and cowpea (*Vigna unguiculata* (L.) Walp) improves food security and soil fertility (Rusinamhodzi et al. 2006). Intercropping cereals with some legumes influences positively *Striga* infestation (see Chapter: Allelopathy in parasite weed management).

There are four possible types of intercropping: mixed intercropping – growing two or more crops (varieties) simultaneously without row arrangement; row intercropping – crops in alternating rows; strip intercropping – crops in alternating strips; and relay intercropping – second crop overseeded into current crop (Wallace 2001). Maize (four seeds m^{-2}) and soya bean (33 seeds m^{-2}) as mixed intercrops are more cost effective than pure stands. Another example of mixed intercrops is forage sorghum into silage maize. Strip intercropping is suitable for maize and soya bean or for cerelas (spring wheat or oats), maize, and soya bean with ridge-till or notill (Sullivan 2003a). Relay intercropping can also be practised with grasses in pasture management.

Mixture intercropping is possible as well with different varieties. The primary reason in implementing variety mixtures would be to reduce pathogen and weed populations but phenotypic variation in varieties may allow choosing those which will suppress the specific pathogen or weed problems by the crop (Mundt 2002). Crop mixtures have also advantages under certain unfavorable conditions such as frost or lodging. Frost-resistant varieties have been found to protect less resistant ones. Similarly, cereal varieties which do not lodge can be a support for components with weak stems (Lastuvka et al. 2007).

Intercropping favors utilization of water, nutrients, cropping area and productivity of cultivated plants, increase the ecological diversity in a field, and may also contribute to the prevention of nitrogen leaching risks. At the same time intercropped plants form a potentially absorptive barrier against pest and fungi to movement between those plants and they can reduce occurrence of weeds and insects (Baumann et al. 2000). These advantageous effects are attributed partially to allelopathic interaction between crops and other organism living in the field. Weeds are controlled by increasing shade and increasing crop competition with weeds through tighter crop spacing during all or part of the crop growth.

Intercropping is most successful when the two crops have the complementary growth and resource needs, e.g., Italian ryegrass (*L. multiflorum* Lam.) was too competitive with the timothy grass (*Phleum pratense* L.), therefore it should not be recommended as a companion crop for timothy establishment (Jefferson et al. 2000).

Allelopathic effects of a selected crop on the component crops must be considered. Strong allelopathic and competitive effects were for example observed in tall fescue (*Festuca arundinacea* Schreb.), white clover (*Trifolium repens* L.) or creeping red fescue (*Festuca rubra* L.) (Weston 1996; Sanderson and Elwinger 1999). Therefore a companion plant, that is selectively allelopathic against certain weeds and does not interfere with the crop growth, should be used. In oat – peas mixture, oat provides early competition with weeds while the peas is established; the peas then climbs on the oat, blocking out light to the soil; the oat competes more with grassy weeds for nutrients and the peas competes with the broadleaf weeds; the oat also takes up excess nitrogen that would otherwise stimulate the weed growth (Wallace 2001).

Intercropping may facilitate weed control if intercrops are more weed competitive than sole crops or are able to suppress weed growth through allelopathy (the weed species is more susceptible to such phytotoxin than crops). If intercrops do not suppress weeds more than sole crops, they should provide yield advantages due to better utilization of resources or by converting resources than in case of sole crops (Liebman and Dyck 1993).

An example, when intercropping suppressed the weed growth more than sole, is a leek (*Allium ampeloprasum* var. *porrum* (L.) J.Gay) – celery (*Apium graveolens* L.); intercrop sown in a row-by-row layout decreased relative soil cover of weeds by 41%, reduced the density and biomass of groundsel (*Senecio vulgaris* L.) by 58% and 98%, respectively, and increased the total crop yield by 10% (Baumann et al. 2000). Increased weed suppression and the crop yield were also demonstrated in cereal-legume intercrops in many different environments (Ofori et al. 1987).

However many factors such as planting date, presence of weeds, spatial arrangement, varieties, relative proportion of component crops, fertility, the crop growth in the given environment, etc., affect successfulness of intercropping (Altieri and Liebman 1986; Ofori et al. 1987). In practice, it is necessary to optimize them as much as possible. Seeding of each crop at two-thirds of its normal rate provided good results. Early-heading varieties of perennial ryegrass (*Lolium perenne* L.) or orchardgrass (*Dactylis glomerata* L.) are more compatible with white clover (*T. repens* L.) (Sleugh et al. 2000). Tall fescue (*Festuca arundinacea* Schreb.) varieties differ in their compatibility with white clover (Pedersen and Brink 1988). Orchardgrass lines with later maturity are more compatible with birdsfoot trefoil (*Lotus corniculatus* L.) (Short and Carlson 1989).

More compatible components for mixtures are being actively sought for cocoa, tea, rubber, grasses mixtures, and tree-based intercropping systems with Persian walnut (*Juglans regia* L.) (Ercisli et al. 2005). One of the possibilities for walnut intercropping is muskmelon (*Cucumis melo* L.) because seedling growth of this crop was increased by juglone (the allelochemical of walnuts) treatments (Kocacaliskan and Terzi 2001). Research is as well oriented to exploiting the allelopathic effects of different healing herbs, e.g., *Mentha* spp., to repress weeds.

The interaction of weeds with crops may be positive too. In a study, controlled densities of wild mustard (*Brassica campestris* L. var. *italica*) interplanted with broccoli (*Brassica oleracea* var. *italica* Premium Crop) increased the yield by 50% (Jimenez-Osornio and Gliessman 1987).

The main disadvantages of intercropping are: competition between crops; possible damage of the other crop during the harvest of one crop component; complication of mechanization and cultivation; decrease of symbiotic nitrogen fixation in legumes caused by plant competition for resources (Soon et al. 2004).

14.8 Allelopathy in Parasite Weed Management

Allelopathy found hopeful utilization in plant protection against parasite weeds. The main world parasitic species are the witchweeds (*Striga* spp.), broomrapes (*Orobanche* spp.), and eventually dodder (*Cuscuta* spp.). Witchweeds and broomrapes attack many economically important crops especially throughout the semiarid regions. Early detection of parasitic weed infestation and protection is difficult because of the growth habit of a root parasite and huge production of dust-like seeds viable up to 20 years (Kebreab and Murdoch 1999).

The main function of allelopathic substances is in the choice of a host and in the development of coactions. However, the effective compounds and their mechanism were described very rarely. Uncinanone B (4″,5″-dihydro-5,2′,4′-trihydroxy-5″-isopropenylfurano-(2″,3″;7,6)-isoflavanone) that induced germination of seeds from *Striga hermonthica* (Del.) Benth. and uncinanone C (4″,5″-dihydro-2′-methoxy-5,4′-dihydroxy-5″-isopropenylfurano-(2″,3″;7,6)-isoflavanone) that inhibited the radical growth of this parasite are compounds contained in root exudates of the legume *Desmodium uncinatum* (Jacq.) DC and they are one of the first examples of identified allelopathic compounds that prevent against the striga parasitism (Tsanuo et al. 2003). Chang et al. (1986) identified a germination stimulant, a p-benzoquinone compound from a natural host (sorghum) of *Striga* spp.

A chemical stimulant, a root exudate, is required to break seed dormancy of a parasitic weed and initiate seed germination. Upon receiving a signal for germination, a radicle emerges from the seed coat. However, an additional chemical signal is needed for the radicle to penetrate host roots and form a haustorium. Therefore several plants can serve as catch crops or trap crops for the reduction of the parasitic weed seed bank in infested soil.

Catch crops are crops that are susceptible to the parasite and thus become infected. The parasite has the chance to set seed, therefore it is necessary to destroy the catch crop before seed formation of the parasite.

Trap crops or so-called false hosts are crops able to stimulate parasite seed germination but are not themselves parasitized. Each trap crop control at least one species but not all genus species. (Abebe et al. 2005). Dodder (*Cuscuta* spp.) infestation can be effectively reduced by growing cereals or other grass crops (false hosts) continuously for several years (Dawson 1987). Other examples of suitable trap and catch crops are given in the Table 14.3.

Intercropping with trap or catch crop against parasitic plants is often practiced in resource-poor regions but as parasitic plants it has considerable success. This approach is more effective than use of pesticides, cheap and environmentally

Table 14.3 Examples of effective parasitic weed control

Parasite	Effective crop	Way of use	Reference
Striga hermonthica (Del.) Benth.	Silverleaf (*Desmodium intortum* (Mill.) Urb.), greenleaf (*D. Uncinatum* (Jacq.) DC.)	Trap crops; between rows of maize = "push-pull" strategy	Khan et al. 2002
	Sudan grass (*Sorghum sudanense* L.)	Catch crop	Oswald et al. 1999
	Cowpea (*Vigna unguiculata* (L.) Walp.), green gram (*Vigna radiata* (L.) Wilczek), crotalaria (*Crotalaria ochroleuca* G. Don), sweet potato (*Ipomoea batatas* (L.) Lam.)	Intercropping	Khan et al. 2007
S. asiatica (L.) Kuntze	Cowpea (*Vigna unguiculata* (L.) Walp.)	Intercropping within cereal rows	Parker and Riches 1993
	Sesbania sesban (L.) Merr., *Tephrosia vogelii* (Hemsley) A. Gary, *Crotalaria grahamiana* Wight & Arn., *Desmodium distortum* (Aubl.) Macbr., *Leucaena leucocephala* (Lam.) de Wit, *Senna siamea* (Lam.) H. S. Irwin & R. C. Barneby, *Senna didymobotrya* (Fresen.),	Trap crops	ICRAF 1996; Rao and Gacheru 1998
O. crenata Forsk.	Oat (*Avena sativa* L.)	Intercropping	Fernández-Aparicio et al. 2007
	Flax (*Linum usitatissimum* L.), alfalfa (*M.* L.), cotton (*Gossipium* spp.), onion (*Allium* spp.), garlic (*Allium sativum* L.), proper (*Capsicum annum* L.), snap bean (*P. vulgaris L.*), maize (*Zea mays* L.), sesame (*Sesamum indicum* L.*)*	Trap crops	Abebe et al. 2005
O. ramosa L., *O. cernua* Loefl.	Maize (*Zea mays* L.), Snap bean (*P. vulgaris* L.)	Trap crops	Abebe et al. 2005
O. aegyptiaca Pers.	Flax (*Linum usitatissimum* L.)	Catch crop	Kleifeld et al. 1994
	Mung beans (*Phaseolus aureus* Roxb.)	Catch crop	Kleifeld et al. 1994
O. minor Sm.	Winter wheat (*Triticum aestivum*), Triticale (*Triticum secalotriticum saratoviense* Meister)	Trap crops	Lins et al. 2006

friendly (Parrott 2005). The best solution is a combination of several methods – crop rotation and intercropping with trap or catch crops. Both trap crops and catch crops do not bring about immediate complete soil eradication. However, they accelerate the depletion of the seed bank (Mloza-Banda and Kabambe 1997).

Linke et al. (1993) established 30% reduction in *Orobanche crenata* Forsk seed bank after one catch crop cycle. Maize and snap bean depleted seed bank of *O. ramosa* L. and *O. cernua* Loefl. by 72.5% per season (Abebe et al. 2005). Odhiambo and Ransom (1996) found that after 4 years of continuous cropping sudan grass as a catch crop with cowpea or cotton *Striga* still remain in the soil. Growing trap crops for two consecutive seasons reduced seed bank of *Orobanche* species by 60%. So, crop rotation with trap crops deplete soil seed bank of parasite weed infestation in 5–10 years (Aalders and Pieters 1987). Therefore using trap and catch crops for the parasite control is limited especially in heavily infested fields (Kleifeld et al. 1994). Large differences in their "trapping" ability exists between varieties, e.g., in lentil *L. culinaris* Medicus (Fernández-Aparicio et al. 2007).

Allelopathic compounds as a defense could play an important role in resistance of the host plant. According to Jacobs and Rubery (1988), accumulation of phenolic compounds alters the hormonal balance of the parasite, resulting in necrosis. High levels of resistance to *O. crenata* have been found in the species *Lathyrus ochrus* DC. and *L. clymenum* L. (Sillero et al. 2005). Arnaud et al. (1999) described the differences among resistance of sorghum varieties. However, Eizenberg et al. (2003) and Labrousse et al. (2001) described the resistance in several wild sunflower species due to their ability to increase wall deposition, vessel occlusion, or broomrape cellular disorganization. Resistant hairy vetch (*Vicia atropurpurea* Desf.) blocked *O. aegyptiaca* Pers. haustorium at the root endodermis layer (Goldwasser et al. 2000). Therefore the mechanism of resistance needs more research.

Against parasitic weeds, plant extracts could be partially effective too. Habib and Abdul-Rahman (1988) found aqueous extracts of Bermuda grass (*Cynodon dactylon* (L.) Pers.), wall goosefoot (*Chenopodium murale* L.), Johnson grass (*Sorghum halepense* (L.) Pers.), and tumble pigweed (*Amaranthus albus* L.) reduced field dodder (*Cuscuta campestris* Yunck.) on alfalfa from 83% to 96%, but the same concentration (0.5 g) injured alfalfa up to 43%. Other possibilities of parasitic weed biological control (insects or fungi) were described by Elzein and Kroschel (2003).

14.9 Varieties with Strong Allelopathic Potential

During cultivation, weed and pest resistance characteristics were ignored, and therefore the selection of high-yielding varieties caused the loss of allelopathic traits (Singh et al. 2001). For example, one of the ancestors of wheat, *Triticum speltoides*, contained significantly higher quantities of the allelochemical 2,4-dihydroxy-7-methoxy-1, 4-benzoxazin-3-one (DIMBOA) than *Triticum aestivum* (Niemeyer 1988). Another example is wild species Maximilian sunflower *Helianthus maximiliani* Schrad.

that produces phytotoxic 8β-sarracinoyloxycumambranolide (Gershenzon and Mabry 1984). The commercial sunflower (*Helianthus annuus* L.) produce the compound also but in dependence upon the variety (Macias et al. 1993). Therefore, the transfer of allelopathic traits from wild types is one of the possibilities for breeding strong allelopathic varieties.

Early seedling emergence, seedling vigor, fast growth, greater plant height, greater root volume, and longer growth duration increase the ability of varieties to compete with weeds (Kim and Shin 2003). However, it is not known if these traits are related to the production and release of allelochemicals.

The initial step in breeding for genetic improvement of allelopathic traits is to select crop varieties with the strongest allelopathic potential. Varieties with strong allelopathic potentials have been carried out in several field crops (Table 14.4), and crop varieties differ in their ability to inhibit the growth of certain weeds. The growing of crop varieties with elevated allelopathic activity could be a great chance for organic farming.

Allelopathic activity was identified as a quantitative trait in rice and wheat (Dilday et al. 1998; Wu et al. 2000; Jensen et al. 2001); therefore allelopathy is affected by both genetic effects and environmental conditions (Dilday et al. 1998). Little available knowledge is about changes of allelopathy at different growth stages and under different environmental conditions (He et al. 2004). For example, selection for allelopathic activity in rice should be performed during the three leaf phase. Allelopathic effects of wheat exhibited the highest heritability in the tillering stage (Zuo et al. 2007).

Jensen et al. (2001) described three quantitative trait loci (QTL) localized on chromosomes 2 and 3, explaining about 30% of allelochemical production in rice. Kong (2005) reported that one main QTL on chromosome 7 was detected, explaining 32.3% of the phenotypic variation was associated with allelopathic effects of rice. Wu et al. (2003) identified two major QTLs on chromosome 2B conferring wheat allelopathic activity. However, it is not known what kinds of gene are responsible for the allelopathic effect, but it is assumed that allelopathic potential might be polygenically controlled because of variation in the germplasm (Courtois and Olofsdotter 1998). It confirmed a sequence analysis of cucumber, when 43 unique genes that shared significant similarities to known plant genes potentially implicated in the autotoxic response were described. These genes are associated with detoxification, reactive oxygen scavengers, signaling components, and transcriptional regulators (Mao et al. 2007). According to Xiong et al. (2007), a “favorable” gene with positive effects might become “unfavorable” following transfer into a new variety due to the large negative additive effects in the new genetic background. Therefore, more emphasis on identifying the best multi-locus allelic combinations instead of pyramiding individual favorable QTL alleles should be done.

The three approaches to create more allelopathic crops are: the traditional breeding; the incorporation of allelopathic properties to hybrid crop; and genetic engineering. The results indicated that the heterotic effect on allelopathy was positively significant, so hybridization could be a promising method. At present, no commercial

Table 14.4 Summary of some strong allelopathic cultivars

Crops	The inhibited species	Strong allelopathic varieties	Reference
Cucumber (*Cucumis sativus* L.)	*Panicum miliaceum* L., *Sinapis alba* L.	PI 169391	Putnam and Duke 1974
Pearl millet (*Pennisetum glaucum* (L.) R. Br.)	*Trianthema portulacastrum* L. and *Amaranthus* spp.	HHB-67, 88004A 833-2	Khanh et al. 2005
Oat (*Avena sativa* L.)	–	PI-266281 the strongest – high content of scopoletin	Fay and Duke 1977
Alfalfa (*M. sativa* L.)	Inhibition of total weed biomass	Rasen, Yuba	Khanh et al. 2005
Wheat (*Triticum aestivum* L.)	Annual ryegrass (*Lolium rigidum* Gand.)	2 Distinct groups – condor-derivatives more allelopathic than Pavon-derivatives	Wu et al. 2000
		Tasman, Khapli, Wattines, AUS# 12627, Triller, SST 6, AUS# 18060, Tunis 2, AUS# 18056, Meering	Wu et al. 2003
		No 6 Lankao', "No 22 Xiaoyan"	Zuo et al. 2007
Triticum speltoides Fla Kslo.	Wild oat (*Avena* spp.).	Ts8, Ts10, Ts22, Ts25 – higher amounts of DIMBOA	Quader et al. 2001
Rice (*Oryza sativa* L.)	Neighboring plants	PI312777, Huagan-1	Kong et al. 2006
	Ducksalad (*Heteranthera limosa* (Sw.) Willd.)	PI 338046, Katy	Dilday et al. 1998
		PI312777	Dilday et al. 1994
		PI294400, PI 277414	Mattice et al. 1998
	Barnyard grass (*E. crus-galli* (L.) P. Beauv.)	Inhibition (%) followed the order : landrace (50), improved varieties (49) greater than or equal to Japonica (48) > weedy rice (44) > Indica rice (39)	Lee et al. 2004; Jensen et al. 2001
		Asian varieties "PI 312777," "Guichao," "Teqing"	Gealy et al. 2002
		Iguape Cateto, PI312777, Azucena, Taichung Native 1, IAC25	He et al. 2004
		RP 2269-424, LD 183-3, LDS 183-7, IET 1444, Dular, CI selection-63, UPR 82-1-7, GZ 1368-5-2, OR 131-58	Hassan et al. 1998
	Cyperus difformis L.	RP 2271-433-231, IET 11754, Dular, OR 131-5-8	Hassan et al. 1998

varieties with allelopathic properties are available. If allelochemicals or genes responsible for allelopathic effects will be identified, allelopathic traits could be easily incorporated into cultivars (Kim and Shin 2003). Detailed information about allelopathic breeding is given in Kim and Shin (2003).

14.10 Other Possible Application of Allelopathy in Weed Management

Except direct use of allelopathic crops as cover crops, smother crops, and intercrops, applications of allelopathy for weed control include the use of allelopathic residues as an herbicide agent, e.g., pellets flours, water extracts, etc. The most common example of crop residue utilization is application of straw on the soil surface (mulching), e.g., rice straw inhibited germination of field bindweed (*Convolvulus arvensis* L.), winter wild oat (*Avena ludoviciana* Durieu), and littleseed canarygrass (*Phalaris minor* Retz.) (Lee et al. 1991; Tamak et al. 1994; Young et al. 1989).

The effect of applied plant residues can be positively influenced by an increase of temperature. Mallek et al. (2007) established that dried and milled crop residues of onion (*Allium cepa* L.) or garlic (*A. sativum* L.) were able to reduce seed germination of barnyard grass (*E. crus-galli* (L.) P. Beauv.), common purslane (*Portulaca oleracea* L.), london rocket (*Sisymbrium irio* L.) during their decomposition in soil, but only at the elevated (39°C) soil temperature. It can support combination of methods for weed control, in this case allelopathy with soil heating treatments (e.g., solarization).

Plant material processed into pellets allows easier application and measuring. Alfalfa pellets (commercial forage fodder) were effective as a natural herbicide against *Echinochloa oryzicola* (Vasinger) Vasinger, *Digitaria ciliaris* Pers., *Cyperus difformis* L. and *Monochoria vaginalis* Kunth in rice paddy fields incorporated at 1–2 Mg ha^{-1} (Xuan and Tsuzuki 2001). Xuan and Tsuzuki (2004) suggested similar use of buckwheat pellets (at same dosage). The early incorporation of buckwheat pellets into the soil provides great weed control in rice (Xuan and Tsuzuki 2004).

As herbicide agents, by-products of crop processing are possible to use too, e.g., Japanese farmers use rice bran (200 g m^{-2}) for weed control and fertilization on transplanted rice (Kuk et al. 2001). Maize gluten meal, a by-product of maize milling process, has been patented as a natural preemergence herbicide (Christians 1993). The maize gluten meal contains chemicals (five dipeptides, Gln–Gln, Ala–Asn, Ala–Gln, Gly–Ala, and Ala–Ala) that inhibit root growth of germinating weeds but does not damage roots of mature plants (Christians 1993; Liu and Christians 1994).

Medium-grain fatty rice bran was the best material for reducing weed emergence (Palmer amaranth *Amaranthus palmeri* S. Wats. and ivyleaf morningglory *Ipomoea hederacea* Jacq. followed by sicklepod *Senna obtusifolia* (L.) H. S. Irvin & Barneby, hemp sesbania *Sesbania exaltata* (Raf.) Cory and prickly sida *Sida* *spinosa* L.) in the minimum effective rate 250 g m^{-2} as preplant incorporated or preemergence in the stand of cotton and maize (Kuk et al. 2001).

Boydston et al. (2008) found that dried distiller maize grains with solubles, a by-product of ethanol production, may be useful for reducing the emergence and growth of common chickweed (*Stellaria media* (L.) Cirillo) at concentration of 5%, annual bluegrass (*Poa annua* L.) at concentration of 10% or more, in container-grown ornamentals (*Rosa* spp., *Phlox paniculata* L.*, Coreopsis auriculata* L.). Amounts of 800 and 1,600 g m^{-2} applied to the surface of transplanted ornamentals decreased the number of annual bluegrass (*Poa annnua* L.) (48%) and common chickweed (*Stellaria media* (L.) Cirillo) (46%) without injury to ornamentals.

However, not all suggested products are effective. For example, application of Indian mustard (*B. juncea* L.) and field pennycress (*Thlaspi arvense* L.) seed meals did not decrease the grassy weed population (Sams et al. 2007).

Extracts are an example of the traditional use of allelopathic plant material. The water extracts of, e.g., sorghum, sunflower, brassica, sesame, eucalyptus, tobacco, etc., contain a number of allelochemicals which are more effective to the weed control (Cheema et al. 1997; Rizvi et al. 1989; Daury 2002; Cheema et al. 2003; Jamil 2004; Anjum and Bajwa 2005). A water extract of mature sorghum plants obtained after 24 h soaking in water, called Sorgaab, is used as a natural herbicide. Cheema and Khaliq (2000) reported that Sorgaab reduced weeds from 35% to 49%. This agent is possible to use alone or in combination with other water extract, e.g., with sunflower water extract or eucalyptus extract. A big challenge is the utilization of the water extracts of medical plants. Aqueous extracts (1–8%, w/v) of the dried powders of terrestrial saururaceae (*Houttuynia cordata* Thunb.) inhibited the germination and initial growths of *Echinochloa* spp. and *Monochoria* sp. in rice paddy field. All the treatments (25–150 g m^{-2}) did not have negative effects on rice, therefore this plant could be used as a natural herbicide to weed control in rice (Lin et al. 2006). Nazir et al. (2007) found that aqueous extracts of rhubarb (*Rheum emodi* Wall.), *Saussurea lappa* C.B.Clarke, and *Potentilla fulgens* Wall. Ex Hook reduced significantly growth of cockscomb (*Amaranthus caudatus* L.) and finger millet (*Eleusine coracana* Gartn.). The extracts of lemon balm (*Melissa officinalis L.*) shoots inhibited the germination and the growth of pendant amaranth (*Amaranthus caudatus* L.), cress (*Lepidium sativum* L.), hairy crabgrass (*Digitaria sanguinalis* (L.) Scop.), timothy grass (*Phleum pratense* L.), and Italian ryegrass (*L. multiflorum* Lam.) under laboratory conditions (Kato-Noguchi 2001). Volatile compounds from *Eucalyptus exserta* F. Muell. and *E. urophylla* S. T. Blake reduced the seedling growth of *Raphanus sativus* L., *Lactuca sativa* L., *Leucaena leucocephala* (Lam.) de Wit and *Acacia mangium* Willd.; volatiles from leaves of *Eucalyptus citriodora* Hook. inhibited weeds like *Bidens pilosa* L., *Digitaria pertenuis* Buse*, Eragrostis cilianensis* (All.) Vignolo ex Jauch.*, Setaria geniculata* (Lam.) P. Beauv (Shiming 2005). Strategies for using the essential oils from plants such as *Mentha* spp., *Satureja montana* (Roy) O. Bolos & Vigo, and *Ocimum* spp. as soil fumigants are developed (Birkett et al. 2001).

14.11 Pollen Allelopathy

Pollen allelopathy is phenomenon when pollen chemicals (e.g., phenols, terpenoids, sesquiterpene lactones, etc.) inhibit sexual reproduction in heterospecific individuals due to influencing of fertilization (Murphy 1992). The phenomenon includes excretion of signaling compounds from the donor cell (pollens, pistil stigma), recognition of a specific signal, transmission of information (pollen), and the development of a characteristic response in the acceptor cell. The possible mechanism of the effect was described in Roshchina (2001).

Pollen allelopathy can find utilization in field cultivations that could contain pollen of allelopathic crops or weeds. Pollen allelopathy could be an effective method for annual weed control that reproduce, at least in part, via wind pollination and flower concurrently with the allelopathic species. The effects of allelopathy should result in the loss of genetic variation and so in reduction of reproductive ability, but some plants are probably able to detoxify the pollen allelochemicals (Murphy and Aarssen 1995a, b). Murphy and Aarssen (1989) suggested possible delaying of weed flowering at later, less favorable times of the season or diurnal period, so decrease in weed pressure. However, infestation by perennial weeds can worsen due to compensation of pollen allelopathy through increase in the formation of rhizomes.

Pollen allelopathy is not common (Murphy 2000). To date, two allelopathic crops were found. Maize (*Zea mays* var. *chalquinoco´nico*) was pollen-allelopathic against barnyard grass (*E. crus-galli* (L.) P. Beauv.), hairy beggar-ticks (*Bidens pilosa* L.), curly dock (*Rumex crispus* L.), *Cassia jalapensis* (Britton) Lundell and *Amaranthus leucocarpus* S. Wats. (Ortega et al. 1988). The second crop, timothy grass (*Phleum pratense* L.), demonstrated pollen-allelopathic effects on *Solidago rugosa* Mill., *Melilotus alba* Medic., *Euphrasia officinalis, Cirsium arvense* L. Scop, *Agrostis lateriflora* Michx., *Aster ericoides* L., *Aster dumosus* L., *Ambrosia artemisifolia* L., *Elymus repens* (L.) Gould, *Bromus inermis* Leyss., *Danthonia compressa* Austin, and *Poa compressa* L. (Murphy and Aarssen 1989).

The most promising allelopathic weeds are hawkweeds (*Hieracium* spp.). They are effective in reducing other asteraceous weeds (Murphy and Aarssen 1995b) and yellow hawkweed (*H. pratense* Tausch.) inhibited Canada thistle (*Cirsium arvense* (L.) Scop.), perennial sow-thistle (*Sonchus arvensis* L.), yarrow (*Achillea millefolium* L.), and annual sow thistle (*Sonchus oleraceus* L.); however, the long-term effect on perennial species is unclear (Murphy 2001).

Pollen grains of another species, parthenium (*Parthenium hysterophorus* L.), contained growth inhibitors which inhibited fruit set in many test species (Sukhada and Jayachandra 1980). However this plant is a noxious weed and its pollen is strong, therefore use of parthenium in agriculture is unlikely.

The main advantage of pollen allelopathy is that allelochemicals occur in a natural form, i.e., pollen grains and are biologically active at low doses (10 grains mm^{-2} on stigmas) (Murphy 2001). In case of pollen allelopathy, autotoxicity was not established (Murphy and Aarssen 1995a).

For pollen-allelopathic breeding, plants with tall growth habit and relatively large quantity of pollen should be selected (Murphy and Aarssen 1989). Pollen of these species could be artificially dusted on the stigmatic surface of other plants. This phenomenon is yet to be studied and field tested.

14.12 Use of Allelopathic Crops in Biological Control

Allelopathy includes not only plant–plant, plant–microorganism interactions but also plant–insect interaction (Durtn-Serantes et al. 2002). Plants are able to produce compounds that act as repellents for herbivorous pests and as attractants for antagonistic organisms, e.g., predators and parasitoids. However, some insects are able to detoxify the chemical and so they can feed on the plant (Capinera 2005). For example, secondary metabolites from barley such as gramine and hordenin help in defence of the plant against armyworm (*Mythimna convecta* Walker) larvae and fungus (*Drechslera teres* (Sacc.) Scoem.). In some cases, allelochemicals can affect pests, microorganisms and plants at once. Ageratochromene of *Ageratum conyzoides* L. acts as anti-juvenile hormone on insect and inhibits the growth of the pathogens like phytopthora root rot of pepper (*Phytophthora capsici* L.), but also suppress ryegrass (*Lolium* spp.) and barnyardgrass (*E. crus-galli* (L.) P. Beauv.) (Shiming 2005). This type of allelopathy can help in organic pest management. In Africa the farmers use Napier grass (*Pennisetum purpureum* Schum.) and desmodium legumes (silverleaf *D. uncinatum* (Jacq.) DC. and greenleaf *Desmodium intortum* (Miller) Urban) for control of stemborers (*Busseola fusca* Fuller, *Chilo partellus* Swinh.) and striga (*Striga* spp.) in maize fields. Desmodium is planted between the rows of maize as a repellent crop. Napier grass is grown around the field as a trap crop because it is preferred to maize for oviposition by stemborers, and it is subsequently removed and used as fodder. This method is called the “push-pull” strategy (Cook et al. 2007). In South China intercropping of *Ageratum conyzoides* L. in citrus orchards is practiced that effectively suppresses microbes, insects, and growth of some weeds through the release of volatile allelochemicals (ageratochromene, monoterpenes, sesquiterpenes, flavones and others) (Kong et al. 2004). Crop rotation with marigold (*Tagetes* spp.) (plant density of about 20 plants m^{-2}) holds damage from root-lesion nematodes (*Pratylenchus penetrans* Cobb) below the economic threshold (Reynolds et al. 2000; Ball-Coelho et al. 2001). Marigold residues are as well toxic to same fungi (Weaver et al. 1994).

Sometimes the strategy used in weed control could be effective against pests and pathogens. Isothiocyanates from cruciferous green manure are potentially useful in controlling *Fusarium oxysporum* Schltdl. pathogens (Smolinska et al. 2003), *Gaeumannomyces graminis* (Sacc). Arx & D. L. Olivier pathogen and they are toxic to eggs of the black vine weevil (*Otiorhynchus sulcatus* Fabricius) (Angus et al. 1994). Biofumigation with broccoli (biomass incorporated into soil) controls *Meloidogyne incognita* (Kofoid & White) Chitwood nematode and positively effects saprophytic nematodes (Roubtsova et al. 2007). Production of biocidal pellets to be used as organic treatments in addition or in alternative to biocidal green manure are reported and discussed, because dried plant material, after water addition, showed, in vitro, a good fungitoxic activity on *Pythium* ssp. and *Rhizoctonia solani* Kühn (Lazzeri et al. 2004).

Combination of two different methods helps to protect plants from weeds and pathogens and pests at once. The combination of solarization and organic amendment (millet residues) can be an effective alternative to pesticides for managing charcoal rot disease of cowpea (*Vigna unguiculata* (L.) Walp.) with heavy infestations of *Macrophomina phaseolina* (Tassi) (Ndiaye et al. 2007). When wheat or barley soil amendments were combined with heating, nematode galling (*Meloidogyne inkognita* (Kofoid & White) Chitwood) was reduced by 99–100% and recovery of pathogens *Sclerotium rolfsii* Sacc. and *Pythium ultimum* Trow was reduced by 84–100% (Stapleton 2006).

14.13 Conclusion

Though allelopathy is too complex a phenomenon and its application is not easy because of different effects in diverse environment, it is very promising from an ecological point of view. Allelopathy should find main use in management of organic agriculture based only on biological processes and cycles with the effort to attain ecological balance. However, allelopathy utilization is possible in conventional, low input or sustainable agricultural systems. Suitable use of allelopathic crops could reduce the pesticide application and so to reduce the environmental and food pollution, decrease costs in agriculture, improve food security in poor regions and soil productivity, increase biodiversity and sustainability in the agro-ecosystem.

Allelopathy plays an important role in many preventive agricultural methods such as use of cover crops, mulches, green manure or intercropping. Roots of allelopathic plants or their decomposing residues release compounds in the soil that are toxic to weeds. Annual, biennial, or perennial herbaceous plants in a pure or mixed stand can be grown for these purposes. Decomposition time of plant residues and amounts of biomass are important factors of weed control by mulching. Biofumigation is the name for one type of allelopathy that includes effects of the chemicals, i.e., highly toxic isothiocyanates, produced by *Brassica* green manure. However, the weed-suppressive effect is influenced by species, planting date, seeding rate and method, weather and other factors and the balance of allelopathic crops in the crop rotations is necessary due to possible autotoxicity.

These days, allelopathic plants as catch crops or trap crops found utilization in plant protection of tropical regions against parasitic weeds. They do not eliminate the parasite completely but decrease the seed bank in the soil. Other applications of allelopathy for weed control include the use of plant residues as a natural herbicide agent, e.g., water extracts, pellets, flours, by-products of crop processing, etc. The strategies for use of volatile compounds as soil fumigants are developed.

Newly investigated pollen allelopathy could effectively reduce the reproductive ability of wind pollination of annual weeds. Pollen of allelopathic species could be artificially dusted on the stigmatic surface of other plants. This phenomenon needs study and field testing yet.

Allelopathic compounds act as repellents for herbivorous pests, so the same strategy used in weed control could be effective against pests and pathogens. Only allelopathy is not possible to use the complete control of weeds, pests or diseases; it is necessary to combine it with other methods of plant protection.

For next development of allelopathy utilization, especially such ways as breeding for stronger allelopathic potential is very hopeful. Hybridization could be a promising method of breeding. However, allelopathic activity was identified as a quantitative trait and therefore this characteristic is affected by both genetic effects and environmental conditions. The main disadvantage of the application of allelopathy is considerable variability in the dependence on environment. Therefore all results achieved in laboratory should be compared with effects of allelopathic crops in field conditions.

Nowadays majority of the obtained experimental results and knowledge about allelopathy come from conventional agriculture therefore more research is needed in conditions of organic farming. Future research should also be oriented on the long-term impacts of allelopathic plant characteristics on weed and on pest and fungi populations and integration of allelopathic crops with the plant protection management.

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Chapter 15
Occurrence and Physiology of Zearalenone as a New Plant Hormone

Jolanta Biesaga-Kościelniak and Maria Filek

Abstract Zearalenone* is a non-steroidal mycotoxin with oestrogenic properties, which is produced mainly by fungi belonging to *Fusarium* (*6-(10-hydroxy-6-oxo-trans–1–undecenyl)-β-resorcylic acid lactone). The toxin-producing ability of *Fusaria* is greatly influenced by environmental factors. Therefore, it was expected that the different weather conditions occurring during the vegetation period would be associated with differences in the preharvest occurrence of *Fusarium* toxins. Sustainable food systems research and practice concentrate on the study of the level of these mycotoxins in soils and crops. However, some experiments show that zearalenone can also act as a hormonal substance and have a favourable effect on the development of plants and animals. This chapter gives an overview of the possible effect of low concentrations of zearalenone on some physiological processes in crops. It has been shown that exogenous application of zearalenone and its derivatives can stimulate generative development in winter plants, which suggest its participation in the mechanism of flowering. Moreover, treatment with zearalenone had an effect on calli proliferation and cell differentiation. The effect of zearalenone was similar to the activity of auxins in *in vitro* cultures, which may confirm the hormonal properties of zearalenone in plants. Watering and soaking wheat and soybean grains with zearalenone solution resulted in higher yields of these plants. These observations, compared with the possibility of weather-related changes in the exogenous content of zearalenone in soils, can be useful in determining the optimal zearalenone dose that would show the favourable effect of this substance in plant development.

J. Biesaga-Kościelniak (✉) and M. Filek
Polish Academy of Sciences, The Franciszek Górski Institute of Plant Physiology,
Niezapominajek 21, 30-239, Krakow, Poland
e-mail: J.Koscielniak@ifr-pan.krakow.pl

M. Filek
Institute of Biology, Pedagogical University, Podbrzezie 3,
3, 31-054, Kraków, Poland
and
Polish Academy of Sciences,
The Franciszek Górski Institute of Plant Physiology,
Niezapominajek 21, 30-239, Kraków, Poland

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15.1 Introduction

Zearalenone is a mycotoxin produced by several *Fusarium* species. The term mycotoxin refers to a large number of chemically diverse toxic secondary metabolites formed by fungi imperfectly growing on agricultural commodities. Since the discovery of the aflatoxins in 1960 and subsequent recognition that mycotoxins are of significant health concern to both humans and animals, regulations gradually developed for mycotoxins in food and feed. *Fusarium* diseases of wheat, barley, and maize cause significant yield losses worldwide and are therefore of great economic importance (Sutton 1982; Diekman and Green 1992; Parry et al. 1995; Miedaner 1997; Mesterhazy et al. 1999; Malekinejad et al. 2007). The influence of host cultivars on the pathogenicity and toxicity of *Fusarium* fungi has been extensively reviewed (Miedaner 1997; Mesterhazy et al. 1999; Miedaner et al. 2001; Magg et al. 2002). Mycotoxins can contaminate grains in the field when environmental conditions favour fungal infection, and levels can increase dramatically if storage conditions are favourable for fungal growth. The influence of climatic factors on *Fusarium* diseases is complicated by the fact that *Fusarium* fungi can cause disease individually or in complex infections (Doohan et al. 1998), and there are numerous reports on how species differentially respond to different environmental variations, particularly temperature and humidity (Doohan et al. 2003). Therefore, it was expected that the different climatic conditions during the years surveyed would be associated with differences in the preharvest occurrence of *Fusarium* toxins. The European Commission has recently specified the maximum levels of *Fusarium* toxins that will be allowed from July 2006 onwards. Maximum levels of 200 and 100 μg/kg have been specified for zearalenone in unprocessed corn and unprocessed cereals other than corn, respectively (Javier et al. 2007; Hans et al. 2007)

In spite of the fact that contamination of cereals and grains and related products with mycotoxins causes food and feed-borne intoxications in man and livestock, zearalenone in low concentrations can be treated as a plant hormone which influences the development and yield of crop plants (Biesaga-Kościelniak 2001). This review focuses on the effect of low doses of zearalenone on the stimulation of selected physiological processes in plants important for agriculture production.

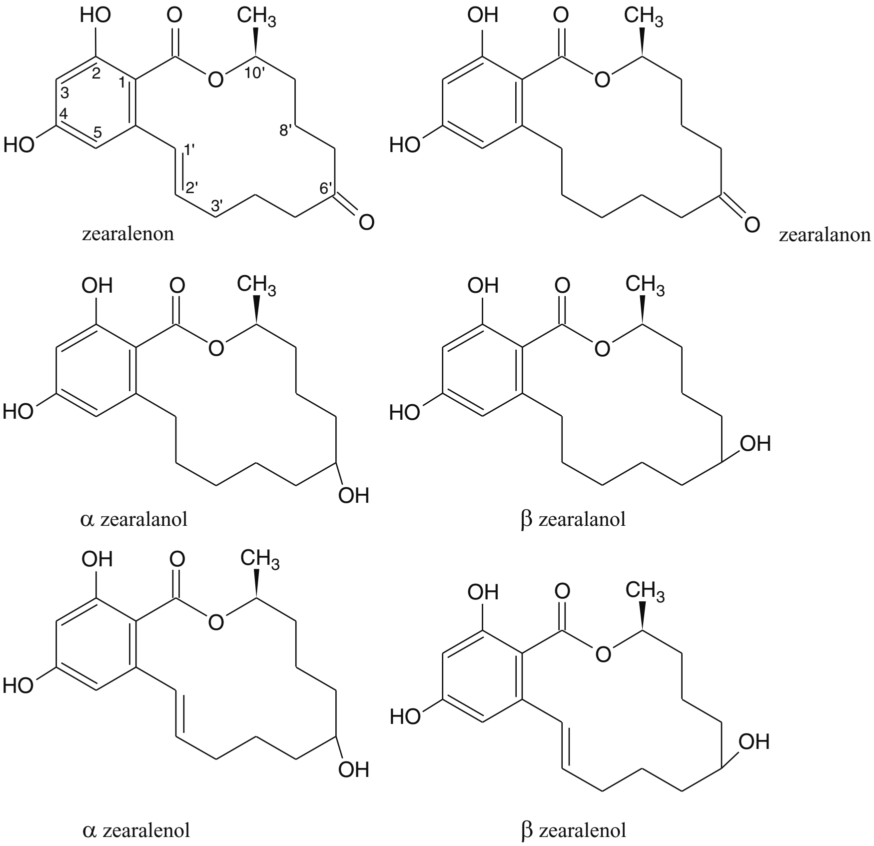
15.2 Chemical Structure of Zearalenone

Zearalenone, 6-(10-hydroxy-6-oxo-trans–1–undecenyl)-β-resorcylic acid lactone, is a non-steroidal mycotoxin with oestrogenic properties. It was first isolated from extracts of fungus *Gibberella zeae* (*Fusarium graminearum*) by Stob et al. (1962). This component is believed to act as an endogenous regulator of the sexual stage of development of their producer fungi. In the organisms of warm-blooded animals, the lactones mimic endogenous 17 β-estradiol, i.e. they stimulate the growth of muscle tissue and affect the functions of the reproductive system (Burkin et al. 2002). Its chemical structure was determined by Urry et al. (1966), and its name is derived from *G. zeae*, the name of the first studied organism that produces it; *r*esorcylic *a*cid *l*actone, the generic name for this group of natural products; *ene*, the standard suffix indicating the presence of the C-1′ to C-2′ double bond; and *one*, the standard suffix indicating the presence of the C-6′ ketone (Fig. 15.1). Nowadays zearalenone is produced commercially by fermentation (Hidy et al. 1977) for use in the manufacture of zeranol (zearalanol) by catalytic hydrogenation (Hodge et al. 1966). It is a secondary fungal metabolite produced by several species of *Fusarium*, mainly by *F. graminearum* and *F. culmorum*. These species are known to colonize maize, barley, oats, wheat and sorghum (Eppley et al. 1974; Mirocha et al. 1974; Jemmali et al. 1978; Bennett and Shotweli 1979; Farnworth and Neish 1980; Kuiper-Goodman et al. 1987; Kuiper et al. 1988; Tanaka et al. 1988; Bennett and Klich 2003) and tend to develop during prolonged cool, wet growing and harvest seasons in the temperate and warm regions of the world (Velluti et al. 2000). Of numerous zearalenone derivatives that can be produced by *Fusarium* spp., only *trans*-α-zearalenol has been found to occur naturally in cereal grains (Richardson et al. 1985). After consumption of zearalenone, the two stereoisomeric metabolites, α- and β-zearalenole (Fig. 15.1), are produced in mammals by reduction of the keto-group at C-6′. Another structurally similar compound is zearalanol (zeranol, Ralgro), which is synthetically produced from zearalenone and is used as a growth promoter in animals and has been banned in the European Union since 1985 (Hagler et al. 2001; Nsahlai et al. 2002). Zearalanol is distinguished from zearalenone by lack of a C-1′–C-2′ double bond. This substance can also be formed in vivo from zearalenone and α-zearalenole, which can be carried over from contaminated feed stuff to animals. Zearalenone and zearalenoles (α and β) act as estrogens because they can adopt a conformation which sufficiently resembles 17 β-estradiol and other natural estrogens to enable binding to the estrogen receptor (King et al. 1978; Miksicek 1994). The physiological effects of zearalanol are similar to those of zearalenone, but zearalanol is generally considered to produce estrogenic effects five to ten times greater than those of zearalenone (Schollenberger et al. 2006).

Owing to their frequent occurrence, zearalenone and zearalenoles are an important class of endocrine disrupters. Their estrogenic potential is comparable to that of the naturally occurring estrogens estrone and estriol and is several orders of magnitude higher than those of well-known environmental estrogens, e.g. organochlorine pesticides (Mirocha et al. 1971, 1974; Krska and Josephs 2001; Dai et al. 2004).

15.3 Chemical and Physical Properties

Zearalenone is a white crystalline compound, which exhibits blue-green fluorescence when excited by long-wavelength UV light (360 nm) and a more intense green fluorescence when excited by short-wavelength UV light (260 nm). In methanol,



zearalenon

zearalanon

α zearalanol

β zearalanol

α zearalenol

β zearalenol

Fig. 15.1 The chemical structures of zearalenone and its derivatives

UV absorption maxima occur at 236, 274 and 316 nm. The molecular formula of zearalenone is $C_{18}H_{22}O_5$, its molecular weight is 318.4 g/mol and its melting point is 162–163°C (Blackwell et al. 1985; Josephs et al. 2003). The maximum fluorescence in ethanol occurs with irradiation at 314 nm and with emission at 450 nm. Its solubility in water is about 0.002 g/100 ml. In an aqueous solution of inositol, the presence of zearalenone can change the crystal structure of this alcohol, which indicates the possibility of interaction between both substances (our observations). Moreover, zearalenone is slightly soluble in hexane and progressively more so in benzene, acetonitrile, methylene chloride, methanol, ethanol and acetone. However, it is readily soluble in aqueous alkali.

In fungal cultures a number of closely related metabolites are formed, but there is only limited evidence that these occur in foodstuffs, although there is experimental evidence for some transmission of zearalenone and α- and β-zearalenols into the milk of sheep, cows and pigs fed with these substances at high concentrations. Zearalenone does not degrade at high temperatures (Zinedine et al. 2007), but may be partly decomposed by heat. Approximately 60% of zearalenone remained unchanged in bread while about 50% survives in the production of noodles. Extrusion cooking may result in significant reduction of zearalenone with higher reductions of this substance at 120–140°C than at 160°C (Mateo et al. 2002).

15.4 Analytical Methods

Because estrogenic mycotoxins usually occur at microgram per kilogram (μg/kg) levels there is special interest in analytical procedures for reliable detection of zearalenone and its metabolites between 10 and 100 μg/kg. In response to the risk of a great economic loss to the industry and the threat to human health as a result of exposure to zearalenone, several methods have been developed for the quantification of zearalenone and its metabolites in different foods, feeds, animal tissues, blood and urine. Detailed reviews have been given by Steyn et al. 1991; Betina 1993; Frisvad and Thrane 1993; Scott 1993; Steyn 1995 and Lawrence and Scott 2000. The determination of zearalenone in cereals can be divided into five steps: grinding of the sample, extraction of the sample, clean-up, separation and detection.

In this regard several sophisticated chromatographic methods, with a quantification limit down to about 0.2 ng/g, have been developed and published for the determination of zearalenone. The methods were mainly based on high-performance liquid chromatography (HPLC) with fluorescence detection (Krska 1998; Visconti and Pascale 1998; Schuhmacher et al. 1998; Tanaka et al. 2000), but HPLC with mass spectrometry detection was also used (Shirai et al. 2000; Josephs et al. 2001).

Another method which uses capillary electrophoresis with laser-induced fluorescence detection can also be employed to detect zearalenone (Maragos and Appell 2007). In order to analyse trace amounts of zearalenone in plants, a sensitive, quick and accurate method, the enzyme-linked immunosorbent assay (ELISA) was developed by Chen et al. 1989.

15.5 Occurrence of Zearalenone in Plants

The occurrence of a zearalenone-like compound as a substance existing endogenously in plants was first reported by Li et al. (1980) and Li and Meng (1989). The aseptic culture of analysed shoot apices of the overwintering wheat plant confirmed that this substance was not due to fungal contamination, but was synthesized endogenously by the plants themselves. It was later confirmed by Meng et al. (1989) and Chen et al. (1989) using the enzyme-linked immunosorbent assay. This substance was identified by them as zearalenone.

The endogenous existence of zearalenone in plants served as a spur to further studies and its identification in different species. Han and Meng (1986) found zearalenone in rape, Meng et al. (1986) in winter wheat, Li and Meng (1989) in *Apium gaveoleus*, Que et al. (1990) in cotton, Han and Meng (1991) in *Lemna* *perpusilla* and Fu and Meng (1994) in tobacco buds. Moreover, Meng et al. (1996) suggested the occurrence of this substance in more than 30 species of plants among others in onion, corn, rice, cotton, carrot, celery and apple. These data were not confirmed by other authors and the difficulty with their verification is connected with the fact that the majority of these articles are published in Chinese. However, our unpublished data indicate that small amounts of endogenous zearalenone can exist in winter wheat, soybean and spring rape. These measurements (high-performance liquid chromatography) were performed on plants cultured *in vitro* in sterile conditions.

15.6 Influence of Exogenous Zearalenone on Plant Generative Development

For agriculture plants, effective flowering is a very important process. In this process, a vegetative meristem changes into a reproductive meristem which is capable of forming floral organs and in this way completes the reproductive life cycle of higher plants (Bernier and Périllex 2005). How the vegetative meristem is able to perceive and interpret signals from the environment as well as from the plant itself is largely unknown. The process by which vernalization – the exposure of a germinating seed or a juvenile plant to a prolonged period of low temperature – promotes flowering in an adult plant has remained a mystery for many years (Michales and Amasimo 2000). Vernalization is an important control for many agricultural and horticultural production species in temperate regions.

Some studies indicated that exogenous zearalenone influences plant growth and development. For example, zearalenone stimulated the initiation of the vegetative bud in tobacco pith callus tissue (Mirocha et al. 1968), inhibited the cell membrane transport of maize roots (Vianello and Macri 1981) and enhanced the α-amylase and β-glucosidase activities of germinating maize seeds.

Meng et al. (1992) found that zearalenone was an endogenous regulator controlling induction of generative development in winter plant. An increase in endogenous zearalenone during vernalization was also recorded by Fu and Meng (1994) in many winter plants. Moreover, they suggested that exogenous zearalenone can partly replace the low temperature requirement for flowering in winter wheat.

In combination with greatly shortened vernalization (14 days, 5°C) zearalenone completely eliminated the flowering blockade of winter wheat cv. Grana, which usually requires vernalization of 8–9 weeks (Biesaga-Kościelniak 1998) (Table 15.1). Moreover, zearalenone in the concentration 2 mg/dm^3 reduced the length of the vegetative phase by as much as about 50 days in comparison with the control sample (Biesaga-Kościelniak 2001) (Fig. 15.2). The stimulating effect of zearalenone on the induction of heading was observed also in other wheat varieties, and its effectiveness was highest in those varieties which needed longer time of low temperature treatment to flowering induction (Table 15.2). Some zearalenone derivatives exercised a greater influence on the induction of heading and the rate of generative development

Table 15.1 The influence of zearalenone on the generative development of winter wheat cv. 'Grana' after various periods of vernalization (According to Biesaga-Kościelniak 1998, modified). Isolated wheat embryos were cultured in sterile conditions on Murashige and Skoog (1962) media supplemented with 0 (control), 0.25, 0.50, 0.75 and 2.00 mg/dm^3 of zearalenone during 14, 28 and 42 days at 5°C (vernalization). After these periods, plants were transferred to soil and cultivated at 20/17°C. Number of headed plants, generative development of apexes and number of vegetative ones was obtained after 100 days of grown at 20/17°C

Concentration of zearalenone (mg/dm^3)	Number of plants Headed	 Generative (non-headed)	 Vegetative	Differentiation of frequency with respect to control
14 days of vernalization				
0.25	57 (95)[a]	3	0	+
0.50	13 (22)	47	0	+
0.75	57 (95)	3	0	+
2.00	60 (100)	0	0	+
0.00 (Control)	13 (22)	14	33	
28 days of vernalization				
0.25	59 (98)	1	0	+
0.50	57 (95)	3	0	+
0.75	60 (100)	0	0	+
2.00	60 (100)	0	0	+
0.00 (Control)	35 (58)	25	0	
42 days of vernalization				
0.25	59 (98)	1	0	
0.50	60 (100)	0	0	
0.75	60 (100)	0	0	
2.00	60 (100)	0	0	
0.00 (Control)	49 (83)	10	0	

'+' Significant differentiation on the basis of $\chi^2_{(p<0.01)}$ test

[a] In brackets percent of headed plants in population

of winter wheat cv. Grana than this substance itself (Table 15.3). Very strong activity has been demonstrated, in particular, by α-zearalanol, which after only 7 days of vernalization at 5°C induced the heading of almost all plants and greatly reduced the duration of the vegetative phase. The effectiveness of zearalenone was increased by an addition of spermidine and tissue extracts from inflorescences of some plant species. The effect of zearalenone on the growth process of wheat was to some extent contrary to its effect on the generative development, since it inhibited the elongation of the shoots, and also reduced their ability to accumulate biomass. The role of zearalenone in inducing flowering of winter wheat plants was confirmed by experiments with an exogenous application of a zearalenone synthesis inhibitor (malathion). This inhibitor decreased the plants' heading ability even after long vernalization (Table 15.4).

The influence of zearalenone on the generative development of winter rape was much weaker in comparison with that of wheat. None of the concentrations which stimulated wheat plants induced the flowering of rape plants. Zearalenone treatment stimulated only the first step of the process of the shoot apices generative differentiation (Biesaga-Kościelniak 2001).

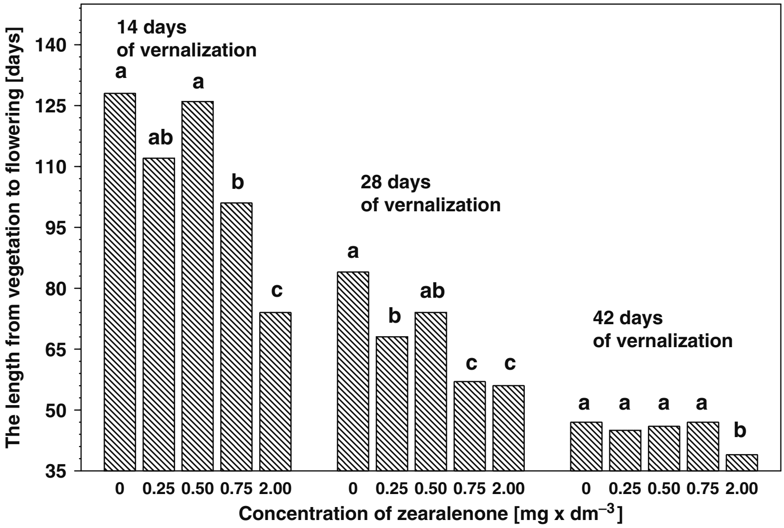


Fig. 15.2 The influence of zearalenone on the length of the phase from vernalization to flowering. Isolated embryos of winter wheat cv. 'Grana' were cultured in sterile conditions on Murashige and Skoog (1962) media supplemented with 0, 0.25, 0.50, 0.75 and 2.00 mg/dm^3 of zearalenone during 14, 28 and 42 days at 5°C (vernalization). After vernalization seedlings were transferred to soil and cultured at 20/17°C (day/night) to flowering. For particular length of vernalization values marked with the same letter do not differ significantly according to Duncan's multiple range test ($p < 0.05$). For all investigated periods of vernalization, the best effect, observed as significant shortening of the length of the period between vernalization and flowering was noticed for 2 mg/dm^3 of zearalenone

Table 15.2 The influence of zearalenone on the generative development of nine winter wheat varieties. Isolated wheat embryos were cultured in sterile conditions on Murashige and Skoog (1962) media supplemented with 0 (control) and 2.00 mg/dm^3 of zearalenone during 14 days at 5°C (vernalization). After this period, plants were transferred to soil and cultivated at 20/17°C. The number of heading and vegetative plants was fixed after 100 days from vernalization. The length of the phase from vernalization to flowering was determined in days

	Number of plants				Differentiation of frequency with respect to control	Length of the phase from vernalization to flowering (days)	
	Control		Zearalenone				
Variety	Headed	Vegetative	Headed	Vegetative		Control	Zearalenone
Kaja	45 (90)[a]	5	44 (88)	6		62	55
Almari	40 (80)	10	39 (85)	7		75	77
Tercja	40 (80)	10	44 (83)	9		75	70
Maltanka	17 (35)	31	21 (42)	29		71	69
Wanda	18 (35)	33	25 (50)	25		81	82
Jubilatka	13 (26)	37	33 (65)	18	+	79	67*
Kamila	12 (25)	36	30 (60)	20	+	85	61*
Zorza	5 (10)	45	44 (83)	9	+	99	71*
Izolda	5 (10)	45	39 (85)	7	+	89	73*

'+' Significant differentiation on the basis of $\chi^2_{(p<0.01)}$ test

[a] In brackets percent of headed plants in population

Table 15.3 Generative development of winter wheat plants after treatment with derivatives of zearalenone (According to Biesaga-Kościelniak 1998, modified). Seeds of wheat cv. 'Grana' were cultured in sterile conditions on Murashige and Skoog (1962) media supplemented with zearalenone and its derivative solutions used in concentration 2 mg/dm^3 during 7 days at 5°C (vernalization). After vernalization plants were replaced to soil and cultured at 20/17°C. The number of heated and vegetative plants was fixed after 100 days of growth at 20/17°C, and for generative plants, the length of phase from vernalization to flowering was determined

Zearalenopne derivatives	Number of plants			Length of phase from vernalization to flowering (days)
	Headed	Vegetative	Differentiation of frequency with respect to zearalenone	
α-Zearalenol	30 (60)[a]	20		63 ab
β-Zearalenol	15 (30)	35		69 ab
Zearalanon	17 (35)	32		73 a
α-Zearalanol	49 (98)	1	+	47 c
β-Zearalanol	45 (90)	5	+	50 c
Zearalenone	30 (60)	20		65 b

'+' Significant differentiation on the basis of $\chi^2_{(p<0.01)}$ test

Mean values marked with the same letter in the last column do not differ significantly according to Duncan's multiple range test ($p < 0.05$)

[a] In brackets percent of headed plants in population

Table 15.4 The influence of the inhibitor of zearalenone (malathion) on the generative development of winter wheat plants. Seeds of wheat cv. 'Grana' were cultured at sterile condition on Murashige and Skoog (1962) media supplemented with 0 (control), melathion (10 ml/dm^3) and zearalenone (2 mg/dm^3) during 5 weeks at 5°C (optimal time of vernalization). After vernalization plants were replaced to soil and grown at 20/17°C. Percentage of headed plants and the length of phase from vernalization to flowering was determined for 100 plants in each kind of medium

Medium	Percent of headed plants	Length of phase from vernalization to flowering (days)
Malathion	16	74
Zearalenon	100	57
0 (Control)	72	77

Biochemical analysis indicated that the stimulation of the generative differentiation in wheat shoot apices after short vernalization, but in the presence of zearalenone was connected with an intensified emission of heat and a decrease in the value of the electric potential of the cells (Biesaga-Kościelniak 2001). Additionally, during vernalization of these plants and after vernalization, zearalenone induced changes in the composition of fatty acids in the fractions of membrane glycolipids and phospholipids. Zearalenone treatment resulted in the increase in content unsaturated fatty acids (calculated as 18:3 to 18:2 ratio). Such an increase in fatty acid unsaturation is usually a result of changes in cell membranes being exposed to low temperatures. On the other hand, zearalenone somewhat hampered the adjustment of the fluidity of the cell membranes, which was indicated by an increase in the content of campesterol and cholesterol in the seedlings. The observed dual effect of this substance on membrane composition is that it can stabilize membrane structure at low temperature, which allows specific domains located on membranes to become more prominent.

Such changes may be involved in the pathway of induction of generative development of winter plants induced by vernalization. The involvement of zearalenone in the vernalization process was suggested by Meng et al. (1996) who indicated two specific zearalenone-binding proteins (39.8 and 12.5 kDa) in the vernalized embryos of winter wheat. They postulated that these proteins might act as activators of certain genes controlling the vernalization process in plants.

The role of zearalenone in generative induction was also confirmed in photoperiodic plants (Meng et al. 1992, 1996; Fu et al. 1995, 2000), which suggests its importance in flowering stimulation. In the short-day plant *L. perpusilla 6746* and the long-day plant *L. gibba* G3, zearalenone enhanced flowering. In the day-neutral tobacco (*Nicotiana tabacum* L. cv. Samsun), zearalenone was one of the important flower stimuli and was related to the flower gradient in shoots (Meng et al. 1996). In the studies of Fu et al. (2000) a connection between zearalenone and flower bud formation in thin-cell layer explants of *N. tabacum* L was indicated. During the formation of flower buds, the authors observed two peaks in the endogenous zearalenone level, one at day 3 and the other at day 9 after the outset of the culture. The inhibitor of zearalenone biosynthesis (malathion), inhibited the biosynthesis of endogenous zearalenone and at the same time flower bud neoformation. Exogenous zearalenone application reduced the effect of malathion and stimulated flower bud neoformation.

15.7 The Effect of Zearalenone in Culture *In Vitro*

The presence of hormones (auxins and cytokinins or substances of similar action) is required for the induction, proliferation and differentiation of cells in *in vitro* cultures (Maheshwari et al. 1995). The dynamic development and the introduction of in vitro techniques to micropropagation and to the study of mechanisms of physiological processes have resulted in the need for the search for new groups of substances playing a role similar to those of plant hormones. Fusicoccine, cotynine, helmintosporine, pestalocine and some other metabolites isolated from fungi belong to this group (Muller et al. 1991).

In tissue culture of wheat and rape, the influence of zearalenone greatly resembled that of 2,4-dichlorophenoxyacetic acid (2,4-D), a synthetic analogue of auxin (Biesaga-Kościelniak 2001; Biesaga-Kościelniak et al. 2003). Zearalenone completely replaced 2,4-D or increased its effect under *in vitro* conditions. It increased the percentage of wheat calli capable of regenerating shoots by more than 2,4-D, and especially the process of effectively regenerating shoots from poorly differentiated wheat calli. Zearalenone enabled the breaking of the blockade of the regeneration of shoots from callus of winter rape cv. "Górczański". Additionally, the application of thidiazurone to theses media increased the percentage of plant regenerated from callus for both wheat and rape. Therefore, it is possible to use zearalenone as an alternative to auxin or as a supplementary hormone analogue in *in vitro* culture of plants. This could be especially important when indirect regeneration of plants via callus induction is planned (Biesaga-Kościelniak et al. 2003; Szechyńska-Hebda et al. 2007).

Moreover, zearalenone stimulated the growth of cell suspension of winter wheat and winter rape (in aqueous media) by more than 2,4-D, contributing to the increment in the volume and dry weight of cells during the culture period (Biesaga-Kościelniak 2001). In the suspension culture of wheat, the addition of zearalenone to a medium containing 2,4-D caused not only an increase in the dry weight of cells, but also an increase in the population of living cells in the culture.

The maize pollination system was used as a model to compare the activity of zearalenone with 2,4-D (Biesaga-Kościelniak 1998). Zearalenone in a concentration 50 times lower than that of 2,4-D demonstrated a similar effectiveness in stimulating the development of haploid embryos in wheat flowers after pollination with maize pollen (Biesaga-Kościelniak et al. 2003). The concentration of zearalenone (6 mM) was most effective in inducing ovary swelling (84 swollen ovaries/100 pollinated florets) and increasing the frequency of embryo induction (18.9 embryos/100 pollinated florets), but these embryos were severely deformed. They had low capability to germinate *in vitro*, while callus was easily formed and indirect regeneration of plants was possible. The results showed that zearalenone had some of the properties of an auxin analogue, while other effects of its actions were unique.

Zearalenone was also found to be more effective than cytokinin treatment in inducing shoots in *in vitro* winter wheat production. Moreover, both zearalenone and cytokinins increased the activity of antioxidant enzymes in wheat callus undergoing regeneration, and it is very likely that they also stimulated the plant regeneration process (Szechyńska-Hebda et al. 2007). The effectiveness of regeneration on media containing zearalenone shows the possibility of using zearalenone as an alternative hormone also to cytokinins in winter wheat callus culture.

15.8 Modifying Plant Growth and Yield Using Zearalenone

Our studies show that zearalenone can be used to increase the yield of wheat (Biesaga-Kościelniak et al. 2006a, b). Plants that were sprayed with zearalenone during the heading stage increased their number of grains per ear and their weight per 1,000 grains. Watering and soaking wheat grains produced even better effects in comparison to spraying (Biesaga-Kościelniak et al. 2006a). Zearalenone-treated plants had a higher number and weight per ear and weight per 1,000 grains. The reproduction of plants was also increased. The best results (yield increase) were noted for a zearalenone concentration of 4 mg/dm^3. In soybean cultivation, treating plants with zearalenone also increased their yield (Biesaga-Kościelniak et al. 2006b) (Fig. 15.3). Watering seedlings, soaking seeds and spraying plants increased the yield, the number of pods and the number of grains per pod and per soybean plants. The increase in the yield of soybean and wheat cultivars in comparison to controls (without zearalenone treatment) was 22% and 19% in terms of the number of seeds (grains) and 28% and 24% in terms of the weight of seeds (grains), respectively.

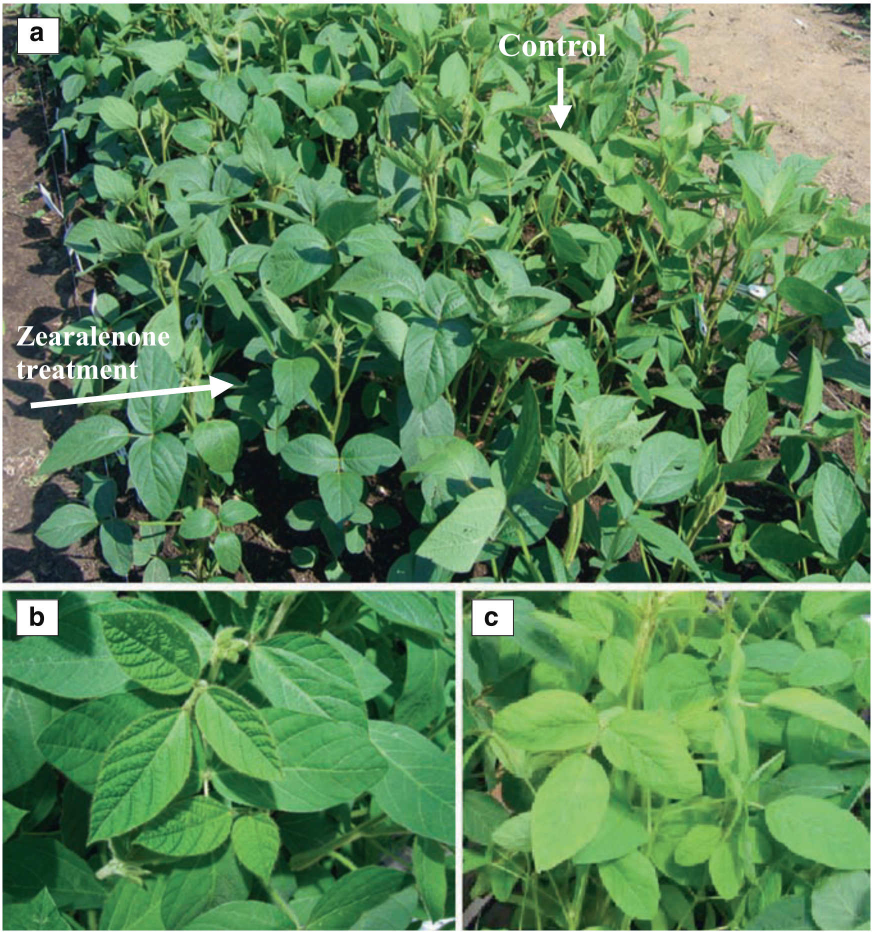


Fig. 15.3 Changes in leaves' shape and height of soybean plants after soaking of seeds in zearalenone solution. (**a**) The picture of the field with plants grown from seeds treated with zearalenone (*left* side) and non-zearalenone treated (control, *right* side). (**b**) Dark-green leaves of soybean plants which were grown from zearalenone-treated seeds. (**c**) Control plants with visible light-green leaves

The effect of zearalenone on crop development may be connected to its influence on the status and functioning of the photosynthetic apparatus (Kościelniak et al. 2008). The after-effects of zearalenone on the growth of soybean and wheat plants, net photosynthesis and transpiration rates, stomatal conductance, photochemical efficiency of photosystem 2 and on final seeds yield were determined. Modifications in leaf area were more pronounced in soybean than in wheat, and this tendency increases in successive developmental phases. The net photosynthesis was stimulated during the juvenile phase and during that of the final one by about 13.6% (average) in soybean plants. Stimulation of transpiration was also observed after zearalenone treatment on both plant species. The response of CO_2 assimilation in wheat plants was less pronounced when compared to that in soybean. Additionally, the quantum yield of photosystem 2 photochemistry in soybean plants increased rapidly after the seeds were treated with zearalenone, and was higher in wheat plants where this parameter increased constantly during whole period of growth (Kościelniak et al. 2008).

The observed effects of zearalenone action on plant development may be connected to the properties of zearalenone, as a component of mycotoxines. It is known that some stress factors (also toxic chemicals) accelerate plant development and stimulate their generative induction. However, our results (data in preparation) indicate that zearalenone may protect cells from some forms of stress. In drought, stresses induced by either NaCl or changes in water potential (poly(ethylene glycol) content), zearalenone applied in concentrations 2 and 4 mg/dm^3 decreased the inhibiting effect of both these stresses on wheat seedlings and significantly increased the dry mass and length of plants. This effect was especially visible in parts of plants aboveground where an increase of about 84% was detected. In roots, zearalenone stimulated about 42% increase in mass in NaCl conditions in comparison to the control (non-zearalenone-treated) plants. Moreover, at the water potential of −0.5 MPa, the dry mass of shoots in plant cultures treated with zearalenone was 58% higher than that of the control (0 MPa). This protective effect of zearalenone may be a result of its ability to increase the metabolism of seedlings. This effect was confirmed by calorimetric measurements, which indicated an increase in the heat energy emitted by wheat plants treated with zearalenone, where this metabolism parameter increased by about 16% in comparison to non-zearalenone-treated plants.

15.9 Conclusion

Temperature, water availability and light are key climatic factors influencing the production of *Fusarium*. In terms of manipulating environmental conditions to control *Fusarium* spp. diseases, adjustment of soil temperature and moisture has been successfully applied in many countries (Katan 1981; Doohan et al. 2003). Although zearalenone is ubiquitous and toxic, it globally presents a potential danger for animal and human health only when it is absorbed in high amounts or over a long period of exposure (Zinedine et al. 2007). Small amounts of zearalenone act as stimulating factors for plant development, and can serve as plant hormone in induction of physiological processes. Thus, low zearalennone concentration in growth media may be useful to stimulate development of crops and to accelerate the flowering of winter plants, which can be an important factor in agriculture production in changing environmental conditions. A particularly interesting question for future research is the possibility of determining the optimal zearalenone concentration in soil (and in crops) to balance the toxic and favourable action of this substance on both plant development and animal health.

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Chapter 16
Homestead Agroforestry: a Potential Resource in Bangladesh

M. Giashuddin Miah and M. Jahangir Hussain

Abstract Homestead, the home and adjacent grounds occupied by a family, is the potential production area in Bangladesh, especially for the resource poor group. Homestead production system is popularly called homestead agroforestry or home gardening. It is the integrated production of crops, trees, and livestock in the household's residence and its surrounding areas. It has been playing an important role in the rural economy of Bangladesh since time immemorial, and providing various essential products and services to millions of rural households. But it receives little attention of the researchers for maximizing the production. This review article highlights the resources and contribution of the homestead to draw attention of the researchers and planners for scientific interventions. The size and structure of homesteads are linked to economic, social, and ecological factors. The homesteads are generally small in size but numerically they are increasing steadily with population. Population pressure and subsistence economy have forced the households to utilize all the sites of a homestead as individual production units. It combines all farming components and forms a highly intensive and multi-strata integrated production system depending on household needs, preferences and knowledge. The homestead agroforestry provides multiple products to the household and meets the diversified needs including food, nutrition, and energy securities, producing a wide variety of fruits, vegetables, and tree products. It also contributes to household income and saving through sales of vegetables, fruits, and other tree products, and to the creation of employment opportunity particularly for the women. Collectively, homestead production system contributes about 70 percent fruit, 40 percent vegetable, 70 percent timber, and 90 percent firewood and bamboo requirement of the

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M.G. Miah (✉)
Department of Agroforestry and Environment, Bangabandhu Sheikh Mujibur Rahman
Agricultural University (BSMRAU), Gazipur, 1706, Bangladesh
e-mail: giashbd@hotmail.com

M.J. Hussain
Livelihood Program, Save the Children, Dhaka, Bangladesh
e-mail: jahangir@dhaka.net

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country (Miah and Ahmed, 2003). Although there is more fascination to planting fast-growing timber species, fruit trees still dominate over other trees. The small farmers tend to plant more trees per unit area. Homesteads serve as the home for biodiversity conservation, which is a serious ecological issue in Bangladesh. They are also used as processing centers for the poor households. Homestead, being the residential part of a household, enables the women, who constitute almost half of the labor force in Bangladesh, to efficiently manage homestead activities. Planting improved plant species, optimum management of the resources, efficient processing, and marketing of the products could contribute significantly to the livelihood of the poor.

Keywords Employment • Homestead agroforestry • Income • Multiple products • Nutrition • Women empowerment

16.1 Introduction

Bangladesh is the most densely populated developing country with a very low per capita arable land (0.06 ha), forest land (0.02 ha) and annual income (US$ 544). It made a tremendous stride to ensure self-sufficiency in cereal food and made considerable progress. Despite the impressive gains in cereal production, about half of the population still lives in absolute poverty level and about 25% live in hard-core poverty level (MoA-UNPD 2000; FAO 2005). According to FAO (2005), about 30% of the population of Bangladesh consumes fewer than 1,800 kcal/day, where the person of the other developing countries consumes average 2,828 kcal/day. The inadequate access of the poor to protein, vitamin, and mineral rich food items is the main reason for such situation. Homestead agroforestry/gardening, and especially the production of horticultural crops, can perhaps most effectively help ensure food and nutritional securities in addition to self-employment, poverty alleviation and income generation of poor farmers. Human life had begun with gardens, and the fruits, vegetables, and roots that grew therein; man's livelihood on the earth had commenced with a collection of whatever products the trees and other plants of that time had borne – fruits, roots, leaves, shoots, and seeds (Ahmad 1995).

Homestead agroforestry refers to intimate association of multipurpose trees and shrubs with annual and perennial crops, and, invariably, livestock within the compounds of individual houses, with the whole crop–tree–animal unit being managed by family labor (Fernandes and Nair 1986). It is the most complex multi-strata integrated production system that combines all farming components (tree, crop, livestock, and occasionally fish) and provides household food security, employment, and income generation opportunity to the millions of households (Miah and Ahmed 2003). It evolved through generations of gradual intensification of cropping in response to increasing human pressure and the corresponding shortage of arable lands (Kumar and Nair 2004). Homestead agroforestry is an integral part of the livelihood strategies of rural households and, so far, the most ancient system of production in Bangladesh, regardless of ecosystems. Historically, households have been planting vegetables, fruits, and forest species, and rearing livestock in their homesteads at various micro-sites with a view to meet their various daily requirements. This is a supplementary food production system, which is under the management and control of household members, particularly the womenfolk.

Homestead agroforestry system provides nearly 50% cash flow to the rural poor (Ahmed 1999). Collectively, homestead agroforestry production system contributes about 70% fruit, 40% vegetable, 70% timber, and 90% firewood and bamboo requirement of Bangladesh (Miah and Ahmed 2003). In addition, the homestead plantations are recognized repositories of non-timber products such as medicinal and aromatic plants, ornamentals, bamboos, khair, lac, honey, cane, murta plants, and grasses.

Another significant feature in homestead agroforestry is the active involvement of women. They play a major role in managing the homestead production apart from food preparation and other domestic activities of the family. Due to the ancient and proven contribution to the household food, nutritional and energy security, income generation, and women's empowerment, homestead agroforestry has been incorporated into the economic and social development strategies of Bangladesh (Talukder et al. 1997). The Government and relevant non-governmental organizations (NGOs) have included homestead development programs for improving homestead production and income, particularly involving poor groups and women.

The objective of this review article is to summarize the current structure, configuration and utilization pattern of homesteads; species diversity and its changing pattern; and major functions towards household benefits with a view to visualize its importance and potential for future development. This objective has been addressed through examining the available published and unpublished information and incorporating the long experiences of the authors.

16.2 Homestead in Bangladesh

The country consists of 68,000 villages and each village contains about 268 homesteads (BBS 2005). It is the center of socioeconomic activities and traditional cultural heritage of villages in Bangladesh. Homesteads are multipurpose entities with dwellings, vegetables, spices, fruits, and fuelwood/timber species (Fig. 16.1). The homesteads the people live in are locally known as "***Bari***," which occur in linear, cluster, or individual pattern (Hussain and Miah 2004). Homesteads are perhaps the most important production unit in Bangladesh, with about 25.36 million of these in the urban and 21.90 million in the rural areas (BBS 2001). These homesteads occupied about 0.54 million hectares of land (BBS 2001) and this figure is increasing at the rate of 5 m^2/ha/year (Anam 1999). The average size of the rural homestead is very small, which varies widely according to region and socioeconomic status of the households. Basak (2002) studied homesteads at different ecological zones in Bangladesh and observed that the average homestead sizes for the landless, small, medium, and large farmers were 0.097, 0.348, 0.486, and 0.850 ha respectively. He also reported that the homesteads and their vegetation in saline (0.36 ha)

Fig. 16.1 Homestead – a source of multiple products (trees, vegetables, cows, chicken)

(southwestern part) and hill (0.53 ha) (eastern part) regions are relatively larger in size compared to dry land areas (0.26 ha) (north western part) due to socioeconomic and climatic advantages. There exists a positive relationship between the farm size and homestead area, i.e., larger the farm size, larger the homestead area (Bashar 1999; Anam 1999; Ahmed 1999; Basak 2002). Depending on the locations, the homestead is raised above the flood level from the surrounding fields.

Generally, a homestead possesses at least a living room, a kitchen room, and a few tree species. Besides, there are some vacant spaces for different production purposes. A typical homestead accommodates a single or several houses of single or joint families and a space for vegetable gardens, a yard for threshing ground and communal activities, a cattle shed, ponds, trees, shrubs, and bamboo (Khaleque 1987; Abedin and Quddus 1990; Haque 1996).

A typical homestead or ***Bari*** consists of different sites. Hussain and Miah (2004) have categorized it into five micro-sites: approach road – a passage or gateway leading to the homestead; front yard – the place connected to the approach road or the outer part of the homestead connected with the approach road; home yard – the open place in front of the living room; backyard – the site behind the household or interior place of the homestead; boundary – the borderlines or demarcation lines of a homestead. These micro-sites represent the smallest production units of the home gardens that provide the opportunity to produce diversified products needed for the households for its own consumption and for cash income. However, a homestead may not have all micro-sites and the number of micro-sites usually depends on the size and location of the homestead.

16.2.1 Homestead Configuration and Utilization

Recent studies and analyses (Hussain 2002; Hussain and Miah 2004) have shown that the homestead production system has been developed based on different micro-sites. In fact, the micro-sites represent the smallest production units having similar configuration of land and serve specific purposes. The strong argument in favor of this subdivision is that the homestead is not a homogeneous system and what may be suitable for an approach road may not be suitable for a backyard, and, similarly, the uses that are feasible along the boundary may not be feasible at the home yard. This makes new thinking and orientation for the researchers, academicians and development workers to divide the homestead into several production units, i.e., micro-sites. However, in any type of homestead, even with a landless group of farmers having only the homestead land, a set of micro-sites is recognizable. These are recognized as approach road, front yard, home yard, backyard, boundary, and sometimes pond site depending on its availability (Hussain and Miah 2004). Experiences with the Small Farmer Agroforestry Development Program under GTZ (German Technical Cooperation) in the northwestern part of Bangladesh have shown that the micro-sites approach of homestead agroforestry production opens new potentials and opportunities even for the innovative/progressive farmers (Miah and Hussain 2003). The brief characteristics of the different micro-sites and their utilization as described by Hussain and Miah (2004) are as follows.

16.2.1.1 Approach Road

The approach road is the gateway towards every homestead, which is either short or long, or narrow or wide. Some homesteads have their individual approach road while homesteads comprising several households in a cluster use have a common approach road. The size and shape of the approach road vary from homestead to homestead. However, whatever the size and shape, the approach roads generally have both sides unplanted or in some cases may have some trees on one or both sides (Fig. 16.2). Occasionally, one may find approach roads having systematic plantation with diverse plant species. However, a well-designed plantation with diverse floristic compositions eventually forms multi-strata/layers configuration, which may provide diversified products and services throughout the year.

16.2.1.2 Front Yard

The front yard is the external part of the homestead, usually connected with the approach road. It is generally wide, leveled, often compact, and usually unfertile. The size of the front yard varies depending on the type of the households. The landless poor or marginal groups' households normally have a very small front yard and they grow seasonal vegetables either on the ground or on the trellis or on both, and plant few fruit trees, palms, etc. (Fig. 16.3). The small and medium-size households have a relatively

Fig. 16.2 Approach road, entrance way to a home having various tree, shrub and herb species

Fig. 16.3 Front yard of a homestead growing various types of vegetables and fruit trees

larger front yard and keep it mostly vacant for using as farmyard for processing of agricultural crops including making straw heaps for the cattle, and for planting some part with few fruit and fodder trees, palms, vegetables, etc. However, there is no standard or systematic design of plantation and other uses matching the front yard size, which could optimize homestead production and utilization of front yard.

16.2.1.3 Home Yard

The open space available in front of the living room is the home yard (locally known as Uthan), which is generally leveled, compact, and less fertile. It is used for multiple purposes including usually cooking, post-harvest activities such as rice threshing, winnowing, parboiling and drying, and processing of non-wood forest products, and partly for cattle shed (Fig. 16.4). Yoshino (1996) added that the home yard is commonly used for raising cattle, goat, chicken, geese and pigeon. Non-agricultural households sometimes plant a large number of fruit trees along with timber and ornamental plants. However, most home yards possess few fruit trees that cover less space (such as lemon, pomegranate, and papaya) and creeping vegetables grown on the roofs, tree support, or on the bamboo trellis. In addition, shade-tolerant vegetables and spices are grown under the trellis or under the trees.

16.2.1.4 Backyard

The backyard is the most interior place of the homestead, usually having the kitchen garden/mini garden of the household. It is generally covered with densely grown vegetation, providing timber, fuelwood, fruits, nuts, vegetables, and spices (Fig. 16.5). Sometimes, climber-type plants, especially vegetables and medicinal plants, are grown using the trees as support. It is also used for rearing cattle and goats.

16.2.1.5 Boundary

Boundary is the outer border or demarcation line of a homestead that makes it an independent unit. It is the most common and developed segment of a homestead, which is either narrow or wide. Homesteads located side by side may have common boundaries while isolated homesteads generally have separate boundaries (Fig. 16.6). Commonly, different types of trees, shrubs, and herbs are grown either in a single row or in double rows along the boundaries. However, a well-planned boundary plantation in view of spatial arrangement with multifunctional species leads to a green belt that eventually protects the homestead from different natural hazards and acts as a productive unit that significantly contributes to the food, energy, and economic security of the household. Privacy of homestead is an important objective as well. Besides protective and productive functions, a well-decorated plantation may have aesthetic and beautification values.

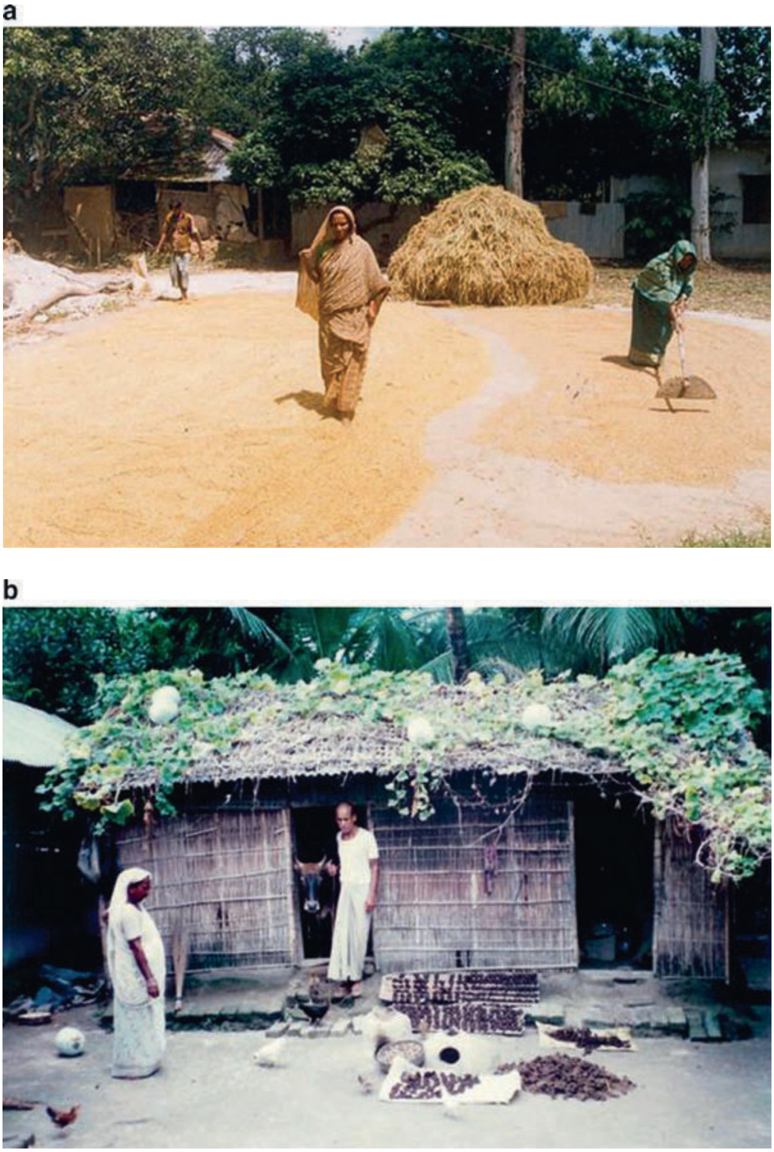

Fig. 16.4 (**a** and **b**). Home yard – a place for crop's post-harvest activities and vegetable production

16.2.2 *Spatial Arrangement of Vegetation*

The homestead irrespective of ecologically distinct locations has a multilayered spatial arrangement of vegetation (Fig. 16.7). Vegetation layer varies from homestead to homestead, which may usually range from three to five (Yoshino 1996; Ahmed 1999; Bashar 1999; Basak 2002; Hussain and Miah 2004) and even up to

Fig. 16.5 Backyard of a homestead with vegetables, fruit, and timber species

Fig. 16.6 Homestead boundary having trees and shrubs with varying canopy structures

six (Millat-e-Mustafa et al. 1996). The first layer is within 1 m height from the ground and is composed of vegetables, tuber crops, and other herbaceous plants. Shade-tolerant plant species like pineapple, turmeric, ginger, taro, etc., belongs to this stratum. The second layer (above 1–5 m) and third layer (5–10 m) are almost continuous and overlapping. Banana, papaya, lime, lemon, guava, pomegranate,

Fig. 16.7 Spatial arrangement of vegetation in a homestead showing 5–6 different layers of plant species

drumstick, jujube, carambola, lotkan, olive, amloki, and other medium-sized trees form these layers. The fourth layer (10–16 m) is composed of medium-tall-sized fruit and forest trees such as jackfruit, mango, litchi, betel nut, hog plum, ghoraneem, arjun, koroi, shimul, kadam, etc. The fifth and the topmost layer (above 16 m) is composed of tall trees such as palmyra palm, coconut (tall variety), jamun, eucalyptus, tetul, and rajkori.

16.2.3 Species Diversity/Richness

Species or plant diversity varies from place to place and are largely influenced by the ecological and socioeconomic factors. It varies among the homesteads even within the similar ecological and socioeconomic groups depending upon individual needs and preferences. The plants grown in the homesteads are broadly classified into food (fruits, vegetables, spices), timber (timber and fuel wood), medicinal, and ornamental species. Irrespective of homestead size, farm category, and location, food/fruit producing species dominate over any other functional groups followed by timber, ornamental and medicinal species (Millat-e-Mustafa et al. 1996; Bashar 1999; Basak 2002). Bashar (1999) in his study conducted at the central part of Bangladesh (Gazipur district) identified a total of 105 useful species in homestead in which 44 were recorded as food/fruit species either perennial or annual, 28 timber, 15 medicinal and 18 ornamental. Similarly, Basak (2002) in a recent study covering 15 different districts of four distinct ecological regions of Bangladesh identified 105 tree species and 27 herbaceous species (vegetables and spices).

Fig. 16.8 A part of homestead comprising a wide range of tree, shrub, and herb species indicates species richness

Among 105 tree species, 42 were perennial and annual fruits, 31 forest trees (timber and fuel wood), 7 medicinal and 22 ornamental/aesthetic species. Across the regions, a relatively higher number of species per homestead were recorded in southwestern and eastern regions, while a smaller number of species was found in the northwestern region (Millat-e-Mustafa et al. 1996; Basak 2002). The household's maximum efforts are mainly centered upon the homestead as their livelihood since their crop field remains under water most of the year may be attributive to the relatively higher species richness in southwestern region (Fig. 16.8). On the other hand, the species richness in the eastern part (hill districts) could be due to favorable climatic (high rainfall and moderate temperature) and soil (good drainage system) conditions and relatively less human interferences. Relatively lower species richness in northwestern region might be due to adverse climatic condition (low rainfall), poor soil fertility, and economic hardship of the households.

16.2.4 Change of Tree Plantation Pattern over Time

Growing of different types of tree species (fruit, timber and fuel wood, medicinal, and aesthetic species) over time has been changing gradually. The fruit trees dominated much more over timber trees a few decades ago but the gap between them has diminished over time remarkably. A recent study conducted across the country showed that about 50 years ago, proportions of fruit and timber trees were 86% and 7%, respectively, which are now closer to 60% and 34%, respectively (Basak 2002).

In the same period, the proportion of medicinal plants decreased from 3% to 1%. The author also reported that such trends have been noticed in case of resource poor farmers as compared to rich farmers. The relatively quick returns from the multipurpose tree species might influence the resource poor farmers for planting more timber and fuelwood species. Anam (1999) reported that during the last 10 years, planting of jackfruit (*Artocarpus heterophyllus*), guava (*Psidium guajava*), jujube (*Zizyphus jujube*), drumstick (*Moringa oleifera*), pomegranate (*Punica granatum*), and lemon (*Citrus* spp.) had increased both in peri-urban and rural areas, while proportion of palmyra palm (*Borasus flabellifer*), date palm (*Phoenix sylvestris*), jamun (*Syzygium cuminii*), etc. reduced drastically. Of the forest species, akasmoni (*Acacia auriculiformis*), mahagoni (*Swietenia mahogoni*), sissoo (*Dalbergia sissoo)*, eucalyptus (*Eucalyptus cameldulensis*) and koroi (*Albizzia lebbeck)* were not usually planted in the homesteads 10 years ago, but recently their plantation has been intensified, whereas the population of indigenous species like pakur (*Ficus infectoria*) and shimul (*Salmalia malabaricum*) have reduced gradually during the same period. This is an indication that farmers are more interested in multipurpose trees having timber and fuel values.

16.2.5 Mode of Plantation

Tree plantation in homestead by the households is influenced by either demand of the tree (demand-driven) or supply of the planting materials (supply-driven) or both. A recent finding across the four ecological regions of Bangladesh showed that about 48% plantations were demand-driven, 42% supply-driven, and 10% both demand- and supply-driven (Basak 2002). He also found a distinct variation in the mode of plantation by farm categories, where demand-driven mode of plantation increased with the increase of farm size, while supply-driven mode of plantation increased with the decrease of farm size. The findings indicated that poorer group of farmers were guided by supply-driven mode because of their poor socioeconomic status, while the larger group of farmers were guided by demand-driven mode because of their better financial capacity to buy the demanded ones. Therefore, homestead of resource poor farmers may be enriched with economic plants if the supply of desired planting materials could be made available at a cheaper price.

16.3 Functions of the Homestead Agroforestry

16.3.1 Homestead Agroforestry – A System for Multiple Products

Historically, homestead agroforestry production system has been providing multiple products to the households and meeting their diversified need through the production of a wide variety of fruits, vegetables, spices, and different tree products (Miah et al. 2002). The prevailing climatic and edaphic conditions of Bangladesh are the key factors for providing such a unique opportunity of producing a wide range of products (Fig. 16.8). It has been reported that homestead production system collectively contributes about 70% fruits, 40% vegetables, 70% timber, and 90% firewood and bamboo requirement of the country (Miah and Ahmed 2003).

16.3.1.1 Fruit

Homesteads, regardless of ecological and socioeconomic diversities, own at least a few fruit crops. Fruit crops cover an area of about 100,000 ha, nearly 80% of which are grown in home gardens (MoA-UNPD 2000). MoA-UNDP further reported that 43 fruit crops were grown in a wide diversity of soils and climates of Bangladesh. Among them, the predominant fruit crops are mango (*Mangifera indica*), jackfruit (*A. heterophyllus*), banana (*Musa* spp.), papaya (*Carica papaya*), coconut (*Cocos nucifera*) and betel nut (*Areca catechu*). The other commonly found species are citrus (orange, mandarin, grape, lime, and lemon), star fruit (*Averhola carambola*), jujube (*Z. jujube*), jamun (*S. cuminii*), guava (*P. guajava*), litchi (*Litchi chinensis*), pomegranate (*P. granatum*), woodapple (*Aegle marmelos*), olive (*Elaeocarpus floribundus*), latkan (*Baccaurea sapida*), palmyra palm (*B. flabellifer*)**,** Hog plum (*Spondias pinnata*), etc. Similar information have also been recorded by Basak (2002) who identified 42 fruit species either perennial or annual in homesteads in 15 districts under four distinct ecological zones (Dry land, Plain land, Hill, and Saline area) of Bangladesh. He also found a wide variation among the locations where the highest number of species was observed at Saline area (34 types) and the lowest in Plain land (12 types). Similarly, several regions specialized in certain fruit crops such as banana in Narsingdi and Jessore, mango in Chapai Nowabgonj and Rajshahi, jackfruit in Gazipur and Chittagong, pineapple in Chittagong and Sylhet, betelnut in Barisal and Rangpur regions, hog plum in Barisal are also reported (MoA-UNPD 2000). Generally, the people who live in remote villages are poor and pay more attention to growing fruit trees in view of getting both fruits and timber/fuel wood from the same species (Fig. 16.9). Most of the fruits produced in homesteads are consumed at domestic level. A study carried out at the Old Brahmaputra floodplain areas of Bangladesh showed that a total of 285 kg fruits were collected from trees and shrubs annually from a homestead of which the maximum portion (244 kg fruit/year) was consumed by the household (Miah and Sadeq 2003). Generally, the rich group of farmers consumed the maximum amounts of fruits by themselves as compared to the poor group of farmers. As the poor group belongs to subsistence livelihood, they have to sell maximum portion of fruits for earning cash to meet the other needs of the families.

16.3.1.2 Vegetable

Like fruit crops, vegetables, which are recognized as nutrition givers of the highest order, are grown in Bangladesh mostly in homesteads from time immemorial. As in the case of fruits, vegetables belong to the group of “protective foods,” which

Fig. 16.9 (**a** and **b**) Part of homestead having a wide range of fruit trees

provide essential vitamins and minerals (Tsou 1992). The land of Bangladesh has a unique opportunity where a large number of diversified vegetables are grown. About 60 different vegetables of indigenous and exotic origin are grown mainly in homestead and flood-free lands (MoA-UNPD 2000). Based on growing seasons, vegetables are categorized into summer/rainy season, winter, and all-season types. Summer vegetables covering an area of 94,000 ha and winter vegetables covering 154, 000 ha are cultivated mainly in homesteads (MoA-UNPD 2000).

Homestead gardening, especially vegetable production is an important household activity contributing to both economic welfare and family diets (Helen Keller International 2001). Vegetables are produced either for commercial purpose or for home consumption. Commercial gardens are often relatively large in size but encompass a fewer number of species, sometimes just one vegetable in the entire season such as pulwal (*Trichosanthes dioeca*). The homestead gardens are usually small in size but encompass a variety of vegetables depending upon farmer's choice for year round production (Fig. 16.10).

An intensive homestead vegetable production model involving 14 vegetables (known as Kalikapur model) proved very effective in proper utilization of the underutilized homestead space, increasing vegetable consumption by the resource-poor farmers, alleviating family nutrition, and involving women and children (Chowdhury et al. 1992). The model was extended to 20,000 homesteads, mostly among the landless and marginal farmers, in 135 thanas of 54 districts across the country (Hossain 1995). A new system suitable for southern part of Bangladesh (saline area) was suggested (Ahmad 1995). This involved digging of mini pond and growing herbaceous and bushy vegetables on their banks and creeping vegetables (such as bitter gourd, bottle gourd, and hyacinth beans) placed on trellis over the pond area as well as cultivating fish inside the pond. This system was found profitable for both

Fig. 16.10 Extended part of homestead having vegetables in a multistory garden

the poor and the middle-class farmers. Miah and Sadeq (2003) identified 14 vegetable species cultivated in the homestead of Old Brahmaputra floodplain areas of Bangladesh most of which are grown in the winter season. They also reported that a family could collect 183 kg of vegetable per year from the homestead of which the major portion was consumed. Results from a pilot program at 290 demonstration plots across the six districts in the northern part of Bangladesh showed that homestead vegetable gardening supplied 267 kg of vegetables in the first year (1997) and 540 kg of vegetables in the second year (1998) from an area of 100 m^2 of land against the requirement of 432 kg for a six-member family (Samsuzzaman 2002). A substantial amount of revenue was earned from the sale of vegetables, which made a supplementary source of income in the subsistence livelihood.

16.3.1.3 Spices

Spices are the essential ingredients in the daily diet/curry. Daily per capita consumption of spices at homestead level in rural areas is about 1 g (MoA-UNPD 2000). Its total demand is increasing in cognizance with the increase of population. The important spices crops are chilli (*Capsicum* spp.), onion (*Allium cepa*), garlic (*Allium sativum*), turmeric (*Curcuma longa*), ginger (*Zingiber officinale*) and coriander (*Coriandrum sativum*). All these are grown throughout the country especially in homestead agroforestry system (Fig. 16.11) though yield levels vary across the locations. Generally, resource-poor and small farmers are the main producers and earn cash income in addition to their own consumption. The greater opportunity of producing spices especially turmeric, ginger, chilli, and coriander in homestead level is the genetic ability of those species to grow under shade provided by different types of trees, and trellis made for growing other vegetables. Research findings showed that turmeric, ginger, aroid, and coriander could grow successfully under 50% shade (Miah et al. 2001, 2003; Moniruzzaman 2004), aroids and chili under 30–40% shade (Miah et al. 2003), while onion can grow well under 25% shade level (Miah et al. 1999). However, all these spices have high demand and market price, but returns per unit area are low due to poor yield levels and lack of processing/storing capacity. If the production and processing levels could be improved, these spice crops would earn more income and contribute greatly in import substitution and export.

16.3.1.4 Fuel Wood and Timber

Fuel wood is the principal energy source in Bangladesh in spite of the rapid growth in the commercial energy sector. Shortage of fuel wood and timber has raised serious concerns in Bangladesh in recent years. Thousands of poor families in rural areas have been forced to reduce the number of cooking meals, especially in rainy seasons (Abedin and Quddus 1990; Miah et al. 1989). Many households are meeting their immediate fuel wood and timber demand by cutting the immature trees. Farmers use dried cow dung cake and most crop residues as domestic fuel instead of recycling them in the crop fields. This is leading to rapid decline in soil fertility of agricultural lands

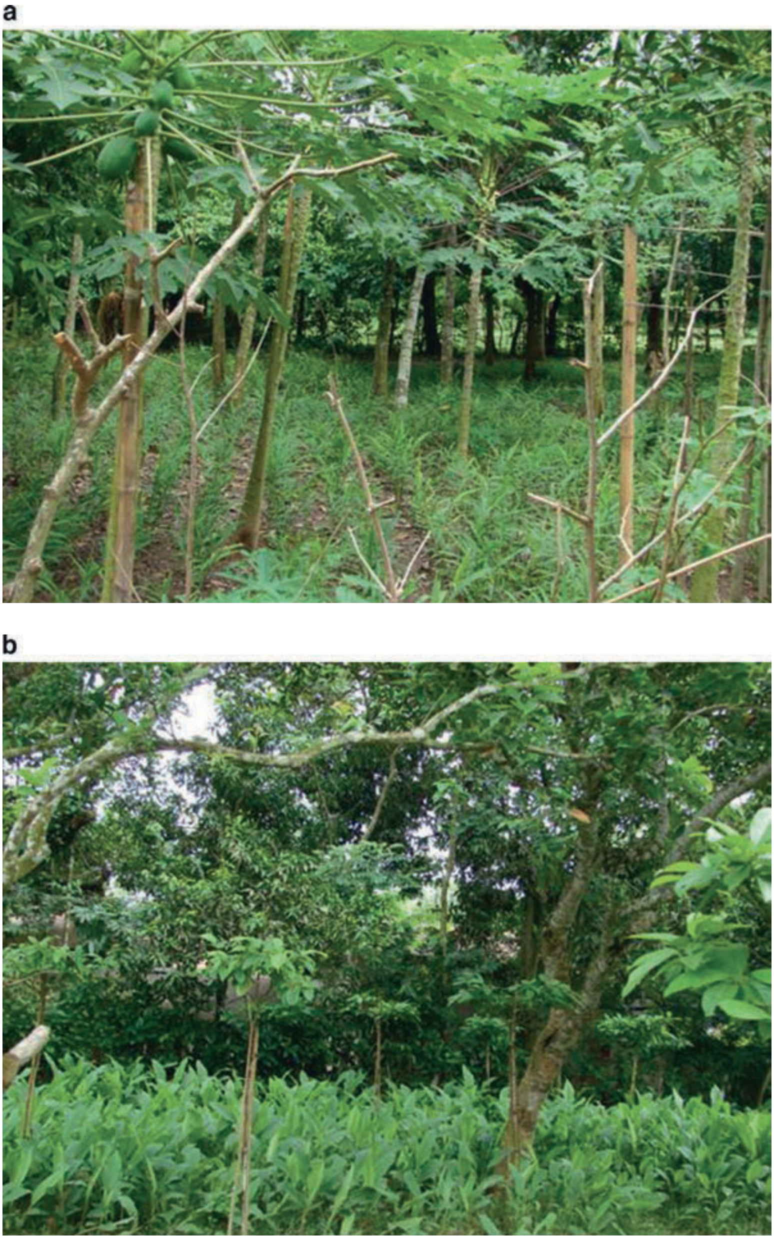

Fig. 16.11 (**a** and **b**) Parts of homestead having spices at understory of a multiple garden

(Sharifullah et al. 1992; Miah et al. 2002). This situation arises due to overwhelming population pressure and poor forest resources. The forest resources, which are inadequate to meet the national demand of forest products, are still shrinking at an alarming rate of 3.3% annually, and consequently severely threatening energy security and quality of life (Miah et al. 2002). Fortunately, tree resources grown in the homestead are acting as a prime source of fuel wood and timber in addition to supply of fruits and other products. In fact, homestead has been supplying about 80–90% of total requirement of fuel wood and timber for a long time (FAO 1982; Haq 1986; Abedin and Quddus 1990) and its contribution is increasing as the supply of forest products are decreasing. Over 80% of traded wood produced in Bangladesh are derived from homesteads and other plantings on village land production. This is estimated to amount to over 5 million cubic meter or Tk 20 million taka (US$1 = Tk 60) per year – the majority from smallholdings (Intercooperation 2000). The jackfruit, jamun, mango, and many other fruit and timber species are the principal sources of timber and fuel wood (Miah et al. 2002), while bamboo, coconut, betel nut, palymra palm, etc. also provide useful building materials for the rural households (Torquesbiau 1992; Basak 2002; Miah and Ahmed 2003). Trees also provide farmers with materials for fence posts, poles, farm implements, and household furniture. Quddus et al. (1989) reported that homestead-grown trees are used as the industrial raw materials in pulp and paper mills, hardboard mills, and in match factories. In the match industries, *Anthocephalus cadamba, Alstonia scholaris,* and *Trewia nudiflora* are used for splint making. The standing trees are purchased and sometimes they are kept standing for sometime if the purchaser comes from the same locality, or they may be harvested as early as possible. In poverty-stricken situations or in the off-season, the price of trees goes down, and the traders take advantage of that situation and buy trees from the farmers and harvest at their convenient time. Fuelwood marketing continues throughout the year, though during the dry season bulk quantities are sold when the commercial activities such as brick making, lime processing, tobacco curing, gur making, etc., take place. During the dry season the traders usually build up their stocks for the coming wet season when the demand for wood fuel is very high for domestic cooking (Hussain 1995). Recent investigation stated that tree-planting pattern has been changed from fruit tree plantation to quick growing fuel wood and timber species in cognizance with own demand and high market prices (Anam 1999; Basak 2002).

16.4 Homstead Agroforestry– A Source for Nutrition, Employment, and Biodiversity Conservation

16.4.1 Homestead Agroforestry – An Excellent Source of Nutrition

Nutritional problem is the key issue along with food security in Bangladesh today. A small percentage of the people have access to nutritious food, whilst the majority is forced to survive on subsistence diets that are unbalanced and devoid of essential food ingredients (MoA-UNPD 2000). Generally, landless and marginal farmers are at

Fig. 16.12 Fruit, sugarcane, vegetable, poultry, and livestock are in a homestead, which provide nutrition to the household

more risk nutritionally than larger households. These households have lower per capita grain availability and higher rates of child malnutrition (Talukder et al. 1997).

Of all the options available to tackle national malnutrition problem, the most practical and sustainable option would be to promote both cultivation and consumption of horticultural crops (fruits, vegetables, and spices) that could provide basic requirement of the essential vitamins and minerals (Fig. 16.12). Production of horticultural crops especially vegetable and fruits may well be the answer to the potential problems of hunger and malnutrition in Bangladesh (Javier 1992; Ahmad 1995). Daily intake of two spoonfuls – about 30 g of colored leafy vegetables can protect a child from vitamin-A deficiency (Hussain 1992). Homestead agroforestry in Bangladesh provides an excellent opportunity for farmers to produce a wide range of horticultural crops. These crops are ideal for the homestead (Talukder et al. 1995). All micro-sites of homestead from home yard to kitchen garden, and even roofs of houses help diversify household's diet through the production and consumption of some of the vegetables they produce (Miah and Hussain 2003). Dietary supplies from home gardens in studied areas in Bangladesh accounted for 3–44% of the total calorie and 4–32% of the protein intake (Torquesbiau 1992). Homestead agroforestry of Hellen Keller International in Bangladesh has been found effective in increasing the production and consumption of vitamin A-rich plant foods and in increasing the diversity of the diet, while one half of preschool-aged children and pregnant women of those countries are affected by micronutrient malnutrition (Helen Keller International 2003). Therefore, it is imperative that effective efforts are to be made for producing more fruits and vegetables through intensification of their homestead production system if severe malnutrition is to be overcome.

16.4.2 Homestead Agroforestry – A Platform for Employment and Economic Security

A vast majority of rural people in Bangladesh who cultivate land for crop production remains unemployed for a considerable period of the year because of seasonality of production activities and labor requirements. Homestead farming is the best answer to such unemployment situation through both vegetable growing, and culture of quick growing fruits enabling the people to remain employed round the year (Ahmad 1995). It has been found that over the decades, small-scale homestead activities have become the most significant income generating activities of poor households (Fig. 16.13). For example, over 5 million people in Bangladesh live in the riverine sand and silt landmasses (known as char in Bengali). These areas are highly prone to sudden flooding and erosion of land, and makes living in the chars hazardous and insecure. The Helen Keller International's homestead food production program was found to provide support to the fragile livelihood in the chars and improved the well-being of the entire household by promoting low cost technologies for gardening and livestock raising, improving food security and dietary practices, providing employment for women and a source of income for the household (Helen Keller International 2003). *A. heterophyllus* (jackfruit) based system (a century old homestead production system in Bangladesh particularly in terrace ecosystem in the central part and hill ecosystem in east and southeast part) provides diversified outputs to the growers. The jackfruits are consumed almost as the main food during the main harvesting periods (July–August) and the seeds are used in various cooked forms (Miah and Ahmed 2003). In addition, nonedible

Fig. 16.13 A homestead showing an excellent area of employment and income for the household

portion of the fruit and green leaves are fed to cattle and goats; its wood is used for making all kinds of household furniture. During the season, almost all members of the family remain busy with harvesting, transportation, and marketing of fruits. In addition, thousands of peoples are also involved in transportation and marketing of jackfruit as usual business during the season. Similarly, latkan (*B. sapida*) based production system, which is predominant in flood free areas of Narsingdi district and in hill districts, where farmers were found to earn significant amount of cash income annually. A high benefit-cost ratio (4) and internal rate of return (51%) was reported from a recent study at Narsingdi area (Alam 2004). Like jackfruits, hundreds of people are involved with the production and marketing of Latkan (*B. sapida*) fruits.

16.4.3 Homestead Agroforestry and Management – A Key Employment Opportunity for the Women

Women, the vulnerable group of the society and half of the country's population, have a great opportunity for self-employment in the income-generation activities through the practice of vegetable and fruit production in the homestead. Homestead agroforestry activities are keeping busy the entire households particularly the women who have minimum opportunities to be involved with other than homestead activities and ensuring the economic security especially to the poorer. The possibility of gender equality for participating in home garden management and sharing of benefits is perhaps one of the major stimuli for continued household food security enjoyed by home gardeners (Kumar and Nair 2004). Homestead being the dwelling place, enables the women for efficient management of homestead activities. Use of family labor, especially women labor, in the production process not only satisfies a wide range of domestic needs more economically but also ensures lowering of production costs and ultimately promotes more income. Average return per decimal of homestead land is far more than that of large farm households, possibly due to the more intensive labor inputs on the part of women in poor households (Ahmad 1995).

In Bangladesh, women were once mostly involved in the household activities particularly in taking care of children and other family members, preparing and serving food to members of the household. But the scenarios have changed gradually as the women are now becoming the potential producer of the of homestead products in Bangladesh (Fig. 16.14). Women are deeply involved in the process of homestead farming from sowing to harvesting, processing and marketing of products (Chowdhury et al. 1992; FSES 1999). Although every member of the family has some contribution in homestead farming, the major labour input is contributed by women (Sultana 1993). Their roles vary widely depending upon the socioeconomic and religious factors. It has been shown that female labors of landless families gave the maximum time compared to other categories of families (Nessa et al. 1998). They spend about one fourth of their total time in homestead production activities and increase family income (Ali 2003). Generally, women with their

Fig. 16.14 A woman engaged in homestead gardening, besides household activities

various homestead production activities such as seedling raising, small-scale animal, poultry rearing, etc., increase family income (Akther 1990). It has been reported that women earned Tk 18,160 (US$1 = Tk 60) annually from homestead farming by spending about 20% of their total time (Miah and Parveen 1993). Although, women play significant role in homestead production and management, still there remains immense opportunity for improvement of homestead production by enriching their knowledge and skill. Women, therefore, need to be empowered in skills and knowledge that will enable them to more active and meaningful participation in the homestead production activities.

16.4.4 Homestead Agroforestry – A Pathway for Plant Biodiversity Conservation

Plant biodiversity is the plant genetic wealth of a country or an area. Bangladesh once was endowed with thousands of diverse species, but its rich biodiversity is on the verge of rapid decline, because the current rate of extinction of different species is many times faster than what it would have been through the natural process because of rapid depletion of natural forest coverage and mono-cropping with high yielding and hybrid varieties. Presently, loss of plant biodiversity has been considered as one of the most pressing ecological and development issues in Bangladesh. Khan et al. (2001) made a comprehensive work on threaten plant species of Bangladesh and listed 106 vascular plant species that are facing threats in various degrees.

Bangladesh has given top priority for conservation of biodiversity; but the way of implementing it is very complex and difficult, because the forest resource which is the best home of plant biodiversity has reduced to 7% areas due to increase human population and associated development activities. Recent information stated that much of the state forest remained unproductive and only 0.84 million ha (about 5.8% of the state forest land) has acceptable forest vegetation (Forestry Department 2004). Under this current situation, homestead agroforestry offer the best option to conserve the diverse range of biodiversity. It is the in situ conservation site of a wide range of plant biodiversity, which is characterized by the measures of species richness, relative prevalence, and inter- and intra-species diversity (Heyhood and Watson 1995). Homestead agroforestry practice, being a multi-strata production system where diverse plant species are grown in intimate association with or without animals could be a potential option for conservation of biodiversity. A large number of higher plants have been recorded in homesteads and rural areas of Bangladesh. Latif et al. (2001) identified 148 species of natives and exotics in village forest. Similarly, Basak (2002) identified 105 tree species and 27 herbaceous species (vegetables and spices) in four ecological regions of Bangladesh. Atikullah (2008) identified 189 different plant species in the homesteads of the southwestern coastal zone of Bangladesh. Uddin et al. (2002) recorded 62 useful plant species in the homesteads of saline area of southeastern Bangladesh, and among them, 30.9% fruits, 29.09% timber, 34.54% vegetables, and 5.45% were spices species. The number and size of homestead have been increasing though areas for field crops have been declining. Mandal (2003) reported that average homestead area per farm has increased from 0.08 to 0.09 acre. This indicates increased opportunities created to some extent for home-based farm and non-farm production system. However, in designing homestead agroforestry system, emphasis should be given to include indigenous species since these are ecologically best suited and economically viable.

16.5 Major Issues for Sustainable Production System

In order to improve the overall productivity of the homestead agroforestry, there is a need to identify suitable species in terms of matching and growth performances to the micro-sites of the homesteads; availability of quality planting materials and their easy propagation; development of pruning and thinning regimes of the individual species; protection measures against the major pests and diseases; optimum rotation period on the basis of cost-benefit analysis; study prevailing wood market structure and agroforestry enterprises in order to promote necessary linkages with industries and trade for employment and income generation of the rural people, particularly for the women.

16.6 Conclusion

The review and discussion cited in this paper on different aspects of homestead agroforestry production system revealed that it appeared a potential area for improving production and income of the rural households of Bangladesh. The paper clearly stated how homestead agroforestry production system meets the diversified needs of the rural households through production of a wide variety of agricultural (food crops, vegetables, spices, fodder, etc.) and forest/tree products (fruits, timber, fuelwood, etc.) as well as medicinal plants? The paper also cited how each and every niches of the homestead (micro-sites) are being utilized by the households especially by the resource poor farmers/women. Though the homestead agroforestry production system in Bangladesh has been playing important role in rural economy of Bangladesh from the time immemorial, but the pressure of the ever-increasing population on homestead land and the rapidly changing social and economical conditions of the people pose a threat to the sustainable development of homestead agroforestry system.

As such, there is a need to conduct in-depth research and development activities on homestead agroforestry in special consideration of the smallest resource bases (micro-sites) of the subsistence farmers in order to work out different options and to facilitate more optimum use of the available resources of the poor farmer for meeting the future challenges. However, the challenges remain for the researchers, academics, and development agencies on how to address the demand-led diversified needs and aspirations of the millions of individual farmers dealing with the homestead agroforestry.

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