14 Sustainable Soil Management Is More Than What and How Crops are Grown

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14.1 INTRODUCTION

Soil management in agricultural landscapes should deploy production practices that are in harmony with soil-mediated ecosystem functions if they are to deliver a broad range of ecosystem services. Such services include edible and nonedible biological products, clean drinking water, processes that decompose and transform organic matter, and cleansing processes that maintain air quality. Several categories of ecosystem services are recognized: provisioning, regulating, cultural, and supporting (Millennium Ecosystem Assessment [MEA] 2005). In agricultural landscapes, provisioning ecosystem services can be delivered effectively and efficiently when the linked regulatory and supporting services are allowed to operate normally. Ecosystem functions that protect and enhance regulatory and supporting ecosystem services in the soil and landscape in which crops are grown appear, in general, to offer an effective way of harnessing the best productivity, ecological, and economic performances.

Thus, agricultural soil management can only be considered sustainable if field soil health and productive capacity are kept at an optimum to provide ecosystem services such as provision of clean water, hydrologic and nutrient cycling, habitats for microorganisms and mesofauna, carbon sequestration, and climate regulation. Across agricultural and mixed land use landscapes, such ecosystem services form the necessary conditions for society to be able to sustainably harness the biological potentials of the altered agroecosystems and the associated provisioning services of food, vegetation, water, etc.

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In general, over the past several millennia, agricultural land use globally has led to soil physical, chemical, biological, and hydrological degradation, and this state of affairs continues unabated in most farmlands (MEA 2005; Montgomery 2007; FAO 2011a). This is true on small and large farms, on farms using mechanized or manual farm power, in developing and in industrialized countries, in the tropics, and outside the tropics. The dominant farming systems paradigm globally is based on mechanical tillage of various types to control weeds (often with herbicides), soften the seedbed for crop establishment, and loosen compacted subsoil. At the center of this paradigm, there are farming practices for crop, soil, nutrient, water, and pest management that are considered by most agricultural stakeholders to be “modern, good, and normal.” However, the same farming practices have also forced farmers to accept that, supposedly, any accompanying soil degradation and loss of ecosystem services are inevitable and "natural" consequences of farming—consequences that can be kept under control but not avoided altogether. This view is increasingly being challenged and considered to be outdated, and inherited farming practices are considered unable to deliver the multifunctional objectives of productivity with ecosystem services now being demanded from agricultural land and producers who use it for farming.

In the past three decades, ideas and concepts, as well as an ecosystem approach to sustainable production intensification, have led to the emergence of an alternative approach to farming across all continents. The title of this chapter is "Sustainable Soil Management Is More Than What and How Crops Are Grown." Not only how and what crops are grown matters but also the interactions of the two in space and time lead to effects and consequences that influence system performance and delivery of ecosystem services. Some ecosystem services involve processes such as hydrological, carbon, and nutrient cycling that operate at the level of the fields on farms, landscapes, watersheds, and beyond. In addition, agricultural soil management is undertaken within different farming systems for the purpose of producing biological products for markets, and a range of production inputs, equipment and machinery, and management skills are needed to operate successfully. Thus, the topic of sustainable soil management has a wide and complex scope as reflected in the list of 10 tenets proposed by Lal (2009).

This chapter is about soil degradation in agricultural land, its root causes, and what solutions are being implemented in different parts of the world to integrate sustainable soil management into sustainable farming and landscape management. Section 14.2 describes what is meant by agricultural soil degradation and its extent. Section 14.3 provides an explanation of some of the major causes of soil degradation in agricultural land use and illustrates three cases of widespread soil degradation in contrasting environments. This is followed, in Section 14.4, by a discussion on the elements of sustainable soil management. Section 14.5 provides an elaboration of sustainable soil management based on the agroecological paradigm that is increasingly being promoted internationally, including how sustainable soil management has been able to restore degraded soils in different agricultural environments. Section 14.6 illustrates the kind of contribution crop management, intercropping, crop–livestock integration, and farm power that can be made to sustainable soil management objective. Section 14.7 presents three examples of large-scale landscape level ecosystem service benefits that are being harnessed from sustainable soil management systems. This is followed by Section 14.8 on policy and institutional implications for sustainable soil management. Section 14.9 offers some concluding remarks regarding the current trend toward sustainable soil management and what policy makers can do to support the trend.

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14.2 AGRICULTURAL SOIL DEGRADATION: DEFINITIONS AND EXTENT

Soil is considered to be a nonrenewable resource that ensures crucial environmental, social, and economic functions, and it has a central role in any approach aimed at defining the principles and practices of sustainable agriculture (Warkentin 1995). To identify the causes of agricultural soil degradation, it is necessary to agree on signs that clearly characterize this phenomenon and its degree. However, the "definition" of what is considered soil degradation has been regarded as a rather relative term, because an objective or quantitative evaluation of the evolution of soil quality and productivity is quite a complex undertaking. Further, similarly to what has been proposed by many authors with regard to the process of soil erosion (Verheijen et al. 2009), the extent of soil degradation, which may be considered "acceptable" or "tolerable" (i.e., which is not understood as such), is far from being clear.

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Agricultural soil degradation is generally understood as loss in the quality or productivity of soil as a result of human activities, leading as a consequence to less intensive usages or even its abandonment for agricultural use. In the *Guidelines for General Assessment of the Status of Human-Induced Soil Degradation* (Oldeman 1988), the different forms of human-induced soil degradation are distinguished comprehensively between two main categories: (1) displacement of soil material through water and wind erosion and (2) chemical and physical deterioration, such as depletion of soil nutrients and organic matter, salinization, acidification, and pollution, but also compaction, sealing and crusting, truncation of the soil profile, or waterlogging. Despite this distinction between the two categories, there is a strong relationship between them once occurrence and degree of soil displacement are appreciated as being a consequence of chemical and physical deterioration of the soil. In addition, both categories of agricultural soil degradation may lead to severe off-site effects such as sedimentation of reservoirs, harbors, or lakes; flooding; riverbed filling and riverbank erosion; and eutrophication of water bodies.

In these earlier definitions and descriptions of agricultural soil degradation, soil is treated mainly as a physical entity. In reality, however, a productive agricultural soil is a living system in which biological processes carried out by soil microorganisms and mesofauna are key elements in the creation, maintenance, and enhancement of soil health and its productive capacity. Soil health represents the soil's physical, chemical, hydrological, and biological status and its ability to respond to agricultural production inputs and to climatic variability including extreme weather events. For example, soil physical and chemical characteristics such as soil structure and porosity, soil aeration, water infiltration and drainage, soil water and nutrient holding capacity, total exchange capacity, and pH are greatly influenced by soil biological properties such as soil organic matter (SOM) turnover and the dynamics of soil biodiversity, which has an intimate relationship with plant roots, affecting its phenotypic expression below and above the ground. Deterioration of soil biological health, and consequent loss in soil productive capacity, is often not given much prominence in agricultural soil management and degradation research or in farming system management. Thus, the role of soil microorganisms and mesofauna and the SOM they require in order to function effectively and self-sustainably in the maintenance of soil health and the important role they play in crop phenotypic expression and crop performance are overlooked. This includes diverse kinds of symbiotic relationships that exist between soil biodiversity and plants about which we know very little (Uphoff et al. 2006), presumably because of difficulty in establishing, through scientific experimentation, the causal relationships with productivity and ecosystem services.

According to The Global Assessment of Human-Induced Soil Degradation (GLASOD), up to half the world's agricultural land is degraded to some degree (Oldeman et al. 1991). Degradation of cropland is most extensive in Africa, affecting 65% of cropland areas, compared with 51% in Latin America and 38% in Asia (CA 2007). Loss of organic matter and physical degradation of soil not only reduce nutrient availability but also have significant negative impacts on infiltration and porosity, which consequently impacts local and regional water productivity; the resilience of agroecosystems; and global carbon cycles. Accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation and degradation of water bodies and infrastructure (Vlek et al. 2010). Nutrient depletion and chemical degradation of soil are a primary cause of decreasing yields and result in low on-site water productivity and off-site water pollution. Globally, agriculture is the main contributor to non-point-source water pollution. Water quality problems can often be as severe as those of water availability. Secondary salinization and water logging in irrigated areas threaten productivity gains. According to the MEA (2005), some two-thirds of our ecosystems are degraded. According to FAO (2011), only some 10% of the global agricultural land is considered to be under improving condition; the rest has suffered some degree of degradation, with 70% characterized as being moderately to highly degraded.

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Unfortunately, the problem of agricultural soil degradation is often considered to be unique to tropical and subtropical regions (Greenland and Lal 1977) or in developing regions, which is now recognized to be not so. Soil mismanagement and the traditional physical view of soils have led to serious soil degradation in temperate agroecologies in the industrialized countries (Pretty 2002; Montgomery 2007). For example, in 2002, the European Union initiated the so-called "Thematic Strategy for Soil Protection," as it recognized that "Soil is a vital and non-renewable resource and had not been the subject of comprehensive EU action." At that time, the Commissioner of Environment even said that "for too long, we have taken soil for granted. However, soil erosion, the decline in soil quality and the sealing of soil are major problems across the EU." The ensuing discussion in the frame of this strategy identified eight major soil threats: soil erosion; decline in SOM; soil contamination; soil sealing; soil compaction; decline in soil biodiversity; salinization; and floods and landslides. Notwithstanding this, the approach to understanding root causes of soil degradation in any agricultural environment has remained relatively narrow, lacking the fuller appreciation of the role of soil biology in the maintenance of soil health, the role of symbiotic relationships between soil microorganisms and crop performance, and the disruptive effect of mechanical soil disturbance on soil health and productive capacity, and on production system resilience (Kassam et al. 2009).

14.3 CAUSES OF DEGRADATION OF AGRICULTURAL SOILS

The root cause of soil degradation in agricultural land use and of decreasing productivity—as seen in terms of loss of soil health—is the low soil-carbon and soil-life disrupting paradigm of mechanical soil tillage, which, in order to create conditions for improved crop performance, debilitates many important soil-mediated ecosystem functions. For the most part, agricultural soils are becoming destructured, our landscape is exposed and unprotected, and soil life is starved of organic matter, reduced in biological activity, and deprived of habitat. The loss of soil biodiversity, damaged structure, and its self-recuperating capacity or resilience, increased topsoil and subsoil compaction, runoff and erosion, and greater infestation by pests, pathogens, and weeds indicate the current poor state of the health of many of our soils. In the developing regions, this is a major cause for inadequate food and nutrition security.

In industrialized countries, the poor condition of soils due to excessive disturbance through mechanical tillage is being exacerbated by

1. overreliance on application of mineral fertilizers, as the main source of plant nutrients, onto farmland that has been losing its ability to respond to nutrient inputs due to degradation in biological soil health—related to declining stocks of soil carbon—including loss/destruction of adequate soil porosity and reduced soil moisture storage and increased runoff, leading to poor root system, nutrient loss, and decrease in nutrient uptake
2. reducing or doing away with crop diversity and rotations including legumes and pastures (which were largely in place around the time of World War II [WWII]) facilitated by high levels of agrochemical inputs, standardized fixed agronomy, and commodity-based market forces that are insensitive to on-farm and landscape ecosystem functions.

The situation in industrialized nations is now leading to further problems of increased threats from insect pests, diseases, and weeds against which farmers are forced to apply even more pesticides and herbicides, and which further damages biodiversity and pollutes the environment.

It seems that with mechanical tillage (intensive or otherwise) and with low soil input of atmospheric carbon and nitrogen and exposed soil surfaces as a basis of the current agriculture production and intensification paradigm, we have now arrived at a "dangerous" point in soil and agroecosystem degradation globally, including in the industrialized North. However, we also know that the solution for sustainable soil management for farming has been known for a long time, at least since the mid-1930s when the Midwest of the United States suffered massive dust storms and soil degradation due to intensive plowing of the prairies. Dust bowls and large-scale soil degradation continue to occur in vast regions and in developed and developing countries (Baveye et al. 2011), despite the recognition of soil health being critical to life on earth.

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For instance, in 1945, Edward Faulkner wrote a book *Ploughman's Folly* in which he provocatively stated that there is no scientific evidence for the need to plow. More recently, David Montgomery in his well-researched book *Dirt: The Erosion of Civilizations* shows that generally with any form of tillage, including non-inversion tillage, the rate of soil degradation (loss of soil health) and soil erosion is generally by orders of magnitude greater than the rate of soil formation, rendering agroecosystems unsustainable. According to Montgomery's research, tillage has caused the destruction of the agricultural resource base and of its productive capacity nearly everywhere, and continues to do so (Montgomery 2007).

For these natural science writers as far back as 1945, tillage, regardless of type and intensity, is not compatible with sustainable agriculture. We only have to look at the various international assessments of the large-scale degradation of our land resource base and the loss of productivity globally to reach a consensus as to whether or not the further promotion of any form of tillage-based agriculture is a wise development strategy. We contend that to continue with intensive tillage agriculture now verges on irresponsibility toward society and nature. Thus, we maintain that with tillage-based agriculture in all agroecologies, no matter how different and unsuitable they may seem for no-till farming, crop productivity (efficiency) and output *cannot be optimized* to the full potential. Further, agricultural land under tillage is not fully able to deliver the needed range and quality of environmental services that are mediated by ecosystem functions in the soil system. Obviously, something must change.

14.3.1 Soil Degradation from an Ecological Perspective

Agricultural land is derived from natural forest, savanna, and grassland ecosystems in which topsoil formation processes are driven by the natural bio-chemo-physical environment. The attending ecosystem functions mediated by soil, terrain, climate, and vegetation are driven by nature. Human-induced changes of the land by removing original vegetation, tilling and cultivating, burning, introducing new species of plants and animals, and adding agrochemicals are significant changes that can equal in their effect to rare catastrophic changes during geological time that set off sequences of erosion and reshaping of the topography. The altered hydrology, limited crop residue input, and long periods when bare soil is exposed to effects of sun, wind, and rain are the basic causes of land degradation. This has been the traditional view held by many experts during much of the past century, which led to large-scale (though, as we now see, insufficiently effective) soil conservation measures that were developed after the North American “dust bowl” disaster in the 1930s. The first measures involved practices such as contour plowing, terracing, and/or strip cropping to reduce runoff and soil erosion. However, they did not specifically target damage to soil aggregation, depletion of SOM, and loss of porosity by pulverization and compaction—which are significant factors in changing the balance between infiltration and runoff.

Tillage results in accelerated oxidation of carbon-rich organic matter by soil biota, faster than it may be being replaced, leading to progressive depletion of carbon-rich SOM. The common belief is that tillage accelerates crop residue breakdown, leading to increase in soil biota and nutrient flushes when residue is mixed with soil. Any positive effect is of very short duration and with little positive effect on soil quality and function. Rapid breakdown of crop residues starves soil organisms of their future source of energy for life processes, with consequent decline in their effectiveness in maintaining/improving the health and quality of the soil as a medium for plants’ rooting and functioning.

14.3.2 Agricultural Intensification Based on the “Interventionist” Paradigm

The post-WWII agricultural intensification placed increasing reliance upon breeding “new” high yielding seeds and more intensive tillage of various types pulled by heavy and more powerful machines, combined with even more chemical fertilizers, pesticides, and herbicides, supposedly making crop rotations superfluous and promoting apparent efficiency through specialization with monocropping. According to our reading (e.g., Perkins 1997; Helvarg 2001; Posner 2005), factories producing nitrates and ammonia for manufacturing explosives needed for WWII had to find an alternate market once the war ended. The crop production sector was susceptible to nitrate and ammonia salesmen who went around convincing farmers, government officials, and scientists that high yields and more profit could be obtained with mineral nitrogen and that there was presumably no real need for crop diversification and rotations with legumes or for adding plant sources of nutrients or animal manure. Crop production could be decoupled from livestock production. This was complemented with the notion that with more mineral nitrogen input comes the need for new more responsive cultivars because traditional cultivars are not capable of responding to higher doses of mineral nitrogen. A slogan of that era, coined by DuPont, was “Better Living through Chemistry.” Agroindustry and the Land Grant Colleges joined forces in promoting an industrial model for agriculture that was based on the use of chemical inputs and large volumes of output. Even FAO launched in 1961 the Freedom from Hunger Campaign (FFHC), which was partly financed by the world fertilizer industry. The FFHC’s main target was to encourage the use of fertilizers by small-scale farmers through education, effective means of distribution, and credit. The overall idea was that agricultural production cannot be significantly increased in developing countries of the world without improving the nutrient status of most soils. In the late 1970s, the FFHC was replaced by FAO’s Fertiliser Programme. Concurrently, rapid urbanization and land consolidation in industrialized countries forced agriculture “labor” to be substituted by “capital,” particularly in the form of agricultural equipment and machinery. Large tractors with large plows became common in the 1980s and symbolized modern farming. This technological “interventionist” approach became the accepted paradigm for production intensification and was promoted globally including in the developing regions—referred to as the Green Revolution paradigm of the 1950s, 1960s, and 1970s—and that, despite boosting crop yields, increased the likelihood of

- Loss of SOM, porosity, aeration, and biota (corresponding to decline in soil health) leading to collapse of soil structure, which in turn results in surface sealing, often accompanied by mechanical compaction, decrease in infiltration, waterlogging, and flooding (Figure 14.1)
- Loss of water as runoff, as well as of soil microorganisms, of soil particles, and of organic matter in top soil as sediment
- Loss of time, seeds, fertilizer, and pesticide (erosion, leaching)
- Less capacity to capture and slowly release water and nutrients
- Less efficiency of mineral fertilizer
- Loss of biodiversity in the ecosystem, below and above soil surface
- More pest problems (breakdown of food webs for microorganisms and natural pest control)
- Falling input efficiency and factor productivities, declining yields
- Reduced resilience and reduced sustainability

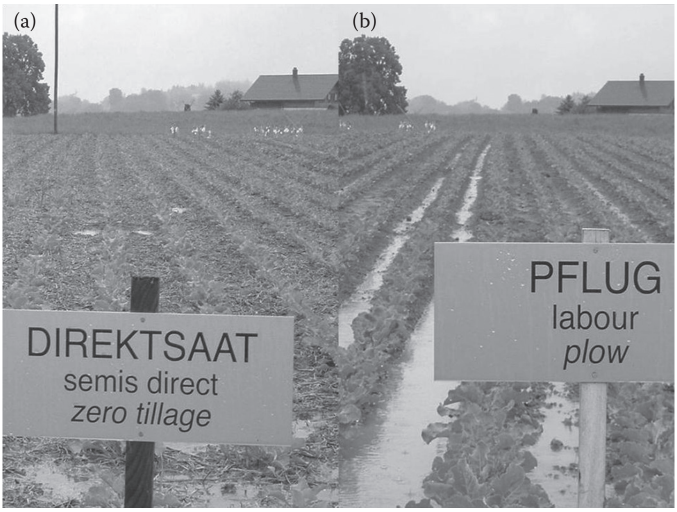

FIGURE 14.1 Soil compaction and loss in water infiltration ability caused by regular soil tillage leads to impeded drainage and flooding after a thunderstorm in the plowed field (b) and no flooding in the no-till field (a). Photograph taken in June 2004 in a plot from a long-term field trial "Oberacker" at Zollikofen, close to Berne, Switzerland, started in 1994 by SWISS NO-TILL. The three water-filled "cavities" in the no-till field were derived from soil samples taken for "spade tests" prior to the thunderstorm. (Courtesy of Wolfgang Sturny.)

- Poor adaptability to climate change and its mitigation
- Higher production costs, lower farm productivity and profit, minimal ecosystem services, and abandoned and desertified farmland and landscapes

Smallholder farmers in developing regions using manual labor to till the land and burning or removing all crop residues from the field also experience the above consequences and remain trapped in a degrading vicious cycle that cannot be broken just by applying mineral fertilizer and replacing traditional varieties with the latest breeding results. This also applies to farms in industrialized regions where the voices demanding more sustainable farming practices, both environmentally and economically, are getting louder. As soil degradation advances, the need for purchased inputs increases until the point where compensatory effect is no longer possible, forcing farmers to use even higher inputs with equally higher environmental impact.

According to Derpsch (2004), research on "conservation" or reduced tillage with early versions of a chisel plow was initiated in the Great Plains in the 1930s to alleviate wind erosion. Stubble mulch farming was also developed and can be seen as a forerunner of no-tillage farming. This collection of practices led to what became known as conservation tillage, which includes a range of tillage practices from high soil disturbance tillage to low soil disturbance that maintains at least 30% soil cover.

The book *Ploughman's Folly* by Edward Faulkner (1945) was an important milestone in the development of sustainable soil management for agriculture. Faulkner questioned the wisdom of plowing and explained the destructive nature of soil tillage. Further research in the United Kingdom, the United States, and elsewhere during the late 1940s and 1950s and the development of herbicide technology made no-tillage farming possible, and the practice began to spread in the United States in the 1960s, and in Brazil, Argentina, Paraguay, and Australia in the 1970s. In 1973, Shirley Phillips and Harry Young published the book *No-Tillage Farming*, the first of its kind in the world, and this was followed in 1984 by the book *No-Tillage Agriculture: Principles and Practices* by E.R. Phillips and S.H. Phillips (see references).

The modern successor of no-till farming—now generally known as conservation agriculture (CA)—goes much further as elaborated in Section 14.4. It involves simultaneous application of three practical principles based on locally formulated practices (Friedrich et al. 2009; Kassam et al. 2011a): minimizing soil disturbance (no-till seeding); maintaining a continuous soil cover of organic mulch of crop residues and plants (main crops and cover crops including legumes); and cultivation of diverse plant species that, in different farming systems, can include annual or perennial crops, trees, shrubs, and pastures in associations, sequences, or rotations, all contributing to enhance system resilience.

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14.3.3 EXAMPLES OF LARGE-SCALE AGRICULTURAL SOIL DEGRADATION

Examples of large-scale agricultural soil degradation from different parts of the world appear to share several common experiences as can be seen from the cases of South America, China, and Australia presented in the following sections. These cases reflect contrasting agricultural environments ranging from the tropical and subtropical environment with summer rainfall in Brazil to subtropical environment with winter precipitation in Western Australia to temperate environment with winter precipitation in northern China from east to west.

14.3.3.1 Brazil

Although in South America there is a diversity of soil types and ecologies, the dominant croplands are found on Oxisols, Ultisols, and Alfisols situated for the most part in tropical and subtropical climates. Usually, in undisturbed conditions, these soils have good physical properties (deep, well-drained, stable aggregates and rapid water infiltration), but they have low natural soil fertility as reflected by low activity clay, acidity, high aluminum content, high phosphorus fixation, and low base saturation. These soils represent one of the world's biggest agricultural soil reserves. Therefore, understanding the risk of soil degradation associated with mismanagement is crucial. The dominant weather characteristics result in high intensity rainfall, especially in the spring and summer seasons, which lead to high risk of water erosion and nutrient leaching. Other processes associated with the weather characteristics are the fast organic matter turnover due to higher soil temperature and moisture, which favors microbial activity year-around. Further, there is also the potential to produce high amount of biomass due to the high solar radiation reaching the land surface. In most humid ecologies, it is possible to design intensive cropping systems with at least two crops per year accompanied with a diversity of cover crops to fill up the autumn time window (Amado et al. 2006).

Until the 1960s, the agricultural features in South America were those of a predominantly subsistent agriculture with land use change from native vegetation (natural forest and grass pasture) to grain crop and sown pastureland. The slash-and-burn and conventional tillage with human and animal traction were dominant practices in this agricultural expansion. The agricultural inputs were mainly any available organic material and very few inorganic fertilizers, thus an imbalance in the input–output status. This soil management was introduced by European settlers and was mainly based upon experiences from a temperate environment. The main aim of agriculture production was to supply the increasing local and regional market demand. Although the soil management practice could be classified as poor, the limited capacity to expand the cropland area due to the associated high labor demand resulted in a relatively low environmental impact. During this period, soil degradation was more intense in mountainous and steep areas due to high erosion rates (Bernoux et al. 2006). Shifting cultivation was a common practice among smallholders in response to rapid soil degradation and loss of soil productivity. The growing use of technology and inputs (investment) and increasing land value induced farmers to stay longer on the same land parcels.

The adoption of mechanization in South Brazil that occurred in the late 1960s resulted in a huge impact on land use change. Mielniczuk (2003) reported that until 1969, the cropland in Rio Grande do Sul State was lower than 1 Mha, but 8 years later, in 1977, it reached 4 Mha. The main cash crops were wheat and soybean associated with long fallow periods. The large-scale application of lime was an important tool to improve soil fertility in the acid Oxisols. Also, phosphorus application resulted in the amelioration of low soil fertility. The improvement in soil fertility was not followed by better production stewardship. Thus, practices such as intensive soil tillage, crop residue burning, low crop intensity, and bare soil were widely adopted by farmers. The high intensive soil tillage system accompanied with high intensive rainfall resulted in unprecedented erosion and contamination of water reservoirs and rivers (Cogo et al. 1978; Gianluppi et al. 1979; Mielniczuk and Schneider 1984). Frequent tillage was used as a tool to control weeds, reduce diseases in wheat, increase water infiltration, incorporate lime and fertilizers, make a seedbed, loosen the soil, break the soil crust, incorporate herbicides, accelerate the decomposition of roots and residues of native vegetation, decrease surface roughness, and eliminate/disguise rill erosion. Thus, the conventional tillage was typically composed of two plow and four to six disc operations per year. During the 1970s, it was estimated that for each kilogram of soybean harvested, approximately 10 kg of fertile soil was lost (Gianluppi et al. 1979; Mielniczuk 2003; Amado et al. 2006). In Brazil, the annual values of erosivity ranged from 3116 to 20,035 MJ mm ha^{-1} h^{-1} $year^{-1}$. Highest erosivity values were observed in November to February, a period that can constitute more than 70% of total annual erosivity (Cogo et al. 2003). This period is coincident with the main summer cash crop (soybean and maize) establishment, increasing the risk of soil erosion (Cogo et al. 1978).

The record soil erosion documented in South Brazil occurred on November 1978. This event was known as red November because of the amount of Oxisol sediments that was carried out to the waterways, changing the color of the river from blue to red. During this event, 90% of cropland was managed under conventional tillage (Mielniczuk 2003), and the soil was bare or recently disturbed with soybean plantings. There was a precipitation event of approximately 200 mm (8 in.) in just 4 days resulting in 192,200 ha that had lost at least 10 cm of topsoil (truncated) by rill and gully erosion (Gianluppi et al. 1979). The loss of seeds, fertilizers, and agrochemical from croplands resulted in US$33 million of damage (Gianluppi et al. 1979). Another environmental indicator of the intensity of soil erosion verified during this period was at the Passo Real Dam, which had 1.6 kg of soil per 1000 L of water, resulting in a total of 6 M Mg of suspended soil sediments in the water.

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The estimated soil erosion in South Brazil during the conventional tillage period was approximately 25 t ha^{-1} $year^{-1}$. After 15 years, adoption of conventional tillage practice resulted in two-thirds of the agricultural land in Southern Brazil showing soil degradation, expressed by the depletion of conservation agriculture (CA) reduced water infiltration rate, structural degradation, soil compaction, and an increase in plant susceptibility to short duration droughts. The social consequences of high erosion and soil degradation were as follows: sedimentation of rivers, smallholders forced to migrate to cities increasing the unemployed population, sales of small farms, and interregional migration of farmers (south to central and north) (Cassol 1984; Amado and Reinert 1998; Pöttker 1977; Bolliger et al. 2006). During the time period that conventional tillage was the prevalent soil management practice, increases in crop yields were very modest regardless of the increase in inputs and germplasm improvement.

In Paraguay, the semideciduous subtropical forest was replaced by agricultural land use, which, along with conventional tillage practice, promoted soil degradation (Riezebos and Loerts 1998), similar to that verified in South Brazil. Prior to deforestation, SOM ranged from 2.09% to 2.42% but decreased to 1.59% under conventional tillage management. Mechanically tilled fields appear to have a more rapid decline in organic matter than manually tilled fields (1.59% vs. 1.89%) suggesting more severe soil degradation in mechanized agriculture. In South Brazil, a decline in SOM in conventional tillage pulled by tractors also was noted, although the effect of poor management in reducing soil carbon was more pronounced in soils with lower content of clay and iron oxides and under high soil erosion rates (Fabrizzi et al. 2009). Séguy et al. (1996) reported that in degraded soils of Brazil, the SOM stocks were depleted by as much as 30%–50%.

Conventional tillage causes the physical destruction of crop residues, increases the soil-residue contact, promotes higher aeration and higher soil temperature, and increases soil N mineralization (Amado et al. 2006; Aita and Giacomini 2007). These processes in combination cause a sharp increase in microbial biomass activity that consume crop residues and labile SOM resulting in an exponential rate of decay (Pes et al. 2011). Soil tillage causes the disruption of soil aggregates and exposes particulate SOM to microbial biomass attack (Amado et al. 2006; Pes et al. 2011).

In summary, the main causes of soil degradation in South America were associated with the cumulative effects of the reduction of plant biomass being returned to the soil, reduction of crop diversity, soil erosion, soil disturbance by tillage, maintenance of bare soil or limited soil cover in periods of high rainfall erosivity, depletion of SOM, depletion of soil fertility by unbalanced input–output agroecosystems, deterioration of soil structure, soil compaction, loss of microbial biomass diversity, and decrease in soil quality.

14.3.3.2 Australia

Historically, Australian farmers had pasture as an alternative "crop." This ley pasture farming system was common up until 1990. It enabled farmers to control weeds with animals and thereby reduce their reliance on herbicides. However, the profitability of this farming system was challenged with poor wool prices in the late 1980s, and it was largely replaced with continuous cropping. Running livestock in dry regions also created soil degradation concerns with compaction common in wet heavy soils and wind erosion common on the sandier soils.

The most obvious and concerning soil degradation issues in dryland Australian agriculture have been wind erosion, followed by water erosion. The emergence of saline soil in Western Australia, about 30 years after clearing of the native vegetation, is a serious threat to some areas of the landscape (George et al. 1997). On the other hand, other areas experience more subtle soil degradation such as nutrient export, compaction, waterlogging, sodicity, water repellence, and acidity.

The degree of concern for each of these issues varies across regions and states in accordance with soil type, soil slope, geological parent material, proximity to the coast, and the local climate. Other temporal issues also had a strong influence, including intensity and duration of wind and rainfall events, level of soil cover, grazing pressure, the level of tillage used, and the level of knowledge of techniques capable of mitigating against degradation issues.

Australia is known as a "land of drought and flooding plains." The last 12 years have seen about 7 years of widespread drought and 3 years of widespread flooding plains. Such contrasting climatic conditions present soil management challenges. The climate across southern Australia is classical Mediterranean with winter wet (June–August) and summer dry (December–February). Toward northern NSW, rainfall becomes more evenly distributed throughout the year, with summer the dominant rainfall period in Queensland.

The strongest Mediterranean climate is found in the southwestern area of Australia. This area has received 40% less winter rainfall since the early 1970s. In contrast, the northern third of Australia, during the same time, has had more rainfall. However, there is limited cropping activity in these northern regions—though there is grazing of livestock, mostly cattle. Therefore, the focus of this article is on southern Australia where cropping is common.

Australian soil is reported to be part of the most ancient and weathered landscape of anywhere in the world (McArthur 2004). Large areas have a very sandy surface—some have almost no clay in the topsoil. When sandy soil is combined with the often dry climate, it creates a recipe for significant land degradation potential. The clearing of the native vegetation of mostly mallee, or Eucalypt trees for agricultural purposes, has predisposed these surface soils to wind (Crabtree 1990) and water erosion (Bligh 1989, 1991). The majority of this vegetation clearing in Western Australia occurred during the 1950s and 1960s. Over 400,000 ha was cleared each year during that decade.

The most profound and obvious forms of soil degradation in Australia were wind and water erosion. Immediately after the land was cleared, soil erosion (caused by wind and water) occurred. Sandy soils, associated with the mallee vegetation of southern Australia, occupy large regions of Victoria and South Australia. Soil erosion began on these soils soon after clearing in the late 1800s. Similar erosion occurred in Western Australia when its sandy soils were released in the early 1960s.

Prior to the availability of herbicides in the 1980s, tillage was essential for controlling weeds. However, the burial of surface organic matter, through tillage, exposed the soil to the erosive forces of the wind. During wetter years, in the 1960s, the level of erosion was small due to the rapid soil cover from re-greening of annual pastures or weeds near the "break of the season." In contrast, the poor ground cover during successive drought years caused serious wind erosion, which could persist for much of the year. The mallee area of Victoria had regularly horrifying dust storms in the 1930s. In Western Australia, similar erosion occurred in the 1969 drought and regularly thereafter during the dry 1970s.

During this time, pasture was often overgrazed and the soil was left bare, and this also predisposed soil to wind erosion. The common practice, at the time, was two pre-seeding tillages to control weeds and soften the soil, for even seed placement. Similarly to sheep grazing, this tillage removed surface vegetation that could protect the soil against erosion (Robertson 1987).

During autumn (March–May), and before the pasture or crop could fully cover the ground with new growth, strong prefrontal winds would blow the topsoil against the seedlings, often cutting the plants off and blowing the soil off-site. Both emerging crops and pastures were damaged. On other sandy soils, on more hilly terrain, and in higher rainfall areas, water erosion was more of a concern to farmers. Similarly, the sandy soil was loosened with tillage and was also left bare, providing little soil cover to protect the soil from water erosion.

14.3.3.3 China

In Asia, population pressure on natural resources is already high, and it is expected to increase further. However, based on past trends, as population continues to grow toward a plateau level of 9–10 billion people, the expansion of land will become increasingly modest. The growth in commodity production in South Asia is now almost completely (94%) based on increases in yields and cropping intensities (FAO Agriculture Towards 2050), and available water resources are the limiting factors there. In East and Southeast Asia, there is still a lot of water that could be used for irrigation, but the agricultural land resources are becoming scarce (Pisante et al. 2010).

China is one of the Asian countries that have been seriously endangered and affected by soil degradation. The area of land degradation is estimated to be 370,000 km^2 corresponding to a direct economic loss of 54 billion yuan ($8.5 billion) each year. Soils in dryland areas have suffered severe degradation and desertification through water and wind erosion impacting the main grain-producing area of the country.

The threat of water erosion in dryland areas is affected by the amount and intensity of rainfall, the type of irrigation, the erodibility of the soil, cropping and management factors, and erosion control practices. The impact of raindrops or the flood irrigation on the soil surface is the beginning, and the most important part, of the erosion process. In recent decades, sand storms in China have also done great harm to the farmland. As affected by all the reasons mentioned above, the degradation of farmland finally caused the decline of productivity.

Annual rainfall ranges from 200 to 600 mm in the Loess Plateau, which is a one crop per year region. Soil in the Loess Plateau is easily eroded and is intensively cropped with dryland winter wheat. Limited crop-available water is one of the major factors constraining agricultural production on the Loess Plateau, and severe erosion has resulted in degradation of soil properties, such as water retention (Zha and Tang 2003).

In cold and semiarid Northeast China, spring maize is one of the most important grain crops in terms of area and output (Liu et al. 2002). The annual rainfall here varies from 400 to 1000 mm, and the average cumulative evaporation is ~1800 mm, which is about four times higher than the average total rainfall received during the growing stage of spring maize. Therefore, the low status of soil moisture in the root zone usually limits productivity of spring maize in this region. Conserving moisture accumulated in the root zone during the rainfall season can increase productivity of spring maize in the dry Northeast China.

In annual double cropping areas of the North China Plain, the annual rainfall is 450–800 mm, and the annual cumulative evaporation hugely exceeds the annual rainfall. Since the 1980s, the cropping system in this region has changed from a single- to a double-cropping system (winter wheat–summer maize) (Liu 2004). Therefore, the demand for plant available water has jumped and water scarcity is a serious issue.

In the pastoral ecology of Inner Mongolia, the annual rainfall is 450–500 mm, and the annual cumulative evaporation is 1300–1880 mm, hugely exceeding the annual rainfall. In some parts of the pastoral areas, the annual rainfall is even less than 50 mm (He et al. 2009a). In the last 100 years, large areas of grassland have been converted into cropland due to an increased population and food demand (Zhang et al. 1998). The agriculture–pasture transition region has about 32.8-Mha land, representing 27.8% of the total land area of Inner Mongolia (LZU 2005). In this region, conversion of grassland to cropping combined with insufficient rainfall and wind erosion has resulted in serious soil nutrient depletion and structural deterioration (Liu et al. 2007).

In Northwest China, water shortage is one of the major constraints to the production of agricultural crop. The average annual precipitation varies from 40 to 200 mm (Xie et al. 2005), and the annual potential evaporation in this region exceeds 1500 mm resulting in a moisture deficit of at least twice the growing season requirements of spring wheat for the area (>600 mm).

The dryland areas of China have soil that are easily eroded and intensively cropped with dryland crops (wheat, maize, etc.), which occupy 56% of the arable land (Zhu 1989). Over the past 20 years, crop yields have increased through fertilizer application and increasing water consumption; however, soil water is often not fully replenished during the fallow period (Huang and Zhong 2003). Since crop yield varies strongly with rainfall (Li 2001), water shortage becomes the greatest threat to crop production. Some 80%–90% precipitation is lost through evaporation or runoff, and only 10%–20% can infiltrate into the soils. Thus, the soil water storage capacity is a crucial indicator for increasing production (Li et al. 2007; Zhang et al. 2009).

Conventional tillage practices based on moldboard plowing and preparing fine seedbeds with residue removed or burned have resulted in poor soil fertility and degraded soil structure as indicated by soil surface sealing, low mesoporosity (pores of diameter <60 μm), unstable soil aggregates, and low SOM content, all of which reduce water infiltration and soil water retention (Elliott 1986; Fabrizzi et al. 2005), creating a harsh environment for crop growth. Notably, after a long period with conventional tillage, a hard plow pan forms, which prevents water infiltration and results in a lower soil water storage capacity, increased runoff, and erosion. Dust storms have increased considerably in recent years (Zhang et al. 2004; Wang et al. 2006).

CA using no-till can improve soil water storage once the hard plow pan is broken through subsoiling or ripping. Soil residues cover and no or minimum tillage can reduce evaporation and promote soil water infiltration by mitigating the direct attack of rainfall and decreasing soil crusting. The decomposed roots can form the channels in the soils, thereby reducing runoff and increasing soil water infiltration. A positive effect of CA in conserving soil water has been proved in demonstration sites established in dryland areas of China (Wang et al. 2008; He et al. 2008, 2009a,b, 2011).

14.4 NURTURING SOILS AND LANDSCAPES AS LIVING BIOLOGICAL SYSTEMS

Alongside the concern for soil erosion and the destruction of soil structure and soil life caused by frequent and intensive tillage has been the growing understanding of the important role soil life and soil biology play in the maintenance of soil health. In the 1940s, Eve Balfour referred to this in terms of "the living soil" as being a necessary condition for healthy crops, environment, and people (Balfour 1943; Primavesi 1980). According to Doran and Zeiss (2000):

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> Soil health is the capacity of soil to function as a living system with ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health.

According to Peter Trutmann, quoted in FAO (2008), this emphasizes a unique property of biological systems, since inert components cannot be sick or healthy. Management of soil health thus becomes synonymous with management of the living portion of the soil to maintain essential functions of soil to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. According to David Wolfe, quoted in FAO (2008), healthy soils maintain a diverse community of soil organisms that help to control plant disease, insect, and weed pests; form beneficial symbiotic associations with plant roots (e.g., nitrogen-fixing bacteria and mycorrhizal fungi); recycle essential plant nutrients; improve soil structure (e.g., aggregate stability) with positive repercussions or soil water and nutrient holding capacity; and ultimately improve crop production.

In this context, ongoing supply of carbon-rich organic matter for soil organisms is essential, from which they source both energy and nutrients. Examples of management practices for maximizing soil health include maintaining vegetative cover of the land year-round to increase organic matter input and minimize soil erosion, more reliance on biological as opposed to chemical approaches to maintain crop productivity (e.g., rotations with legumes and disease-and weed-suppressive cover crops), and avoiding physical (mechanical) interventions that might compact, alter, or destroy the biologically created porous structural arrangements of soil components (FAO 2008).

A key factor for sustainability in any production system, in contrast to sustainable intensification, was described by Uphoff et al. (2006) as follows:

> Of particular importance for sustainable agriculture is the enhancement of soil water-holding capacity and drainage. This is very dependent on the kinds of biological activity that lead to better particle aggregation, creating soil that can be both better aerated and infused with water at the same time. …Improving soil characteristics through biological activity and management will store water, the most essential source for agriculture, in soil horizons and root zones where it is most needed…

Similarly, in FAO (2008), it was described as follows:

> Sustainability of land's capacities to continue yielding both plant products and water year after year depends primarily on maintaining the soil in fit condition for active life processes of the whole soil/plant system. This relates to the ongoing generation and re-generation of the porous soil architecture—the soil's 'self-recuperation capacity'—with respect to the repair of damaged soil and to its physical resilience in the face of adverse shocks of weather and/or of poor management.

It is now recognized more widely that a productive agricultural soil, together with its inhabiting plants and other biota, is a living biological system (Tikhonovich and Provorov 2011; Doran and Zeiss 2000; Doran 2002) that is made up of a complex web of interactions between a large diversity of microorganism and mesofauna and between microorganisms and plant roots as well as aboveground parts. Relatively little is known about this complex agrobiodiversity or soil biota and its ecosystem functions as its role in crop productivity has been generally ignored, even during the recent decades.

For example, four main aggregate ecosystem functions are performed by the belowground soil biota (Swift et al. 2008): (1) decomposition of organic matter brought about by the enzymatic activity of bacteria and fungi, and facilitated by soil animals such as mites, millipedes, earthworms, and termites; (2) nutrient cycling, which is closely associated with biological nitrogen fixation, uptake of various nutrients from lower soil horizons, organic matter turnover, and organic decomposition, with transformations mediated through microorganisms; (3) bioturbation through the activities of plant roots, earthworms, termites, ants, and some other soil mesofauna and macrofauna that form channels, pores, aggregates, and mounds, and physically moving particles from one horizon to another; and (4) disease and pest control through, for example, the regulations of activities of pathogens by the microbivore and micropredator portions of the soil biota that feed on microbial and animal pests, respectively.

The above-described soil biological processes and ecosystem functions cannot be performed adequately in soils that are mechanically disturbed by tillage and whose structure and porosity are repeatedly impaired as a result. Soil biological health is further hindered by the inadequate amount of organic substrate being supplied to feed and maintain soil microorganisms and their functions at rates equal to, or faster than, its rate of oxidation following tillage.

In addition, we are discovering the importance and significance of the fact that living organisms including plants and animals each have coevolved with a large number of symbiotic endophytes and nonendophytes that form mutually beneficial relationships with plants and animals that can lead to a superior phenotypic performance from the same genotype. In other words, the G × E (genotype × environment) equation can work differently depending on whether certain microorganisms are present or not in the soil, in the rhizosphere, and within the plants. In some cases, microorganisms such as the Rhizobia, which are well known for their ability to fix atmospheric nitrogen in legumes, have recently been shown to behave as a symbiotic endophyte in rice plants, where it has been shown to penetrate through the root system all the way into the leaves, increasing unit leaf photosynthesis rate by some 15% (Mishra et al. 2006). Similarly, in the case of mobile phosphorous level in the soil, values as high as 50 to 60 ppm have been recorded in soils with phosphobacteria, which would otherwise show phosphorus deficiency (Ref Nature article).

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What is being discovered is that a living soil has a different productive capacity and resilience when farming practices encourage and facilitate soil life to play its important role in maintaining soil health and quality. Such soils respond differently and more efficiently to farming practices that are applied to intensify production, and there is increasing evidence that the phenomenon of "more from less," which is often observed with biologically active soils, is due to the role soil microorganisms play in the various ecosystem processes and functions in the soil (Uphoff et al. 2006).

14.5 SUSTAINABLE SOIL MANAGEMENT BASED UPON AGROECOLOGICAL PRINCIPLES

Evidence from different parts of the world suggests that it may not be possible to separate sustainable soil management from sustainable production system management. Both are inextricably linked in ways that sustainable crop production systems must first be ecologically sustainable. This means that any production system that permits the mechanical disruption of soil life and biology and soil structure and quality, and therefore ecosystem services, cannot be considered to be sustainable ecologically. The aim of "sustainable soil management" should be to reverse the trends indicated by the items listed above, via the inducing of improvements in the quality of the soil as a rooting environment for plants. Also, an agricultural soil system is of no value if the crops grown are attacked by weeds, insects, and pathogens. In other words, sustainable soil management is not enough for sustainable production as an outcome, and certainly not where sustainable production intensification is the objective in which crop, soil, nutrient, water, pest, and farm power management in space and time must be taken care of to remain ecologically and economically viable.

The agroecological principles that underpin sustainable production systems for small and large farmers from an eco-commercial viewpoint relate to resource conservation and efficiency of resource use, both natural and purchased, while profitably managing sustainable production intensification and ecosystem services. At the core, and based upon large amount of empirical evidence from farmers themselves in all continents, we can say that sustainable production derives from a number of practical principles that can be applied simultaneously through combined crop–soil–water–nutrient–pest–ecosystem management practices. These practices are locally devised and adapted to capture a range of productivity, socioeconomic, and environmental co-benefits of agriculture and ecosystem services at the farm, landscape (watershed), and provincial or national scale (Pretty 2008; Kassam et al. 2009; Godfray et al. 2010; FAO 2011b; Pretty et al. 2011).

However, different from the tillage-based *interventionist approach* to farming described above, there are now many production systems with a predominantly *ecosystem or agroecological approach* generally characterized by minimal disturbance of the ecosystem, with both natural and managed biodiversity in order to provide food, raw materials, and other ecosystem services. Biologically healthy soils underpin these systems. Thus, in order to achieve sustainable intensification, a production system must be able to support and maintain the ecosystem functioning, and services derived from it, by limiting interventions (which may appear necessary for intensifying the production) to levels that do not disrupt these functions.

Sustainable production systems based on ecosystem approaches offer a range of productivity, socioeconomic, and environmental benefits to producers and to society at large. To achieve the increased productivity required to meet 2050 food demands and the range of ecosystem services expected by society, sustainable production systems should be based on five technical principles:

- Simultaneous achievement of increased agricultural productivity and enhanced ecosystem services.
- Enhanced input-use efficiency, where key inputs include water, nutrients, pesticides, energy, land, and labor.
- Reduced dependency from external inputs derived from fossil fuels (such as mineral fertilizer and pesticides) and preference for alternatives (such as biological nitrogen fixation and integrated pest management).
- Protection of soil, water, and biodiversity through use of minimum disturbance of natural systems; interventions must not have accumulative effects but must have an impact and frequency lower than the natural recovery capacity of the ecosystem.
- Use of managed and natural biodiversity to build and/or rebuild system resilience to abiotic, biotic, and economic stresses.

Over time, systems following these principles will show increasing production levels and decreasing levels of input use. In many degraded situations, better retention of incoming water—its capture, infiltration, and in-soil storage at plant-available tensions—is an important achievement, which makes possible the optimum functioning of the entire soil/plant system.

14.5.1 Conservation Agriculture as a Base for Sustainable Soil Management and Production Intensification

The farming practices required to implement the above-mentioned key principles will differ according to local conditions and needs but will have the following required characteristics, based on optimizing conditions in the root zone as being essential to (1) biotic activity; (2) provision of water and crops; and (3) assurance of self-sustainability of soil structure and porosity.

These include capacities for achieving the following: maximum rain infiltration/minimum runoff and optimum water storage; minimum compaction; reduced diurnal temperature ranges in upper soil layers; regular supply of C-rich organic matter to the surface; minimal loss of SOM by oxidation; N levels in soil maintained; and optimized P availability. Such are best achieved by incorporating the following three main tenets of CA as a base or a foundation for sustainable soil management (see www.fao.org/ag/ca):

1. *Minimizing soil disturbance by mechanical tillage.* Whenever possible, seeding or planting directly into untilled soil, in order to maintain SOM, soil structure, and overall soil health.
2. *Enhancing and maintaining permanent mulch cover on the soil surface.* Use of crops, cover crops, or crop residues to protect the soil surface conserves water and nutrients, promotes soil biological activity, and contributes to integrated weed and pest management.
3. *Diversification of species.* Utilize both annuals and perennials in associations, sequences, and rotations that can include trees, shrubs, pastures, and crops (some or all of which may be N-fixing legumes). All will contribute to enhanced crop nutrition and improved system resilience.

CA practices related to the above-described principles are now widely used in a range of farming systems in all continents on nearly 10% of the global crop land. They add to sustainability of production and soil systems and generate a range of ecosystem services (Table 14.1). They also improve soil conditions (Table 14.2a) and result in beneficial outcomes for production, ecosystem services, and socioeconomic conditions (Table 14.2b). However, to achieve the sustainable *intensification* necessary to meet future food requirements, these CA practices need to be complemented by additional best management practices:

- Use of well-adapted, high-yielding varieties, and good-quality seeds
- Enhanced crop nutrition, based on healthy soils
- Integrated management of pests, diseases, and weeds
- Efficient water management
- Careful management of machines and field traffic to avoid soil compaction

Sustainable crop production intensification (SCPI) is the combination of all of these improved practices applied in a timely and efficient manner. For this, the ensuring of soil stability and the favoring of self-recuperation of appropriate soil structural conditions are essential (see Table 14.1 and Figure 14.1a and b). Thus, sustainable soil management depends on how and what crops are grown. However, for sustainable production *intensification* to occur, the core or foundation CA practices must integrate with other complementary practices that allow the intensification of output and the optimization of the production inputs. Such sustainable production systems, and the associated sustainable soil management practices, are knowledge

TABLE 14.1

Effects of Production System Components Fully Applied Together on Sustainability and Ecosystem Services

	System Component			
To Achieve	**Mulch Cover**[a]	**No Tillage**[b]	**Legumes**[c]	**Crop Rotation**[d]
Simulate optimum "forest floor" conditions	√	√		
Reduce evaporative loss of moisture from soil surface	√			
Reduce evaporative loss from upper soil layers	√	√		
Minimize oxidation of SOM, CO_2 loss		√		
Minimize compactive impacts by intense rainfall, passage of feet, machinery	√	√		
Minimize temperature fluctuations at soil surface	√			
Provide regular supply of organic matter as substrate for soil organisms' activity	√			
Increase and maintain nitrogen levels in root zone	√	√	√	√
Increase CEC of root zone	√	√	√	√
Maximize rain infiltration, minimize runoff	√	√		
Minimize soil loss in runoff and wind	√	√		
Permit and maintain natural layering of soil horizons by actions of soil biota	√	√		
Minimize weeds	√	√		√
Increase rate of biomass production	√	√	√	√
Speed up soil porosity's recuperation by soil biota	√	√	√	√
Reduce labor input		√		
Reduce fuel-energy input		√	√	√
Recycle nutrients	√	√	√	√
Reduce pest pressure of pathogens				√
Rebuild damaged soil conditions and dynamics	√	√	√	√
Pollination services	√	√	√	√

Source: Friedrich T. et al., Conservation agriculture, In: *Agriculture for Developing Countries,* Science and Technology Options Assessment (STOA) Project, European Technology Assessment Group, Karlsruhe, Germany, 2009.

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[a] Crop residues, cover crops, green manures.

[b] Minimal or no soil disturbance.

[c] As crops for fixing nitrogen and supplying plant nutrients.

[d] For several beneficial purposes.

TABLE 14.2a
How CA Improves Soil Conditions

	Key Features of Conservation Agriculture ⇒			
Components of Soils' Productive Capacity	**No-Till** ⇓	**Mulch** ⇓	**Rotations** ⇓	**Legumes** ⇓
Hydrological	1	4		
Physical	2	5	7	10
Biological	3	6	8	11
Chemical			9	12

Note: Key: 1 = Water percolation; 2 = Varied soil porosity; 3 = Favors biological soil layering; 4 = Buffers impacts of rainfall, wide diurnal ranges of surface temperature; 5 = Prevents soil crusting; 6 = Source of energy and nutrients; 7 = Augments root channels—distribution and depth; 8 = Favors biodiversity in soil; 9 = Beneficial root exudates;10 = Favors development of optimum soil architecture (solids × spaces); 11 = Nitrogen + C-rich organic matter; 12 = Nitrogen.

Please verify whether this is the intended meaning.

TABLE 14.2b
Some Resulting Beneficial Outcomes with CA

For Agricultural Production	For Ecosystem Services	For Socioeconomic Conditions
Greater security of output under varying weather conditions.	Diminished water pollution by agrochemicals and eroded soil; reduced costs of water treatment.	Greater efficiencies of use of labor and financial resources.
Greater efficiency of rainwater use, leading to more stable yields.	Less frequency, depth, and duration of flooding after unit storms of equal severity.	Better health and nutrition.
No/minimal soil erosion; smaller losses of applied energy, fertilizers, seeds, etc.	Longer duration of streamflow; recharge of groundwaters.	Reduced frequency of flooding and severity of damages to roads, bridges, etc.
Improved soil health provides better biological controls of weeds and pests.	Reduced loss of SOM by tillage-induced oxidation to CO_2.	More time for diverse activities on-farm (technical).
Recirculation of carbon, micronutrients, and macronutrients.	Maintenance/improvement of soil carbon content.	More time for diverse activities off-farm (social).
Lesser effects of climatic drought events.	Lesser damage to normal multiple functioning of soil in wider ecosystem.	
Etc.	Etc.	Etc.

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and management intensive and relatively complex to learn and implement. They are dynamic systems, offering farmers many possible combinations of practices to choose from and adapt, according to their local production conditions and constraints (Kassam et al. 2009; Godfray et al. 2010; FAO 2011b; Pretty et al. 2011).

The development of SCPI requires building on the core principles and practices outlined above as the production base and finding ways to support and self-empower producers to implement them all, through participatory approaches and stakeholder engagement. In addition, SCPI must be supported by coherent policies, institutional support, and innovative approaches to overcome any barriers to adoption. Monitoring and evaluating the progress of change in production system practices and their outcomes at the farm and landscape levels are critical.

One of the main criteria for ecologically sustainable production systems such as CA is the maintenance of an environment in the root zone to optimize conditions for soil biota, including healthy root function to the maximum possible depth. Roots are thus able to function effectively and without restrictions to capture plant nutrients and water as well as interact with a range of soil microorganisms beneficial for soil health and crop performance (Uphoff et al. 2006; Pretty 2008). In such systems with the above attributes, there are many similarities to resilient “forest floor” conditions (Kassam et al. 2009). Maintenance or improvement of SOM content and soil structure and associated porosity are critical indicators for sustainable production and other ecosystem services.

A key factor for maintaining soil structure and organic matter is to limit mechanical soil disturbance in the process of crop management. For this reason, no-tillage production methods—as practiced, for example, in CA—have in many parts of the world been shown to improve soil conditions, reduce degradation, and enhance productivity. However, as a stand-alone practice, the elimination of tillage would not necessarily lead to a functioning sustainable production system. This requires a set of complementary practices to enable a functioning soil system as well as the whole agroecosystem to deliver a range of ecosystem services.

The contribution of practices that implement the technical principles of CA—including mulch cover, no-tillage, legume crops, and crop rotations—in important ecosystem services is shown in Table 14.1 and Figure 14.1a and b. Even where it is not possible to install all desirable practical aspects in the production system at the same time, progressive improvements toward those goals should be encouraged. However, for any agricultural system to be sustainable in the long term, the rate of soil erosion and degradation (loss of organic matter) must never exceed the rate of soil formation (though the steeper the slope, the greater the danger that this could happen). In the majority of agroecosystems, this is not possible if the soil is mechanically disturbed (Montgomery 2007). For this reason, the avoidance of mechanical soil disturbance can be seen as a starting point for sustainable production. Once it has been brought into good physical condition, no further tilling of the soil is therefore a necessary condition for sustainability but not a sufficient condition. For SCPI, including ecosystem services, other complementary techniques are required as mentioned already, of which the practices related to the above three CA principles constitute the bare minimum for ecological sustainability (FAO 2011b).

To achieve and sustain the necessary intensification of these production systems to meet the increasing demand for food and other ecosystem services, productivity needs to be optimized by applying best management practices such as good-quality adapted seeds, adequate nutrition, and protection from pests and diseases (weeds, insects, and pathogens) and avoiding soil compaction. In addition, efficient water management and timely operations are required within suitable cropping systems to achieve desirable and acceptable outcomes.

In light of the above, it is clear that sustainable soil management depends on both what and how crops are grown, as well as on additional aspects of soil and landscape management, which includes the horizontal integration of other production sectors such as livestock and forestry. The special role of deep-rooted legumes such as pigeon pea (*Cajanus cajan*), lablab (*Dolicos lablab*), and *Mucuna* (*Stizolobium cinereum*) in building soil structure and biopores for drainage and aeration, in contributing biologically fixed nitrogen to improved nitrogen stocks in soils, and in generating both biomass and edible products is a case in point. Beneficial effects of cover crops on soil and water quality, ecological sustainability, and crop and livestock productivity have been known for many years (e.g., Hargrove 1991). Similarly, species diversification as the third principle of CA is related to integrated management of insect pests, pathogens, and weeds, and the effectiveness of control of pests, pathogens, and weeds depends on both what and how crops are grown. Species diversification involving crops of different durations and complementarity is also related to the use and management of resources of different crops in space and time to maximize and optimize the production during the growing season every year to its fullest potential in an increasingly variable and unpredictable climate. Furthermore, in order to establish diversity of soil biological activity, it is necessary to include in the cropping system a diversity of crops instead of monocropping or reduced crop diversity.

CA is now adopted on about 125 million ha of arable land worldwide, which corresponds to nearly 10% of the total cropland (Friedrich et al. 2012). Some 50% of this area is located in the developing regions. During the past decade, it has been expanding with an average rate of more than 6 million ha/year. The highest adoption levels, exceeding 50% of the cropland, are found in the southern part of South America, the Canadian prairies, and Western Australia. Fast adoption rates are now being seen in Central Asia and China, alongside increasing policy support and early large-scale adoption taking place across Africa, particularly in Zambia, Zimbabwe, South Africa, Tanzania, Kenya, Morocco, and Tunisia. Europe now has some few pockets of adoption, particularly in Finland, Spain, France, Italy, the United Kingdom, and Switzerland (Kassam et al. 2010; Derpsch and Friedrich 2009; Friedrich et al. 2012).

14.5.2 Linkage with Landscape Health

Soil forming factors include topography, climate (microclimates), and parent materials, all of which vary by landscape type and magnitude (Jenny 1980). Soils are variable according to their positions in the landscape. Landscapes distribute water and energy according to landform characteristics. In the northern hemisphere, the north-facing side of a hill, in contrast to the south-facing side, will receive less radiation and be cooler and moister, have more organic matter, and be less drought prone. The top or crown of a hill or hummock will catch less rainfall, and a shallow or more weakly developed soil profile will be found. By contrast, a depression or foot slope position will receive more water and have a deeper soil profile.

Soils formed on different landform facets will have different risks and fragility characteristics related to crop conditions. Soil biologic processes will occur differentially as well by landscape position because of the variable microclimate conditions and soil development (or degradation). Land managers need to recognize the range of soil health and functional characteristics associated with landscapes in order to develop conservation agriculture systems as well as monitoring and evaluating performance and risks.

Soil quality strongly affects agricultural land use and thus the shaping of the landscape. Any change in soil quality, whether through degradation processes or soil health improvement, will have consequences not only on the field or farm level but also on a greater scale, the landscape. In addition, landscape normally consists of a combination of different ecosystems that are interlinked more or less closely with each other. The healthier the soil is under agricultural use, the lesser the off-site effects that can be expected upon adjacent ecosystems of the same landscape.

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> Good land husbandry is the active process of implementing and managing preferred systems of land use and production in such ways that there will be an increase—or, at worst, no loss—of productivity, of stability, or of usefulness for the chosen purpose. Also, in particular situations, existing uses or management may need to be changed so as to halt rapid degradation and to return the land to a condition where good land husbandry can have fullest effect (Shaxson et al. 1977).

If a production system, as represented by the features of the type of land use and those of its management characteristics, is imposed on an area of fragile or hazardous land (e.g., sandy soil, steep slope, and/or shallow depth, etc.), any erosional degradation arising from inadequacy of management will occur more rapidly toward a condition of lower productive potential than if the enterprise were located on flatter and/or less fragile land; the land itself will "wear out" toward a condition of lower productivity.

This has two implications:

- If the enterprise cannot be transferred to another ”safer” or suitable location, then a more protective production system such as CA or agroforestry (Saha 2010) would provide increased security and prolong the soils' usefulness (better management systems).
- If a choice of sites on a landscape is possible, then the safest strategy will be to locate the physical production system(s) on a (varied) landscape in such ways that there is rational matching of "hazardous" land uses onto the "safer" land units and of the "safer" uses onto the land units of greater hazard (site-specific management).

  To achieve any such rationalization, due attention needs to be given to catchment-oriented land resource survey, assessment, and mapping,

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> followed by physical planning of layout of fields and infrastructure items in catchment-related patterns, to facilitate effective management of any runoff that may occur in consequence of excessive rainstorms (Carver 1981; Shaxson et al. 1977). This is of particular significance where "new" land is being opened to cropping. This is because a physical allocation of proposed land uses that is sensitive to the physical characteristic of the chosen landscape is more forgiving of mistakes in management than where land use allocations have not taken account of such realities.

Achieving this effectively represents the achievement of good land husbandry (Shaxson et al. 1989).

14.5.3 Restoring Degraded Agricultural Soils and Landscapes

A sustainable approach to soil management in rainfed and irrigated production cannot be a single technology but rather a range of mutually reinforcing practices. For both tillage and no-tillage systems, their best performances can be achieved only when the production systems are supported by effective plant nutrition, soil moisture provision, and best agronomic practices. Production systems are most sustainable and function best when all three key soil, crop, and environmental management principles listed in Section 14.5.1 are applied simultaneously. CA is a good example of progress in this regard as it is based on no-till and maintenance of soil cover and has now spread across all continents and ecologies (Hobbs 2007; Friedrich et al. 2009; Kassam et al. 2009, 2010). There are other complementary ecosystem-based approaches, such as the SCPI, that have also proven to be successful as a basis for sustainable intensification in all continents under a wide range of circumstances (Uphoff et al. 2011; Kassam et al. 2011b). The responses of rice plants to aerobic soil environment suggest the possibility of discovering comparable positive responses in other crops also and establishing the scientific knowledge that can explain the effects of the symbiotic interactions between root systems and their coevolved soil microorganisms on the crop's phenotypic performance.

Sustainable production systems also mobilize plant nutrients through biological transformations of organic matter, providing micronutrients that may not otherwise be available (Flaig et al. 1977). For example, mulch-based no-till production systems can retain and mimic the soil's original desirable characteristics ("forest floor conditions") on land being first opened for agricultural use. Throughout the transformation to agricultural production, sustainable systems based on an agroecological no-tillage approach can safeguard desirable soil characteristics, sustain the health of long-opened farmland that is already in good condition, and regenerate land that has reached poor condition due to past misuse (Doran and Zeiss 2000).

Such types of information from soils and ecosystems in good condition under CA systems provide a range of "yardsticks" against which to compare the benefits of CA and the health of the soil and the ecosystem, as against the "classical" tillage agriculture. Tillage agriculture with monocropping and no organic cover represents the most vulnerable and detrimental production system, whereas CA represents a more sustainable option (Montgomery 2007).

Sustainable soil management as practiced in CA systems has resulted in the enhancement or rehabilitation of the soil resource base and its agroecological potentials, thus enabling the avoidance of soil degradation and repair of lands, leading to sustainable intensification and the harnessing of ecosystem services. This is illustrated in the examples for Brazil, Australia, and China given in the next sections.

14.5.3.1 Brazil

The soil degradation in South Brazil was reverted initially by reducing tillage intensity. This involved the use of a chisel in substitution of the moldboard plow and the reduction in the number of disc operations. The first no-till experimental plots were set up in the early 1970s in Rio Grande do Sul and Paraná States. However, the successful diffusion of no-till systems on a broader scale remained erratic until late 1980s. The first obstacles that had to be overcome were control of weeds without soil tillage or a hoe, as well as unavailability of planters able to work with crop residues. There was also the need to select appropriate cover crop options to intensify the cropping system in substitution of fallow, to produce enough crop residue to protect the soil and offset the scarce technical assistance, high price of herbicides, and many technical doubts about the efficiency of lime and fertilizer surface broadcast instead of soil placement (Amado and Reinert 1998; Bernoux et al. 2006; Bolliger et al. 2006).

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In the 1980s, farmers began to organize themselves into no-till–promoting associations, such as the "Clube da Minhoca" ("Earthworm Clubs") and the "Clubes Amigos da Terra" ("Friends of the Soil" clubs or "Earth" clubs), as well as private research institutions, such as the "Fundacão ABC" (ABC Conglomerate of Farmers' Cooperatives) to promote the adoption and diffusion of no-till (Borges Filho 2001; Dijkstra 2002).

The initial drive to expand the adoption of no-till was led by pioneer farmers, who also organized the first Brazilian no-till conference in 1981 (Steiner et al. 2001). No-till technologies and systems subsequently spread fairly rapidly from Paraná to other Southern Brazilian states and neighboring Paraguay, where similar environmental conditions existed.

A steady interregional migration of farmers from Southern Brazil to tropical Brazil brought a transfer of the basic zero-till principles in its wake, but the different agroecological conditions of humid subtropical Southern Brazil compared to those of frost-free, seasonally dry, tropical Brazil, as well as the different scales of large cerrado farms compared to generally smaller farms in the South, meant that no-till systems had to undergo scale and regional adaptation (Spehar and Landers 1997; Bolliger et al. 2006). The first records of mechanized no-till in South America were in the Brazilian state of Goiás dating from 1981/1982 (Landers et al. 1994). In Brazil, especially, no-till-type land management expanded from an estimated less than 1000 ha in 1973/1974 to nearly 26 million ha in 2010/2011 (Bolliger et al. 2006; Kassam et al. 2010).

More than 45% of total cultivated land in Brazil is now estimated to be managed with no-till (Scopel et al. 2004), although in Southern Brazil, this figure is reported to exceed 80% (Amado et al. 2006; Denardin and Kochhann 1999; Bolliger et al. 2006). Among the leading no-till nations, Brazil is purportedly the only one with both substantial no-till in the tropics as well as, importantly, a significant amount of smallholder no-till farms (Ralisch et al. 2003; Wall and Ekboir 2002; Bolliger et al. 2006). The latter is perhaps of particular significance, as, contrary to no-till spread in general, the adoption of true (permanent rather than sporadic) no-till systems by smallholder farmers worldwide has been poor, remaining, as yet, relatively marginal outside Brazil, Paraguay (where appropriate systems have spread from Southern Brazil), and small parts of Central America, where similar systems were already traditional (Buckles et al. 1998). Berton (1998) suggests that the main reasons for smallholder farmers in Southern Brazil to adopt no-till practices include labor and time savings, erosion control, greater income, and higher yields. Ribeiro and Milléo (2002) concur that once plowing and mechanical weeding are discontinued, labor savings and less drudgery are the major incentives expressed by smallholder farmers. Some Brazilian farmers are now into their third decade of practicing no-till land management.

In regions that experience high-intensity rainfall and support undulating terrain and/or erodible soils, protecting the soil from erosive raindrop impact through sufficient vegetative mulch is conceivably the best strategy against excessive runoff and erosion (Amado 1985; Calegari 2000, 2002; Erenstein 2003; Wildner 2000). Only not plowing, in turn, means that a protective biomass cover or mulch from previous crops is maintained on the soil surface.

The main advantages of mulch agriculture include reducing evaporation from bare soil (Stone and Moreira 1998), mediating soil temperature extremes (Derpsch et al. 2001), providing a buffer against compaction under the weight of heavy equipment (Séguy et al. 2003), smothering weeds (Darolt 1997; Kumar and Goh 2000), creating a favorable environment for beneficial soil fauna and flora (Balota et al. 1996), and preventing soil and water contamination from pesticides and nutrient leaching (Scopel et al. 2004). However, the practice may also make the planting process more complicated, allow pests and pathogens to reproduce and spread longer in close proximity to crops (Forcella et al. 1994), protract the warming up of soil after cold periods, induce erratic crop germination, and decrease the efficiency of fertilizers and herbicides (Banks and Robinson 1982; Rodrigues 1993). Nevertheless, no-till in itself, without soil cover (e.g., if residues are burnt, grazed, or otherwise exported from the field) or under an unbalanced nutrient budget, can lead to similar soil degradation and reduced crop productivity issues as conventional tillage system.

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Rather than rely purely on crop residues from a main crop to provide adequate and permanent soil cover, especially in regions where the climate favors fast decomposition of residues, one of the major Brazilian adaptations of no-till has been the strong emphasis on integrating fast-growing winter cover crops and summer crop rotations into no-till cropping systems. Such crops can be intercropped prior or planted immediately after the harvest of the main crop and rapidly produce abundant mulch, consequently allowing a succession of enhanced, year-round biomass accumulation. This can compensate for fast residue decomposition, as well as offsetting any potential lack of soil cover (Séguy et al. 1996).

Due to the high amount of mulch left on the soil surface at seeding time, Brazilian farmers hence commonly refer to no-till as “plantio direto na palha” or “planting directly into straw" (Amado et al. 2006). Derpsch (2001) and Steiner et al. (2001) argue that the complete integration of cover crops into no-till cropping systems is probably the single most fundamental key to the success of such systems in Brazil. Two decades of farm experience with cover crop management in fully integrated no-till systems result in good improvement. Seed quality and genetic material of cover crop are key points. Cover crops in cropping systems deserve the same attention in the quality of management as do cash crops. Cover crops sometimes need fertilizer input such as nitrogen and phosphorus or can even be used after chiseling or ripping the soil when the soil resistance is too high. The mixture of cover crops is a very ecological approach, and many mixtures used include black oat and vetch, black oat and radish oil, rye and black oat, Secale cereal and vetch, and so forth. Some mineral Edit OK? fertilization can be split between cover crops and cash crops; farmers call this a crop rotation fertilization instead of cash crop fertilization. The main advantage of this system is the avoidance of applying too much fertilizer in a single application, which increases the environmental impact, increases the cover crop biomass, stimulates nutrient cycling, and stimulates biological activity.

Functions of cover crops broadly include the following: (1) providing additional fodder, forage, food, biofuel, and secondary commercial or subsistence products for livestock and humans; (2) directly adding or sparing nitrogen to/from the soil through symbiotic N_2 fixation from the atmosphere; (3) converting otherwise unused resources, such as sunlight and residual soil moisture, into additional biomass and, concomitantly, upon the breakdown of their residues, increasing the buildup of SOM; (4) capturing and recycling easily and moderately easily leachable nutrients (NO_3, S, K, Mg, and Ca) that would otherwise be lost beyond the rooting zone of commercial crops; (5) ameliorating soil structure and buffering against compaction by creating and stabilizing additional root channels that differ from those of the main crops and by stimulating soil biological activity through, inter alia, the release of root exudates; (6) improving the management of acidic soils by releasing various products that can mobilize lime movement through the soil profile, decarboxylize organic anions, function in ligand exchange, and add basic cations to the soil; (7) facilitating weed management by competing against or smothering weeds that would otherwise become noxious in the main crop cycle; and (8) breaking the cycle of, or repelling or suppressing, certain pests and diseases that could otherwise build up in continuous monocropping systems. On the other hand, integrating cover crops into existing cropping systems generally incurs extra costs of seed and agrochemicals (e.g., herbicides to terminate the crop before the next main crops or nitrogen and phosphorus fertilization), extra labor and managerial skill required to establish and maintain the crop, as well as the opportunity cost of the land and equipment, while the rewards of cover crops may well take time to properly manifest themselves.

Tropical soils have a mineralogy that is dominated by low-activity clays and sesquioxide material, making soil fertility and functionality integrity much more SOM dependent than temperate soils. In some tropical Brazilian soils, 70%–95% of cation exchange capacity (CEC) is dependent on the SOM (Bayer et al. 2000a). In such soils, SOM status is crucial to ensuring good crop productivity and is often postulated as the single most important element of the soil restoration process associated with Brazilian no-till regimes. In principle, both the decreased erosion losses of SOM-rich topsoil (Lal 2002; Rasmussen and Collins 1991) and the slower SOM mineralization rates in zero-till soil compared to plowed soil suggest that no-till provides more favorable conditions for SOM buildup than conventional tillage. Not turning the soil, for example, means the following: (1) less soil macroaggregates are disrupted, consequently leading to the increased formation of stable microaggregates that occlude and protect particulate organic matter (POM) from microbial attack (Amado et al. 2006; Feller and Beare 1997; Lal et al. 1999; Six et al. 1998, 1999, 2000; Fabrizzi et al. 2009); (2) there is less stimulation of sharp increase in microbial activity and concomitant release of CO_2 in response to enhanced soil aeration (Bayer et al. 2000a,b; Bernoux et al. 2006; Kladivko 2001); and (3) there is less mixing of residues deeper into the soil where conditions for decomposition are often more favorable than on the soil surface (Blevins and Frye 1993; Karlen and Cambardella 1996). In this context, Mielniczuk (2003) estimated the rate of SOM mineralization under conventional tillage regimes in Southern Brazil to be, on average, 5%–6% per year compared to an average of about 3% per year in no-till soils. Although the actual amount of SOM storage potential in a given soil is in turn largely determined by climate and the capability of soils to stabilize and protect SOM, this itself generally is largely determined by soil texture, soil mineral surface area, and soil mineralogy, with soil parameters such as water-holding capacity, pH, and porosity acting as rate modifiers (Six et al. 2002b). The large majority of Brazilian literature does indeed suggest that SOM accumulation in no-till soils exceeds that of plowed soils and that this is the case over a range of soil textures, from sandy loams (Amado et al. 1999, 2000, 2001, 2002, 2006; Bayer et al. 2000a,b, 2002) to heavy clay (>60% clay) soils (Amado et al. 2006; De Maria et al. 1999; Perrin 2003), both in Southern Brazil (Muzilli 1983; Sá et al. 2001a,b; Zotarelli et al. 2003) as well as in the degraded savanna region known as the cerrado further north (Corazza et al. 1999; Freitas et al. 1999; Resck et al. 1991, 2000; Scopel et al. 2003). Bernoux et al. (2006) reviewed some 25 published and unpublished data sets on the rate of C accumulation in Brazilian no-till soils and observed that reported C accumulation rates in excess of those found in comparable plowed soils vary from around 0.4 to 1.7 t C ha^{-1} $year^{-1}$ for the 0- to 40-cm soil layer in the cerrado region and between 0.5 and 0.9 t C ha^{-1} $year^{-1}$ in Southern Brazil, with an overall average accumulation of 0.6–0.7 t C ha^{-1} $year^{-1}$.

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Brazilian research data also indicate that the composition and quality of SOM in no-till soils differ from those of plowed soils. Various studies have also found that the relative amount of free labile or more recent (e.g., POM) rather than humified and occluded SOM fractions is higher in no-till soils compared to plowed soils, which in turn has important ramifications for soil structure and nutrient cycling and as a source of energy for soil microbial biomass. Other studies suggest that SOM responds linearly to increasing rates of residue input over a variety of soils and climates (Bayer 1996; Black 1973; Burle et al. 1997; Rasmussen and Collins 1991; Testa et al. 1992; Teixeira et al. 1994). For example Burle et al. (1997) obtained a close relationship between SOC in the 0- to 17.5-cm soil layer and residue quantity added by 10 different no-till cropping systems. Sisti et al. (2004) and Amado et al. (2006) further studied the role of N additions in SOM buildup under no-till in Brazil, and both found that where rotations with N_2-fixing legumes were included, much more SOM was accumulated, hence highlighting the fact that for there to be an accumulation of SOM, there must be not only a C input from crop residues but also a net external input of N. They further postulated that where net N balance was close to zero over the whole crop rotation, little SOM accumulation was to be expected. Amado et al. (2006) reported that pigeon pea and *Mucuna* cover crops integrated into no-till maize cropping systems had the highest C accumulation rates under no-till and that intensive cropping systems, including mixtures of black oat with hairy vetch in winter and maize with cowpea in summer. Sá (1999) suggests that the immobilization process is most intense during the first years of no-till but, after 5 or more years, gradually diminishes due to the increased surface concentration of SOM acting as an N source, thereby effectively counteracting N limitations induced by residues input on the soil surface.

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Both in tropical and subtropical Brazil, legume residues left on the soil surface decompose rapidly and provide a prompt N release, sometimes so fast that it causes asynchronies with maize demand (Acosta 2005; Aita and Giacomini 2003; Vinther 2004). Common vetch residue left on the soil surface in Santa Maria, for example, released 60 kg of N per hectare in only 15 days (Acosta 2005).

14.5.3.2 Australia

Australian farmers became increasingly concerned about soil degradation during a dry period in the 1970s. They saw how plowing of the soil was not sustainable in such an unforgiving and harsh climate (Crabtree 2010). There were also other dry periods where soil erosion was a serious concern, particularly in the 1930s and then potentially again in the first decade of the 2000s. However, during this recent decade, Australian farmers were prepared! They had widely adopted no-till farming, and this greatly mitigated the severely damaging effects on the soil and maintained financial viability during such droughts.

No-till solved most degradation: An in-depth Australian experience with land degradation and the usefulness of no-tillage techniques to manage these concerns are well documented in Crabtree (2010). It was wind erosion concerns that initiated farmers' determination to find a better way to farm. There was no other soil degradation concern that motivated farming practice change. As two broad-spectrum herbicides, SpraySeed (paraquat:diquat) and Roundup (glyphosate), became available in the early 1980s, farmers began reducing their reliance on tillage. Through trial and error, both farmers and researchers gained confidence in the technique (Crabtree 1983, 2010; Flower et al. 2008).

While the initial adoption was slow, the technique of spraying herbicides, and then planting the crop, with little soil disturbance, was the beginning of no-tillage in Western Australia. The experience of farmers revealed many other soil benefits. In fact, most of the concerns with soil degradation were significantly mitigated with no-tillage through time.

No-till both improved soil structure with less vehicle compaction and increased the steady state of microbial activity, which gave the soils some biological structure. Waterlogging became less common due to better infiltration (and some dryer years). Soil salinity was somewhat mitigated as soil water runoff was less common and there was less water running to low-lying areas where it contributed to elevated water table levels. Perhaps three soil degradation challenges are not improved by no-tillage: nutrient removal, acidity, and water repellence.

Nutrient removal: The soils of South West Australia are highly weathered and generally have coarse-textured surfaces with low soil fertility and acidity, limiting crop and pasture production (Moore 2001; McArthur 2004). Soil availability of macronutrients nitrogen (N), sulfur (S), potassium (K), and phosphorus (P) and micronutrients copper (Cu) and zinc (Zn) have the potential to limit crop and pasture growth (Moore 2001). While calcium (Ca), magnesium (Mg), manganese (Mn), and molybdenum (Mo) are important nutrients, they are generally not considered to be limiting plant production. Soil fertility of Australian soils has been increased by the application of fertilizers (Weaver and Wong 2011). Nevertheless, cropping results in significant removal of nutrients, and continued application of nutrients is required to maintain long-term sustainability and productivity of cropping systems.

Soil acidity: Soil acidification is a natural process enhanced by agriculture. Each crop that is harvested is essentially alkaline material. Since no-tillage increases whole farm yields, it is effectively removing more alkaline material from the paddocks. Also, the use of nitrogenous fertilizers and the growing of pulse crops cause acidification. Consequently, soils are becoming more acid through time, especially when cropped. Lime application is required to maintain the productivity of most soils, the exception being soils with an alkaline base. Acidification happens more rapidly in slightly acid sandy soils and where leaching rains are common. Also these soils have low levels of organic carbon, less than 1.5%, giving the soil low capacity for the prevention of soil pH decline.

Some native Australian plants have adapted to these acidic conditions, over many thousands of years, and they can also fix atmospheric N, further acidifying the soil. The most common of these species comes from the *Acacia* genus. After many years, their N fixation results in the soil becoming very acidic at depth. Such soils in Western Australia are known as Wodgil soils; however, the area affected by these naturally very acidic soils is less than 5% of Western Australia's agricultural land (Gazey and Davies 2009). The result of such strong acidification is severe soil degradation, making the soil unproductive.

The solution to this form of soil degradation is the addition of large amounts of lime. Under a no-tillage system, the movement of this lime into a 20-cm soil profile depth can take 4 years (Flower and Crabtree 2011). For a more rapid amelioration of these acid subsoils, farmers have also used deep tillage or plowing. By doing so, they are exposing themselves to soil erosion risk. However, large yield responses have been achieved immediately (Davies 2011), and this has encouraged farmer adoption of this technique.

Water repellence: Native vegetation can induce water repellence (McGhie 1980). Nevertheless, Australian sandy soils that contain less than 3% clay are also capable of becoming water repellent within 10 years of agriculture practices (Crabtree 1983). The sands develop a wax coat around individual sand particles (Mashum et al. 1988). The wax is the remnant of plant residue decomposition, and it causes water to run to the lowest-lying hollows, causing wetting in preferred pathways. Such a phenomenon exists across several countries. However, Australia has the largest area, with about

5 million ha naturally predisposed to the problem (Summers 1987; Crabtree and Henderson 1999; Cann 2000).

This problem is debilitating to farming. King (1981) discusses crops and weeds germinating over a 3-month period and how water repellence makes weed control very difficult. Nutrients are tied up in the dry topsoil, and microbial activity is restricted. Insects can become established on the first flush of emerging weeds that typically grow in the hollows, making later-emerging weeds, in colder conditions, more exposed to insect attack.

Several solutions have been adopted to overcome the problem. The most common and successful technique is to apply clay to the topsoil and physically mix the sand into the clay such that the top 15 cm of soil now contains an average of 3%–5% clay (Cann 2000). The hydrophilic nature of the clay overcomes the hydrophobic nature of the waxed sand. The technique is called "claying," and it is considered a likely permanent solution. After claying, farmers typically revert back to no-tillage.

In some environments, no-till can reduce the impact of water repellence. The technique requires disc seeders, continuous no-till, full stubble retention, no sheep in the farming system, and no pulse crops in the rotation (Margaret Roper, personal communication). The less tillage, the better, and indeed work by Roper at Munglinup (Western Australia) has shown that such a system creates biopores that assist in soil wetting. It is not clear if this option has broad applicability, though.

Compaction: Soil compaction is a real constraint, although subtle and often unseen. The driving of vehicles across paddocks causes compaction at up to 50-cm depth (Ellington 1986). This compaction restricts root growth. Farming with livestock can also cause surface compaction. Some soils, with shrink-and-swell clay characteristics, can self-heal, while others, like loamy sands, do not and may require deep tillage to ameliorate them (Jarvis 2000). Improved microbial activity, as a result of no-tillage and stubble retention, also helps to soften soils.

A combination of controlled traffic and no-till has been shown to give strong yield improvements and enables soils to soften (Tullberg et al. 1998). The technique has been readily enabled by GPS-guided farming machinery with matching implement widths and is becoming increasingly adopted.

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Waterlogging and sodicity: These two degradation issues are restricted to small areas of the Australian cropping landscape. No-till enables more diverse crop rotations, which help manage waterlogging. Permanent raised beds (PRBs) are also used with good effect (Bakker et al. 2005). Sodicity is improved with no-till and further improved with the addition of gypsum.

Australia is a harsh and unforgiving countryside, due to some poor soils and erratic weather where drought and floods are common. Australian farmers had to make radical adaptations to their agricultural practices to minimize the extent of soil degradation. The standout and single most successful soil management strategy, which has had almost complete adoption in Western Australia, is no-till. No-till adoption was largely and proudly farmer led, with minimal government support or investment. The Australian farmer groups, the universities, and the Australian and state governments each play a necessary part in monitoring and providing insight into the best practices to help overcome soil degradation and even to improve Australian soils over their natural state.

14.5.3.3 China

Conservation agriculture for soil conservation: China is paying more attention to tilled soils being more susceptible to water and wind erosion. The best solution to control water and soil erosion is to eliminate tillage. Practices that improve water use efficiency and natural resource management by reducing runoff and erosion are of great importance. Therefore, the adoption of CA practices, providing more residue cover and less soil disturbance, has received considerable attention. Since their beginnings in response to issues from the American "dust bowl" era, several decades of development have demonstrated that CA systems are a valuable means of reducing erosion by both water and wind (Uri et al. 1998) because of low soil disturbance and soil surface protection with crop residues.

Conventional tillage (CT) in dryland farming areas of northern China includes moldboard plowing to a depth of about 20 cm, followed by harrowing, hoeing, rolling, and leveling. All the residues in the fields are removed for animals or as fuel before plowing. In some parts of northern China, particularly in the North China Plain, burning crop residue has increased during the last decades.

Long-term moldboard plowing and residue removal/burning have increased the risks of wind and water erosion and the formation of hardpan in the deep soil layer. It has also resulted in poor soil physical and chemical properties, as well as high inputs of energy and labor, which apparently lead to low farmer incomes. To address these

TABLE 14.3
Magnitudes of Soil Sediment Transport in Comparisons of CA and CT

Region	Testing Site	Collection Time	CA (g)	CT (g)	Reduction (%)
Loess Plateau of China	Yanggao, Shanxi	March 25, 2004–April 3, 2004	8.4	15.1	44.7
Northeast ridge tillage areas	Lingyuan, Liaoning	March 25, 2004–April 3, 2004	16.3	10.2	37.3
North China Plain	Fengning, Hebei	March 22, 2002–April 21, 2002	12.7	42.5	70.0
	Zhangbei, Hebei	April 8, 2002–May 8, 2002	12.7	42.5	70.0
	Changping, Beijing	March 28, 2005–April 17, 2005	16.7	19.0	12.1
	Yanqing, Beijing	March 16, 2005–March 20, 2005	4.2	5.0	17.0
Farming—pastoral areas	Chifeng, Inner Mongolia	April 22, 2003–May 3, 2003	4.7	7.1	34.2
	Zhenglanqi, Inner Mongolia	March 23, 2003–April 27, 2003	11.3	25.0	54.8
	Wuchuan, Inner Mongolia	March 26, 2003–April 6, 2003	2.9	7.4	61.6
Northwest China	Hetian, Xinjiang	March 16, 2004–April 27, 2004	7.4	105.5	92.9

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problems, various kinds of CA practices have been developed in northern China, such as no-till, controlled traffic, and PRBs, leading to a range of beneficial effects on soil quality, including increase in SOM, decrease in bulk density and improvement in soil structure, higher infiltration rate, greater soil moisture holding capacity, and reduced runoff and erosion (Bai et al. 2008; Gao et al. 2008; Chen et al. 2008).

Effect of CA on wind erosion: Research measuring springtime wind erosion losses in the Yanggao region of the Loess Plateau has shown that CA treatments reduced topsoil loss by 44.7% compared to CT (Table 14.3). At nine other sites across northern and north central China, from the dry, windy conditions of the far west to the relatively temperate plains in the Beijing area, CA treatments consistently reduced springtime wind erosion losses from 12% to 93% depending upon the measurement duration, ambient conditions, and erosive winds (Table 14.3).

14.6 INTEGRATING SUSTAINABLE SOIL MANAGEMENT PRINCIPLES INTO FARMING SYSTEMS

Sustainable soil management and crop production principles of CA can be integrated into most if not all types of production or farming systems. This is because they provide the ecological underpinnings to production and farming systems to generate greater productivity and environmental benefits. Below are some examples.

Organic agriculture based on CA can lead to greater soil health and productivity, increased efficiency of use of organic matter, and reduction in use of energy. Organic CA farming is already being practiced on a smaller scale in the United States, Brazil, and Germany, as well as by subsistence CA farmers in Africa and elsewhere. Tillage-based organic farming is often characterized more by what practices it excludes from its production systems than by what it actually does to harness sustainable production intensification and ecosystem services. Introducing CA principles into organic farming would reduce soil disturbance, improve weed control with mulch cover and crop diversification, and generate greater amounts of organic matter from in situ sources within a more diversified cropping system involving legumes (Altieri et al. 2012).

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Agroforestry systems involve the cultivation of woody perennials and annual crops together in a sustainable manner and are increasingly practiced in degraded areas with perennial legumes (Saha 2010). CA works well with trees and shrubs and within agroforestry and related systems. In fact, several tree crop systems in the developing and developed regions already practice some form of CA, but these systems can be further enhanced with improved crop associations including legumes and integration with livestock. Alley cropping has been one innovation in this area that is beginning to offer productivity, economic, and environmental benefits to producers (Sims et al. 2009).

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CA with trees has now become an important option for many farming situations, particularly in the tropics. These CA systems incorporate varying densities of fertilizer trees in order to enhance biological nitrogen fixation, increase biomass production for surface residue, and conserve moisture. They have become the basis for major scaling-up programs with hundreds of thousands of farmers in Zambia, Malawi, Niger, and Burkina Faso (Garrity et al. 2010; Garrity 2011). The incorporation of the indigenous acacia species *Faidherbia albida* into maize-based conservation agriculture in Zambia on a large scale is a noteworthy example. These programs have demonstrated the practical opportunities for combining fertilizer trees with CA in both small-scale and commercial-scale farming systems.

Shifting agriculture, also referred to as "swidden" or "slash and burn," entails the clearing of land to prepare a cultivation plot and subsequently returning this to regrowth and eventual natural reforestation, during which damaged soil structure and depleted "indigenous" plant nutrients are restored. Shifting cultivation has acquired a negative connotation, particularly because of the burning of vegetation. However, for sustainable intensification, such systems can be adapted to follow CA principles, changing from slash-and-burn systems into *slash-and-mulch* systems with diversified cropping (including legumes and perennial crops) that reduce the need for extra land clearing.

The *System of Rice Intensification* (SRI) has taken root on an international scale in more than 40 countries across all developing regions, including China, India, Indonesia, and Vietnam, moving beyond its origins in Madagascar (De Laulanié 1993). Trained farmers have shown SRI to offer higher income and productivities (use efficiencies) of inputs of labor, nutrients, and water, and to require less seeds, water, energy, fertilizer, and labor compared with conventional irrigated or rainfed flooded rice production systems. SRI advantages have been shown to apply to traditional as well as modern cultivars. As with crops in CA systems, SRI phenotypes are widely reported by farmers to be less susceptible to pest and disease damage. The SRI production concept has been defined on the basis of a set of practices (i.e., seedlings 10 days of age for transplanting, or direct seeding; single plant; wide spacing; mainly moist, not saturated and flooded, soil water regimes; regular weeding to also facilitate soil aeration; and liberal use of organic fertilizers) (Uphoff et al. 2011; Kassam et al. 2011c; Uphoff and Kassam 2009). An SRI system based on CA principles is being practiced on permanent nontilled raised beds as well as in unpuddled paddies in Asian countries, thus eliminating puddling and the soil-disturbing ways of weeding (Sharif 2011). The wheat–rice cropping system in the Indo-Gangetic Plains involves the production of no-till wheat over some 3 million ha with residues from the previous rice crop providing soil cover. It would now seem appropriate to introduce no-till SRI rice in the wheat–rice cropping system and manage the cropping system based on the CA principles.

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14.6.1 CROP MANAGEMENT PRACTICES AND SUSTAINABLE SOIL MANAGEMENT

Standard agronomic crop management practices comprise crop and cultivar choice, crop establishment and yield response to water, crop genetic improvement, pest management, fertilizer and nutrient management, and crop rotation and intensification. Individual crop management practices that form a constituent part of good integrated production systems are often interrelated. The interactions among practices can work synergistically to produce outcomes in terms of productivity via improvements in conditions of the soil as a rooting medium, enabling the better expression of plants' genetic and epigenetic potentials. For example, for a given amount of rainfall, soil moisture availability to plants depends on how the soil surface, SOM, soil structure, and plant root systems are managed. Also, high water productivities under good soil moisture supply are possible only when plant nutrition is adequate. Similarly, no amount of fertilizer application and use of modern varieties will improve water use efficiency and water productivity if the soil has a hardpan in the rooting zone or if the soil has little organic matter to build and maintain good soil structure and porosity for maximum moisture storage and root growth. Equally, without the maintenance of good water infiltration and without soil cover to minimize evaporation from the soil surface, it is not possible to fully optimize and maximize water use and water productivity. Another example is the above-described SRI system: the interrelation of the soil characteristics, providing an optimal rooting environment, allowing different plant spacings, which can lead to different phenotypic plant development as compared to conventional practices.

Thus, agricultural soils maintained in good health and quality will offer the possibility of making optimum soil moisture and nutrients available for crop production over the period of the crops' development and of optimal input use efficiencies through good agronomic manipulation or good crop management. However, good crop management is not an independent variable but a function of how sustainably the production system as a whole is being managed in order to maintain or intensify production while harnessing the desired ecosystem services.

14.6.2 Sustainable Soil Management with Intercropping as an Alternative in Permanent No-Till Systems

In tropical regions, the high rate of organic material decomposition associated with warm and wet climate conditions is a challenge to meeting the prerequisite of permanent soil cover required by CA. Most of the straw input, even when maintained on the soil surface, is decomposed in 20 to 60 days according to the C/N ratio, N content, and lignin content of plant material. This fact results in bare soil and risk of soil erosion and degradation. Also, the weed infestation, depletion of SOM, nutrient leaching, and soil compaction are processes associated with bare soils in the tropics. The decrease in soil productivity as a consequence of deterioration in soil quality is a threat to permanent no-till in the tropics. In order to overcome this situation, the farmers try to increase the amount of crop residue input and select pearl millet as a grass-type cover crop in order to maintain soil cover for a longer period.

The use of perennial forage plants, such as *Brachiaria*, intercropped with grain crops is a promising alternative to providing greater soil sustainability in no-till systems in tropical Brazil. The large-scale success of *Brachiaria* in strengthening soil and production sustainability in Brazil provides a specific example of why participating crops in no-till cropping systems are important to both sustainable soil management as well as sustainable production. There are many species of *Brachiaria* that were introduced from Africa into Central Brazil in the early 1960s, the most common being *Brachiaria brizantha*, *B. decumbens*, and *B. ruziziensis* (Landers 2007). The best *Brachiaria* intercrop alternative with corn has been investigated with N fertilization. The straw of *Brachiaria* in combination with corn stalks can input as much as 17 tons of dry mass per hectare and provide soil cover for more than 100 days. *Brachiaria* pastures on cerrado soils can last up to 5 years and can raise average livestock carrying capacity from 0.3 to 1.0 AU/ha (Machedo 1997). It has been estimated that some 85% of pastures in the cerrado are *Brachiaria* (Landers 2007).

Brachiaria has a deep, well-developed root system that can penetrate depths of more than 1 m, with at least 20% of the total root system present below 0.30 m. Intercropping increases soil aggregation and stability of aggregates, lessens bulk density, and increases macroporosity and water infiltration.

The total dry biomass of a *Brachiaria* root system can reach 1.7 t ha^{-1}. This fact is important for cycling nutrients like potassium, magnesium, sulfur, and nitrogen that are subject to leaching in tropical agriculture soils. The *Brachiaria* mulch decreases the soil temperature, keeping the soil environment cool and wet, thus increasing soil biological activity. Therefore, the intercrop system is very efficient in nutrient cycling and reducing nutrient losses by runoff and leaching.

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This intercrop system can sequester soil carbon in the range of 0.5 to 1.0 t C ha^{-1} $year^{-1}$. These rates are double those for regular no-till carbon sequestration with systems that have only a tillage change grain crops held constant. The soil loss was reduced to the range of 0 to 3 t ha^{-1} $year^{-1}$, which is around three times lower than other no-till grain systems, and it is in equilibrium with soil formation.

The large amount of aboveground *Brachiaria* biomass is important to reduce weed infestation, especially with *Conyza bonariensis, Commelina benghalensis, Euphorbia heterophyla*, and *Cenchurs echinatus*. Weed infestations are one of the most serious threats to continuous no-till in the tropics. The total weed reduction provided by *Brachiaria* generally is in the range of 30%–70%.

Brachiaria can suppress important diseases of soybean and black beans such as *Fusarium solani* infestation by approximately 60%. Also, *Rhizoctonia solani* can be reduced by *Brachiaria* intercropped with grain crop production. One of the most common pathogens in the South American tropics is *Sclerotinia sclerotiorum*, and the combination of a grain crop with *Brachiaria* is one of the best options to reduce this disease. Intercropped *Brachiaria* and maize provides competitive maize yields and forage to cattle during an otherwise fallow period, providing income diversification. This system is an important option to sustain no-till for the long term in tropical environments. It has restored degraded pastureland and degraded forestland in Central Brazil.

14.6.3 CROP–LIVESTOCK INTEGRATION FOR SUSTAINABLE SOIL MANAGEMENT

Pastureland has important ecological functions. It often contains a high percentage of perennial grasses, which have the ability to sequester and safely store high amounts of carbon in the soil at rates that exceed by far those of annual crops. This capacity can be enhanced with appropriate management, for example, replacing exported nutrients, maintaining diversity in plant species, and allowing for sufficient recovery periods between use by grazing or cutting. In conventional farming systems, there is a clear distinction between arable crops and, mostly permanent, pastureland. Under CA-based farming, this distinction does not exist anymore, since annual crops may rotate into pasture and vice versa without the destructive intervention of soil tillage, just an additional element of cropping diversity.

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Integrated crop–livestock systems including trees and pasture have long been a foundation of agriculture. In recent decades, there have been practical innovations that harness synergies between the production sectors of crops, livestock, and agroforestry that ensure economic and ecological sustainability while providing a flow of valued ecosystem services. System integration increases environmental and livelihood resilience through increased biological diversity, effective/efficient nutrient cycling/recycling, improved soil health, and enhanced forest preservation and contributes to adaptation and mitigation of climate change. The integration of production sectors can enhance livelihood diversification and efficiency through optimization of production inputs including labor, offer resilience to economic stresses, and reduce risks (Landers 2007; FAO 2010).

Integration can be on-farm as well as on an area-wide/catchment (three-dimensional) basis. Successful crop–livestock integration should be seen through the lens of nutrient use efficiency and nutrient cycling benefits, of ecosystem health advantages, and of positive biosecurity outcomes, all of which are strong public goods. Successful integration can also halt and reverse land degradation. In many fragile ecosystems, livestock is the mainstay of livelihoods, but at the same time, uncontrolled grazing can lead to land degradation. Under such cases, the issue of mutually beneficial area integration between the primary and secondary production sectors must be addressed at the community and regional levels. Issues to be addressed include dynamic grazing and functional biomass management, species composition for feed quality and ecosystem services, and matching stocking rate to carrying capacity in the context of the prevailing climatic and landscape variability in space and time. In extensive rangeland systems, greater precision in matching stocking rate with feed availability and the exposure time to the recovery requirements of vegetation is possible with satellite-guided overhead remote-sensing systems (FAO 2010).

14.6.4 FARM POWER AND MECHANIZATION FOR SUSTAINABLE SOIL MANAGEMENT

One of the most important yet commonly overlooked inputs in agricultural production systems is farm power. Lack of sufficient farm power in many countries is a bottleneck to increasing and intensifying production, especially where it depends on manual or animal traction power.

Farmers working manually on average can feed only three other persons. With animal traction, one farmer can feed six other persons, and with a tractor, the number further increases to 50 or more persons (Legg et al. 1993). Labor output levels vary widely according to the mechanization level and climatic conditions, and there is a clear correlation between the production levels and the farm power input (Giles 1975; Wieneke and Friedrich 1989), but they also depend on the kind of farming system used (Zweier 1985; Doets et al. 2000). At each of these levels, the energy for the respective farm power needs to be supplied, either through human food, animal feed, or tractor fuel, which could also be biofuel. Bearing in mind the pressure to produce more food for an increased population, increasingly concentrated in urban centers (already now about 50% of the population no longer lives in rural areas), the need for increased mechanization of agricultural crop production becomes obvious (Mrema 1996). It is worth noting that suitable mechanization options can lead to improved

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energy efficiency in crop production, leading to better sustainability, higher productive capacity, and lower environmental damage (Baig and Gamache 2009; Lindwall and Sonntag 2010).

Suitable CA mechanical technologies are commercially available for all technology levels, from the small farmer using exclusively manual power to the large-scale mechanized farmer applying precision farming with satellite guidance. However, small-scale hand and animal traction tools and equipment for CA so far are easily accessible only to farmers in Southern Brazil and Paraguay, while single-axle tractors with CA attachments can be found on the market only in Bangladesh and Brazil. The actual challenge is to improve the accessibility and commercial availability of such tools and equipment for the smallholder farmer in Africa and Asia, as well as in parts of Latin America. In several developing and middle-income countries in Africa and Asia, small workshops and manufacturers are now starting to produce manual and animal traction no-till planters as well as tractor-drawn direct seeding equipment (Friedrich and Kassam 2011; Sims et al. 2011).

Modern technologies do allow a much more efficient use of energy and other production inputs, and they have also been instrumental for allowing ecologically oriented crop production concepts, such as CA, to develop. A crucial input into the development and increased adoption of CA is direct seeding technology, which enables the establishment of crops in undisturbed soils. These modern mechanized technologies have contributed to the success and area spread of CA, which facilitates also the improved delivery of ecosystem services and allows the development toward sustainable agriculture through the reduction of waste and an increased input efficiency (Baker et al. 2007). Yet, in addition, agricultural mechanization can also directly—with more precise application equipment for agricultural inputs and the additional use of precision farming tools—contribute to a reduction in input use. GIS technologies further allow control of traffic of agricultural machinery, so as to minimize areas of soil compaction and, with this, facilitate the development of a functioning soil ecosystem, increasing at the same time the energy efficiency of crop production systems (Tullberg 2007; Wang et al. 2009).

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14.7 LARGE-SCALE LANDSCAPE-LEVEL BENEFITS FROM SUSTAINABLE SOIL MANAGEMENT

Benefits from sustainable production systems are scale independent. They do occur at the field-point scale, but benefits accrue to landscapes, farms, communities, and regions. The four major sets of benefits from sustainable soil management and production systems are as follows:

1. Higher stable production output, productivity, and profitability
2. Adaptation to climate change and reduced vulnerability
3. Enhanced ecosystem functioning and services
4. Reduced greenhouse gas (GHG) emissions and "carbon footprint" of agriculture

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All these are of direct benefit to producers and society as a whole. The relevant socioeconomic indicators include the following: farm profit, factor productivity (efficiency), amount of pesticides applied per unit of output, yield per unit area and per farmer practicing sustainable intensified systems, and stability of production. The relevant ecosystem service indicators include the following: clean water provisioning from catchment areas under an intensive agriculture area; reduced erosion, both wind and water (Mello and Raij 2006; Laurent et al. 2011); increased biodiversity/wildlife within agricultural landscapes; and increase in carbon sequestration and reduction in carbon footprint and GHG emissions of methane and nitrous oxide (Baig and Gamache 2009; Kassam et al. 2011c; FAO 2012).

It is important to identify key indicators that would detect changes in the desired direction at the field, farm, and physiographic landscape level within whose boundary the farm is located and whose management has an impact on the aggregate behavior of the landscape as a whole. CA-based ecosystem services operate in different parts of the world and include the following: the agricultural carbon offset scheme in Alberta, Canada; the hydrological services from the Paraná III Basin in Brazil; the control of soil erosion in Andalusia, Spain; the controlling of water erosion and dust storms and combating of desertification and drought in the Loess Plateau of the Yellow River basin in China; and reducing susceptibility/increasing resilience to land degradation in Western Australia. Controlling land degradation, particularly soil erosion, caused by tillage, exposed soils, and depletions of SOM, has been a main objective of most of such initiatives. Such landscape schemes are possible only when the landscape has a contiguous network of sustainable soil management that mediates such large-scale environmental and economic benefits to the producers and rural as well as urban society. With sustainable soil management practices being applied over large areas, it is then possible to overlay landscape-level development programs to harness large-scale ecosystem services such as carbon sequestration in Alberta, Canada; water-related services in Paraná Basin, Brazil; or erosion control in Andalusia, Spain.

14.7.1 CANADA: CARBON OFFSET SCHEME IN ALBERTA

The province of Alberta has operated a GHG offset system since 2007 that allows regulated companies to offset their emissions by purchasing verified tonnes from a range of approved sources including agriculture projects (Haugen-Kozyra and Goddard 2009). This compliance system for large emitters has provided a rich venue for learning on behalf of all players—the regulated companies, government, scientists, consultants, aggregator companies, and farmers. Climate change legislation was amended in 2007 to require regulated companies to reduce their emissions to a set target below their 2003–2005 baseline. If they could not achieve their target in any year, they could settle their accounts with any of three options: pay into a research fund at a fixed rate of C$15 per tonne CO_2e; trade emission performance credits if they were generated by any company reducing emissions beyond their target; or purchase verified offsets generated within Alberta using Alberta government-approved protocols. The latter option triggered interest and activities in developing protocols across all industrial sectors including agriculture. Offset tonnes trade at a discount to the C$15 fund payment option in order to cover the aggregation and transaction costs.

The Alberta government provides the enabling legislation and regulations. They also provide oversight of protocol development and approvals. Beyond that, the private sector invests in development of protocols, aggregation of offsets and assembly of projects, third-party verification of projects, and the bilateral sales to the regulated emitters. A nongovernment agency, Climate Change Central, also plays a role of facilitator and is the designated operator of the registry of the offsets. All verified tonnes are serialized and tracked by the registry through to the retirement (used for a compliance year) of a particular tonne. The regulator/government ministry holds annual review meetings with the players in the market to review performance, new developments, regulatory changes, and guidance. The amount of offsets used by companies for compliance has been relatively consistent at about 36% of the total annual accounts (CCC 2011). Agricultural offsets have contributed about 36%–40% of all offsets. The most popular protocol has been the Tillage System protocol, which acknowledges the soil carbon sequestration through implementation of no-till practices. The Tillage System protocol has contributed over 8 million tonnes of offsets worth C$100 million over the last 5 years of the offset system.

There are occurrences of 'tonnes' abbreviated as 't'. Please check if this should be made consistent.

The offset system has had many co-benefits beyond reducing GHG emissions and reducing the C footprint of industries. Scientists come together in helping to develop protocols and share a systems view of the production system under review. Science and policy come together and integrate to form protocols and develop a market. The private sector of aggregator and verification companies have integrated efforts and developed streamlined systems to bring offsets to market efficiently. Farmers have developed improved production and record systems. Very often, the financial benefits to the farmer by adopting a protocol far exceed any offset payment for the GHG savings portion. All players are now further along the capacity curve to be in a better position to see and take advantage of other ecosystem good and service opportunities.

14.7.2 Brazil: Watershed Services in the Paraná Basin

As part of a strategy for improvement, conservation, and sustainable use of natural resources, the Itaipú Dam *Programa Cultivando Água Boa* ("cultivating good water") has established a partnership with farmers to achieve their goals in the Paraná III Basin located in the western part of Paraná State on the Paraguay border (ITAIPU 2011; Mello and van Raij 2006). The dam's reservoir depends on the sustainable use and management of soil and water in the watershed/catchment for efficient electricity generation. Sediments and nutrients entering the reservoir resulting from inappropriate land use pollute the water used by the turbines to generate electricity. This phenomenon shortens the reservoir's useful life and increases the maintenance costs of power-generating turbines, increasing therewith electricity generation costs. Thus, in principle, payments could be made through a program to improve the conditions of electricity generation. The spatial unit covered by this program is the whole watershed/catchment. Functioning as a community joining many farmers in the watershed, they reach a scale where environmental impact can be monitored with suitable indicators to establish a system of payment for environmental services.

One of the partnerships established in the *Cultivando Água Boa* program and developed through an agreement with the Brazilian No-Till Federation (FEBRAPDP) is the Participatory Methodology for Conservation Agriculture Quality Assessment (Laurent et al. 2011), based upon former positive experiences with catchment development in Brazil. The first phase in the program is that the partners plan to measure the impacts of farm management through a scoring system indicating how much each farm is contributing to the improvements of the water conditions. (The system is available online in Portuguese at http://plantio.hidroinformatica.org/.) In this regard, a scoring index model for rating the quality of no-till systems has been devised. The model relies on expert knowledge and is being applied to identify soil erosion and land degradation risks arising from any weakness in the adopted CA practices, and possible action needed to address the weakness (Roloff et al. 2011). Consolidating this phase and adapting the principles established for the "water producer" by the National Water Agency, the partners will assign values to ecosystem services generated from farms participating in the program (ANA 2011). Considering the polluter/payer and provider/receiver principles set in the Brazilian Water Resources Policy, farmers with good scores will be paid for their proactive action to deliver watershed services once the Paraná Watershed Plan is established. This will be a new framework for services provided by farmers as compensation for their proactive approach to improve the reservoir water quality and reduce costs for electricity generation by the Itaipú Dam.

14.7.3 SPAIN: SOIL CONSERVATION IN OLIVE GROVES

Olive orchards are an important agroecosystem in the Mediterranean. Andalusia, the southernmost region of Spain, is the main olive cultivation area in the world as it produces a third of the world's olive oil, and around 1.5 Mha or 17% of the surface area is covered with olive groves (Gomez et al. 2009a), which account for 60% of the Spanish olive growing area. Historically, olive cropping has been concentrated on hilly lands, where soil erosion happens to be a very severe and widespread problem. Locally, historical soil loss rates have been reported to reach up to 184 Mg ha^{-1} $year^{-1}$ (Vanwalleghem et al. 2010). Erratic but high-intensity rainfall especially during winter, but also the management of the orchards, lies at the origin of soil erosion. Commercial olive orchards, mainly grown under rainfed conditions, are characterized by extremely adverse management conditions as farmers tend to till intensively to avoid competition of weeds with tree water and nutrient uptake. Therefore, simple conservation strategies, such as no-till with natural vegetation or the establishment of cover crops, are not easily adopted by farmers. Conventional tillage has been the dominant management system in olive orchards over the last decades. The combination of this human-induced low vegetation cover with the steep slope gradients on which these orchards are located, together with the high-intensity rainfall events that characterize the Mediterranean climate, explains why high soil erosion rates have been associated with olive oil production (Beaufoy 2001).

Despite these alarming erosion rates that have been reported in olive groves on sloping and mountainous land, there are authors questioning the severity and extent of water erosion in olive orchards in southern Spain (Fleskens and Stroosnijder 2007). Other authors, however, insist on soil erosion being a widespread threat to the sustainable land use through olive production (Gomez et al. 2008; Vanwalleghem et al. 2010, 2011). Moreover, land use change and the abandonment of the terraced slopes, functioning as anthropic hydrological infrastructures, which protected the soil and preserved the natural vegetation in the recent past, have been progressively collapsing, mainly due to the rapid removal of the soil, causing important land degradation problems (Dunjó et al. 2003).

Despite the gradual introduction of no-till as the soil management system in olive groves, a first agri-environmental measure scheme was introduced in Andalucía in the late 1990s aiming to fight soil erosion in olive orchards mainly by vegetation cover between trees and natural vegetation on the land borders. Other soil erosion control practices were also promoted such as soil tillage along contour lines and the maintenance of pruning residues in the interrow space (Franco and Calatrava 2006). The adoption especially of no-till increased tremendously from 1995 onward and covers today, depending on the study region, between 50% and 95% of the area under olive production (Franco and Calatrava 2006; Leyva et al. 2007; Martinez 2009).

Despite this notable progress in terms of adoption of soil conservation measures in the case of perennial crop production in Spain (Table 14.4), there are still regions where the adoption of soil conservation practices is very low, and, in general, there is much room left for the extension of policy measures to mitigate and invert soil degradation (Calatrava et al. 2011). In addition, the findings of Gomez et al. (2009b) that

TABLE 14.4

Evolution of the Area Under Cover Crop Soil Management Systems in Total Woody Crops and Olives in Spain

	2011	%	2010	%	2009	%	2006	%
Total woody crops (ha)	4.932.002	100	4.986.046	100	5.043.896	100	5.039.440	100
With cover crops (ha)	1.178.297	23.9	1.218.726	24.4	1.066.182	21.1	836.731	16.6
With no-till (bare soil) (ha)	453.219	92	443.309	8.9	431.472	8.6	347.449	6.9
Olives, total area (ha)	2.580.577	100	2.572.793	100	2.568.383	100	2.476.540	100
Olives with cover crops (ha)	680.510	26.4	683.363	26.6	627.1668	24.4	438.828	17.7
Olives no-till (bare soil) (ha)	341.674	13.2	328.716	12.8	299.711	11.7	225.998	9.1

Source: ESYRCE 2006, 2009, 2010, 2011.

Please provide complete details for the works cited here, and please include them in the References.

bare soil, though untilled, is capable of providing more runoff and sediment yield in olive groves under certain conditions should be seriously taken into account while designing conservation strategies. Those have to be driven by their real delivery of ecosystem services and not just by cost-effective minimal conservation approaches. Edit OK? The faster adoption of cover crops compared with no-till as a soil conservation measure in perennial woody crops, and especially in olives (Table 14.4), can therefore be considered an important step toward the mitigation of soil erosion and degradation.

14.8 POLICY, INSTITUTIONAL, TECHNOLOGY, AND KNOWLEDGE IMPLICATIONS

An enabling policy and institutional environment is needed to promote sustainable soil management for agriculture development, which in practice entails a change Edit OK? in process in which interested stakeholders become engaged to produce, in nondestructive ways, based on available and affordable resources, agricultural products desired by the producers, individual groups, and society. However, it is necessary to implement an enabling environment to promote farmers' interest in undertaking sustainable soil management and production intensification and maintenance of ecosystem services. For this, given the necessary understanding, the requirements include effective and integrated development planning and policies backed up by relevant research and advisory/extension systems, and the mobilization of concerned stakeholders in all sectors.

14.8.1 Policy and Institutional Support

Principles of sustainable soil management for agriculture production based on an ecosystem approach form the basis for good agricultural land use and management. It indicates the urgent need for a significant change in "mind-set" concerning care of the soil and landscape, after the realization that erosion of soil (deemed a major and continuing problem) is a *consequence* rather than a prime cause of land degradation, in as much as loss of stable soil aggregates and their counterpart spaces in the soil precedes the accumulation of runoff. This understanding has major implications for how best to encourage and achieve sustainability of productive land uses. It indicates the need to respect and make best and careful use of agroecosystem processes, rather than try to usurp their functions by use of technologies that prove to be inimical to soil life and therefore not suitable or ecologically sustainable.

Policy coherence and cohesion are critical as all governments already have a number of institutions involved in caring for the development of their natural resources. However, the fragmented nature of their organizational arrangement across several ministries (e.g., Agriculture, Forestry, National Parks, Energy, Water), the disconnection from production sectors, and nonworkable relationships within a government often inhibit their full effectiveness.

At national and state levels, the adoption of CA policies is often congruent and supportive of other policies related to the environment, natural resources, energy efficiencies, and more recently, climate change. Policy makers need to both align and document the support, compatibilities, and synergies that may arise from suggested

CA policies. Since CA is a systems approach, policy impacts are numerous and interrelated.

At an agriculture sector level, CA is compatible with robust policies for innovation, technologies, diversity, resource conservation, enterprise risk management, and community development. Policy research and analysis is needed to identify sector policies and institutions that publically fund policies that are counter to CA adoption, societal values, and government directions. For example, some governments have historically had fuel subsidies for farmers to reduce costs (and lower income risks). With increasing fuel costs, the burden on society is projected to increase. CA realizes fossil fuel savings, so the argument for a subsidy diminishes. Crop insurance programs are another example where historic policies favor conventional cultivation systems over CA.

The private sector is another rapidly emerging champion of CA systems. Large retailers have adopted sustainability policies and are starting to require simple certification or proof of production practices. Practices favored are often components of CA systems, or conversely, full CA is the optimization of the desired production characteristics. The early work in life cycle analysis focused upon carbon, GHGs, or energy. More recently, work has moved toward more comprehensive or encompassing approaches such as environmental footprints. Again, CA profiles more favorably than conventional production systems. Financial institutions are other players in the private sector that are increasingly looking at production practices of clients, including agriculture, from an environmental risk perspective and innovation in market opportunities. CA receives high marks. The private sector is unique in that it can formulate and implement policies much more quickly than governments. The private sector has leading players in CA policy that governments need to pay attention to.

Thus, it is necessary to ensure that all relevant institutions in both private and public sectors and at all scales (international to local) have a clear awareness of the basic agroecological and socioeconomic principles upon which sustainable land use is based, and of the ways in which each institution's particular interests and responsibilities may be able to support and embody the CA principles. This commonality of underlying concern with the care of land, underpinning policy cohesion, will facilitate the needed interdisciplinary collaborations to be undertaken with farmers and other land users and the alignment and linkages of new progressive policies.

Agricultural development policy can and should therefore have a clear commitment to sustainable soil management and production intensification. Best sustainable systems cannot be devised based on high-soil-disturbance agriculture. Where agriculture development is maintained by tillage systems, it will generally not be possible to maintain production intensification as well as to continue to deliver ecosystem services because of suppression of soil biotic capacities for self-repeating soil structure regeneration. Hence, all agricultural development activities dealing with crop production intensification should be assessed for their compatibility with dynamic ecosystem functions and their desired services. Any environmental management schemes in agriculture, including certification protocols and payments for environmental services that do not promote the emulation of CA principles and practices as a basis for sustainable soil management, are unlikely to be economically and environmentally sustainable in the long run. This does not mean that non-CA alternatives based on tillage agriculture cannot be considered in new developments, but when they are being planned for deployment, the results in terms of output, productivity, and ecosystem services will generally not match those from agroecological low-disturbance systems in terms of sustainability, and the decision makers and policy planners must be made aware of this.

Regardless of which institution is developing or revising policies, the policies need to be adaptable to changing societies, changing markets, and developing farming practices. This is a case for creating adaptive policies (Swanson and Bhadwal 2010). Analysis must be integrative and forward looking, not a reinvention of the past. Collective and collaborative discussions are needed to ensure that concepts and understanding are consistent and that all points of view result in common values and agreement on direction. Ultimately, adaptive policies have automatic adjustments that arise because the system is well understood, and policies adjust when anticipated conditions arise. Such is not the case with CA, and a more conservative approach of formal policy review and continuous learning should be favored. A key component of adaptive policy is to enable self-organization and social networking. Successes in CA are associated with these developments, and further support is needed for CA organizations. Finally, because CA is complex, an integrated promotion of variation in policy should be analyzed. If a variety of policies are directed at an issue from different directions or sources, and if one fails, then the others may succeed.

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14.8.2 TECHNOLOGY AND KNOWLEDGE SUPPORT

Current crop production systems vary widely. There are many production systems that take a predominantly ecosystem approach and are not only productive but also more sustainable in terms of environmental impacts (FAO 2011b; Pisante et al. 2012). Such sustainable production systems, when fully developed, are based on sustainable soil management. They are, by definition, management and knowledge intensive and relatively complex systems to learn and implement as they must work with nature and integrate as much as possible of the natural ecosystem processes into the design and management of the production systems. This is a continuing task with many possible permutations for farmers to choose from so as to suit their local production circumstances and constraints. They cannot be reduced to a simple standard technology, and thus, pioneers and early adopters face many hurdles before the full benefits of such systems can be realized. Indeed, the upscaling of no-tillage systems to achieve national impact requires a dynamic complement of enabling policies and institutional support to producers and supply-chain service providers.

One bottleneck is often insufficient knowledge about the new soil management and production system. Site-specific research is needed to assist farmers in responding to no-till soil management and production system changes such as in nutrient requirements and pest, disease, and weed problems, as well as for options of green manure cover crops to be incorporated into the crop rotations.

Farmers are not alone in the need for education. Across the countryside, farm consultants and input suppliers also need to learn about and understand CA systems. They are important partners and contributors to local clubs, farmer associations, and CA conferences. If field staff of consulting and retail companies understand

CA systems and see both what is needed at the field level for adoption and how their corporate culture and policies are supportive or not, they can then serve both sides by becoming catalysts for policy changes at the corporate level. Corporate executives will appreciate advice from their own staff to compare against what they are hearing from farmers and farm associations. Farm organizations will appreciate informed dialogues with consultants who are at the forefront of knowledge supporting CA. Consulting and farm input retailers can develop win–win situations with their clients and companies.

Academic institutions (universities, colleges) and large research agencies funded by governments or commodity commissions also need to catch up to CA through their policies and programs. Universities focus on training in reductionist science and place little effort on integrative science. CA is an integrative discipline and, thus, likely unfamiliar territory to those developing curricula and lecturing in the agriculture sciences. Similarly, large research institutions have inertia that is difficult to alter. They may see CA as only a deviation from conventional, intensive production systems and study only components rather than the system. Indeed, in western Canada, innovative agronomic scientists with the federal agriculture department pushed for agronomic treatments to be imposed on no-till rather than conventional-till plots/fields. Only in the last decade has all agronomic research at all prairie federal research stations been carried out on no-till land. Sadly, plant breeders in many places (Canada and elsewhere) still conduct trials and selections on tilled plots. One speculates as to what traits are being selected for that favor CA cropping. Disease or pest issues in residues have been cited as concerns as has a lack of plot-sized equipment.

A particular bottleneck for wide adoption of CA is the availability of suitable equipment. While small-scale CA can be undertaken without special tools by just using a narrow hoe or planting stick, the full benefits of labor saving and work precision can be achieved only using special tools or equipment. These tools all exist at manual, animal traction, and tractor power mechanization levels, yet their local availability for the farmers in most parts of the world is a real challenge. Even where this equipment, such as no-till planters, is on the market, it is often more expensive than corresponding conventional equipment and constitutes a considerable initial investment for the farmer. These bottlenecks can be overcome, for example, by facilitating input supply chains and local manufacturing of the equipment, where feasible, and by offering contractor services or sharing equipment among farmers in a group to reduce the cost for a single farmer. In most small-farm scenarios, even animal traction no-till planters have a working capacity that would exceed the requirements of a single farmer.

Knowledge, information, and technology are increasingly generated, diffused, and applied through the private sector. Exponential growth in information and communications technology (ICT), especially the Internet, has transformed the ability to take advantage of knowledge developed in other places or for other purposes. The knowledge structure of the agricultural sector in many countries is changing markedly (OECD 2011), incorporating a greater awareness in education, research, and development of the need for ecological sustainability of agricultural production systems and landscape management.

14.9 CONCLUDING COMMENTS

Essentially, we have two farming paradigms operating, and both aspire to manage the soil and landscape sustainably. The two paradigms are as follows: (1) The tillage-based farming systems, including intensive tillage with inversion plowing during the last century, aim at modifying soil structure to create a clean seedbed for planting seeds and to bury weeds or incorporate residues. This is the *interventionist paradigm* in which most aspects of crop production are controlled by technological interventions such as soil tilling; genetically engineered varieties; protective or curative pest, pathogen, and weed control with agrochemicals; and the application of mineral fertilizers for plant nutrition. This is still the predominant cropping system around the world. (2) With the development of no-tillage technologies from the 1940s onward, and the discovery of specific farming systems since the 1970s, many of those have taken a predominantly ecosystem approach and are productive and ecologically sustainable. This is the *agroecological paradigm* characterized by minimal disturbance of the soil and the natural environment; the use of traditional or modern adapted varieties; plant nutrition from organic and nonorganic sources including biological nitrogen fixation, feeding first of all the soil from which crops then derive a balanced nutrition; and the use of both natural and managed biodiversity to produce food, raw materials, and other ecosystem services. Crop production based on an ecosystem or agroecological approach can sustain the health of farmland already in use and can regenerate land left in poor condition by past misuse.

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The core agroecological elements of sustainable soil management, and of production intensification based on it, are the practices that implement the three principles—minimum mechanical soil disturbance, permanent organic soil cover, and species diversification—plus other best practices dealing with crop management, including integrated pest control, plant nutrition, water management, and so forth, as well as the integration of pastures, trees, and livestock into the production system, supported by adequate and appropriate farm power and equipment. This concept and associated practical implications must be placed at the center of any effort to intensify production at any farm scale.

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With suitable forms of feeding, protection, and management, the living components of the plant/soil ecosystems integrate and energize the other key components of agricultural production systems—chemical, physical, hydrological—effectively almost free of charge. Through its capacity to reproduce itself, the soil biota sustains the land’s potentials and their outcomes. Damaging these capacities within agricultural systems of land use, through poor husbandry of these resources, should be avoided since it reduces the resilience, sustainability, and potentials for intensification of the current systems, with results that in fact can be foreseen and can therefore be avoided (FAO 1982).

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The development of sustainable soil management and intensification systems requires the acceptance of these principles and finding ways to support and empower the producers to implement them through participatory approach/stakeholder engagement, policy cohesion, coherent policy and institutional support, innovative approaches to overcome equipment bottlenecks, and monitoring progress of change in production system practices and their outcomes at the farm as well as at the landscape level.

There are three nested levels of economic, social, and environmental impacts that can be recognized for identifying, monitoring, and measuring progress by different stakeholders, including farmers. At level 1, it is the change in people's concepts and mind-set as well as production system practices that is the goal. (For example, to monitor progress in the case of sustainable production systems and practices based on CA principles, the indicators would be the specification of effectiveness and stability of the production system, the number of farmers practicing and the area covered, and the rate of innovation.) At level 2, it is the outcomes resulting from the change in mind-set and practices that are being sought (e.g., yield, income, stability, and productivity [efficiency], as well as ecosystem services such as soil health and quality, SOM, biological nitrogen fixation, water infiltration, soil biota [especially earthworms], erosion/runoff, crop health, and specific components of biodiversity such as pollinator bees or natural enemies of pests or specific soil microorganisms). There would be outcomes on the social side such as increases in innovative farm business management, on-farm trialling, and social capital development in terms of farmers coming together to innovate and capture economies of scale. At the third level, it is the change in the state of the economic, social, and environmental conditions of the target group and their area that is being sought. (For example, in the case of the environment, four parameters are important for monitoring progress—physical state of landscape and soil quality, of functional biodiversity, and of water resources in quantity and quality, and climate change mitigation.) In terms of the change in social and economic conditions, social benefits can be decreased stress in the community, increased institutional innovation, stable incomes, and greater resilience. This includes the target groups' own perceptions of type and degree of change.

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Our overall conclusion is that sustainable soil management as a basis for sustainable agricultural production is essential and practicable but depends on both how and what crops are grown, as well as on the engagement of all stakeholders who are aligned toward transforming the unsustainable tillage-based farming systems to conservation agriculture systems regardless of soil, climate, and farmers' economic capacity to invest. It is possible to develop a sustainable production system based on how and what crops are grown but always following CA principles. This would allow the maintenance of the underpinnings of ecological sustainability of production systems in good order so that sustainable production of food and other ecosystem services becomes the norm. This transformational change is now occurring worldwide on all continents and ecologies and covers nearly 10% of the global arable land.

To enable the reduction or elimination of soil degradation on all agricultural soils as a basis for sustainable agriculture, the following policy and institutional action points for policy makers and institutional decision makers are suggested:

- Establish clear and verifiable guidelines and protocols for agricultural production systems, which would qualify as sustainable intensification based on conservation agriculture and other good practices from a socioeconomic and environmental point of view.
- Institutionalize the new way of farming with sustainable soil management in public-sector education and advisory services as officially endorsed policy.

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- Establish the conditions for a conducive environment to support this new kind of agriculture involving sustainable soil and landscape management, including research and technology adoption and the provision of suitable technologies and inputs through the commercial supply markets.
- Establish incentive mechanisms such as payments for environmental or community services, based on the adherence to the established protocols for sustainable soil management and production intensification, and align any eventually existing payments to farmers to such a service-based approach.
- As adoption levels of sustainable soil management increase and the sustainable production intensification becomes an accessible option to every farmer, introduce penalties for polluting or degrading ways of agricultural land use and landscape management as additional incentive for late adopters.

ABBREVIATIONS

Ca: calcium
CA: conservation agriculture
CEC: cation exchange capacity
CT: conventional tillage
Cu: copper
FEBRAPDP: Brazilian No-Till Federation
FFHC: Freedom from Hunger Campaign
K: potassium
Mg: magnesium
Mn: manganese
Mo: molybdenum
N: nitrogen
P: phosphorus
POM: particulate organic matter
PRBs: permanent raised beds
S: sulfur
SCPI: sustainable crop production intensification
SRI: System of Rice Intensification
Zn: zinc

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