

Chapter 2

The Field System

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The field system represents the most basic socio-ecological system through which human communities interact with the biosphere. Field systems are complex, comprising both biotic components (plants, animals, fungi, and bacteria) and abiotic components (chemical and physical elements such as soil minerals, sunlight, moisture, and temperature) that interact through biogeochemical cycles and ecological processes. Energy from the sun flows into the field system and flows out as crop and animal products. Field systems affect natural ecosystems that surround them and, when aggregated, influence regional and global systems.

An agricultural plot is an excellent example of a field agroecosystem. For many smallholders, a single plot is the entire farm enterprise. For others, multiple plots make up a farm enterprise. The mosaic of fields that create a farm is, together with adjacent or adjoining natural areas, part of a local watershed and a larger regional ecosystem. Natural processes as well as decision making at these larger spatial scales affect processes and decision making within the single field and vice versa. For example, a farmer's decision to plant corn intercropped with beans enhances diversity of the field and creates positive benefits for the field system such as additional nitrogen and host plants for beneficial insects. Furthermore, should one of these crops fail, the other may still be marketable. This provides an economic buffer for the farm system. Activity in an agricultural field also influences and is influenced by related social systems such as markets and governance. A good example of the relationship between policy and field systems is the application of subsidies—government inducements for farmers based on production. Often subsidies are given to farmers for specific crops, which can decrease the incentive for maintaining a diversified mix of crops in the field system. This, in turn, can have devastating effects on biodiversity in the field over the long term. In the Philippines, price supports have led to severe erosion and water quality problems as hillsides once covered by forests have been converted to corn and temperate zone vegetables (Coxhead et al. 2001). Given this interrelatedness, sustainable management of individual field systems is a priority in sustainable agriculture and natural resource management development programs.

Field System Components and Processes

A field may be nested within a farm, forest, or other terrestrial landscape system, or may be part of a larger aquatic ecosystem. The following description characterizes the components and processes of an agricultural field system. The components and processes discussed, however, are

present in similar or equivalent forms in most field systems. The description provided here should inform an assessment of any field system.

Continuing with the example of an agricultural plot as a field system, the primary components are soil, water, living organisms, and energy.

Soil is the foundation of an agricultural field and mediates processes essential to the functioning of the system, including: biogeochemical cycling of elements such as carbon and other mineral nutrients; provision of habitat for soil organisms; movement, storage, and decontamination of water; and promotion of plant growth (Brady and Weil 2002). The term “soil quality” reflects the capacity of the soil to carry out ecological services such as resisting erosion, and limiting the negative impact of agricultural production on water and air resources (Karlen et al. 2001). Low soil quality can significantly constrain both the productive capacity of a field system as well as the capacity of the system to provide critical ecosystem services to higher system levels.

Water is essential for crop and animal maintenance and growth, thus representing a basic component of an agricultural field system. For many field managers, water is a limiting factor in the production of crops and livestock. Water is a transient component of the field system, entering naturally as rainwater or applied through irrigation. Regardless of how water enters the system, conservation of water within the field is critical to supporting crop and animal growth. Management of water in a field system also has a significant influence on the quantity and quality of the global water supply.

The living organisms in the agricultural field system play a critical role in its resilience and productivity. Most importantly, living organisms fill ecological niches that sustain the field system. For example, soil biota are key drivers of biological processes that mediate nutrient cycling, efficiency of plants’ water use, and the impact of pests such as insects and disease. These organisms also support ecological services in other systems. Living organisms are also present in the field system as crops and/or animals that represent important components of net primary and secondary production, for example, the consumable and/or marketable products produced in the field. Also present in the field system are competitive and parasitic agents such as weeds, insect pests, nematodes, and diseases that can interfere with or threaten the health and agricultural productivity of the system.

Energy is a primary driver of activity within an agricultural field system. The most important source of energy is sunlight, which is transformed during photosynthesis. Through this process, plants convert carbon dioxide into simple sugars that in turn provide the energy that living organisms need to function. In most natural systems, sunlight represents the only source of energy required to maintain the system. Managed systems, in contrast, often require external sources of energy to produce and/or extract desired products. In an agricultural field, external energy is commonly used for mechanized tilling, planting, weeding, and harvesting; and to manufacture and apply chemical fertilizers and pesticides. Today, many field managers are dependent on finite fossil fuel resources to provide these external energy inputs.

As illustrated in figure 1, the four components of an agricultural field system are linked through biogeochemical processes. The cycling of carbon, nutrients, water, and energy are processes in which each field component plays an important role. Microorganisms, for example, drive terrestrial carbon cycling by decomposing organic materials in the soil. Through this process, nutrients from organic materials are mineralized, carbon is released to the atmosphere as carbon dioxide, and byproducts are formed. The byproducts from decomposition of organic matter undergo the process of humification to become soil humus, a stable sink or reservoir for carbon. Plant species in a field system may also serve as a sink for carbon through the conversion of sunlight energy to

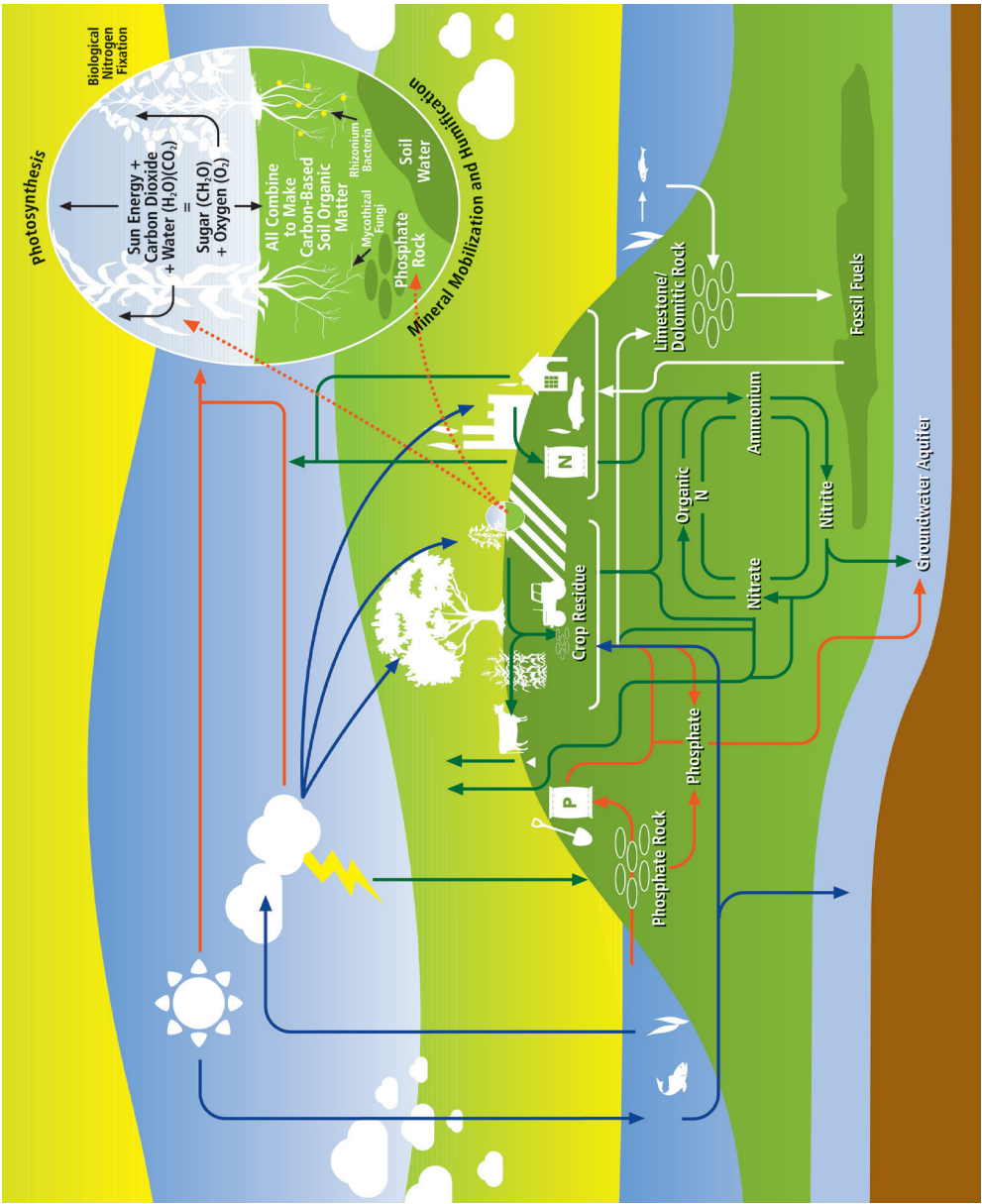


Figure 1. Four components of an agricultural field system linked through biogeochemical processes (reprinted with permission from the Rodale Institute).

sugars during photosynthesis. The carbon cycle, therefore, is driven by soil, living organisms, and energy in the field system. Figure 2 illustrates several carbon sources and sinks.

Soil, particularly soil organic matter (SOM), plays a central role in mediating the transformation and cycling of nutrients essential to plant and animal growth. SOM encompasses living microorganisms as well as plant and animal tissues in various stages of decomposition (Craswell and Lefroy 2001). There are several mechanisms through which soil organic matter regulates nutrient solubility and plant uptake. First, soil organic matter influences the composition, size, and activity of the soil microbial population, which in turn determines the rates at which materials are decomposed and nutrients from those materials are mineralized, or made available for plant uptake. For example, soil microbial populations mediate the cycling of nitrogen in a field system. As living organisms die and return to the soil, microorganisms break down these materials into their components, including organic nitrogen. Organic nitrogen in the soil is further processed by other species of soil microbes and converted to ammonium, a process called mineralization. In this form, nitrogen may be consumed by soil microbes, immobilized but stored in the soil for future use; taken up by plants; or converted to nitrate, which can also be utilized by both microbes and plants. Figure 1 illustrates the nitrogen cycle and nitrogen transformations carried out by soil microbes. Each of these nitrogen transformations is dependent on the microbial population present. If soil microbes are deficient or lacking a source of carbon from which to derive energy, nitrogen transformations may be suspended, resulting in the unavailability of the nitrogen needed to support crop growth.

Second, soil organic matter has a high cation exchange capacity (CEC). Soils with a high CEC are able to bind and hold positively charged cations such as potassium (K^+), ammonium (NH_4^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), many of which are essential nutrients for plant growth. In addition, soils high in organic matter stimulate chelation, or reversible binding, of minerals that are not readily soluble. Both of these qualities improve the availability of minerals already present in the soil so that they may be taken up by plants. Finally, increasing soil organic matter enhances the capacity of soils to resist changes in pH (also called pH buffer capacity) that can adversely affect crop growth. Increases in SOM generally have a positive impact on long-term soil fertility from biological and chemical mechanisms. Like the cycling of carbon, the transformation, uptake, and transfer of nutrients represent a relationship between soil, living organisms, and energy in the field system.

As a resource essential to the survival of all living organisms in a field system, from soil microorganisms to livestock, water has an indirect influence on the cycling of carbon and nutrients. If water were not available to the organisms that drive carbon and nutrient cycling, these processes would not take place. Water itself is also mediated by other components within the field system, namely, soil and living organisms. Organic matter is the key soil component mediating the water-soil relationship. Soil organic matter provides the glue that causes the aggregation of soil particles. Aggregation, in turn, can increase water infiltration, percolation, retention, and availability to crops, all of which favor conservation and efficient use of water. As demonstrated in figure 3, soil water content is directly proportional to the quantity of soil organic matter when soil water is at field capacity (saturated) and wilting point (the point at which plants are no longer able to extract water from the soil). As figure 4 illustrates, cycling of water through the field system is also closely linked to plant life of the system. Water moves through plants as part of the hydrological cycle, entering primarily through the root system and leaving through transpiration—the evaporation of water from the leaf through openings in its surface. Plants can also intercept rainfall, influencing the quantity and distribution of water that reaches the soil.

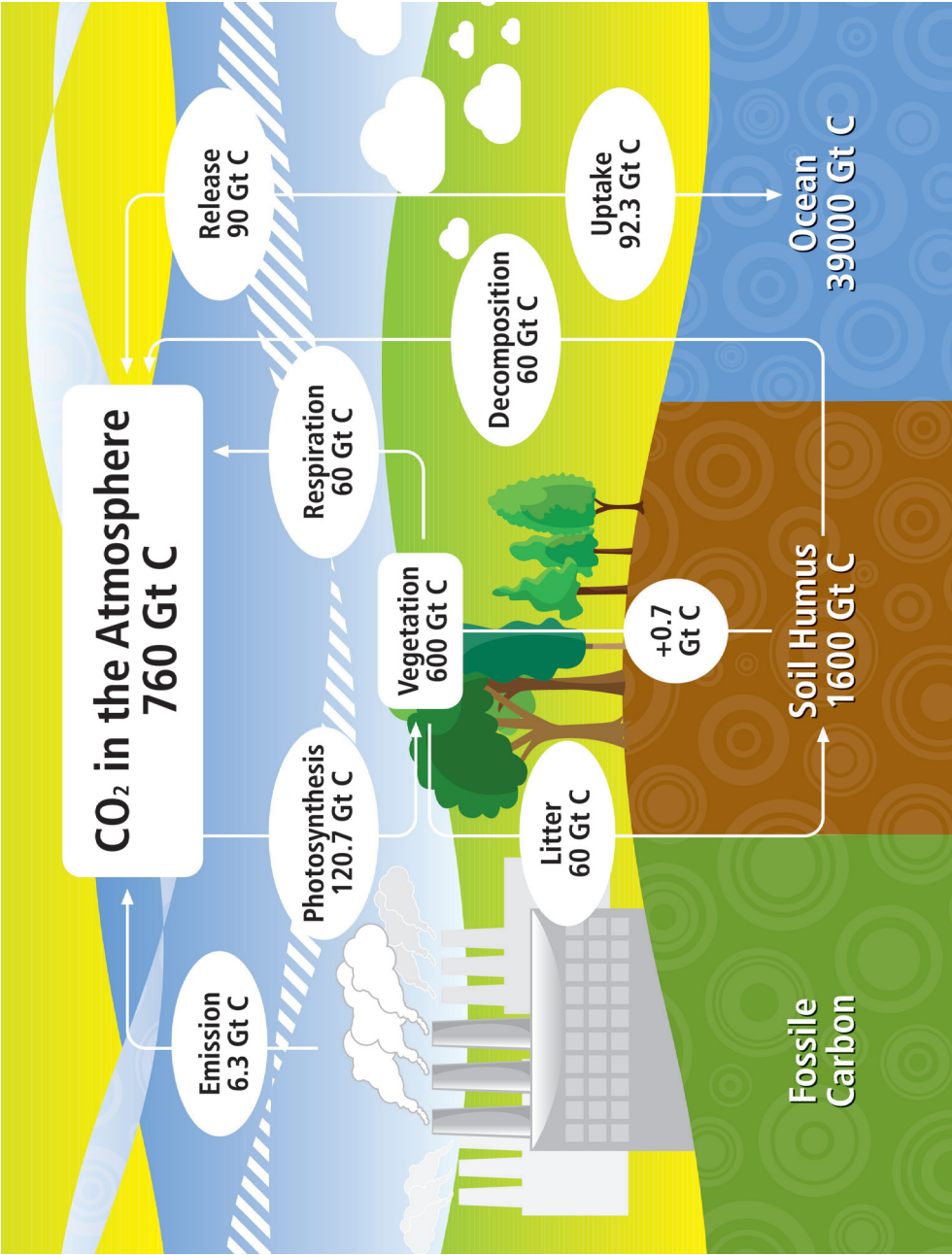


Figure 2. Carbon cycle (reprinted with permission from the Rodale Institute).

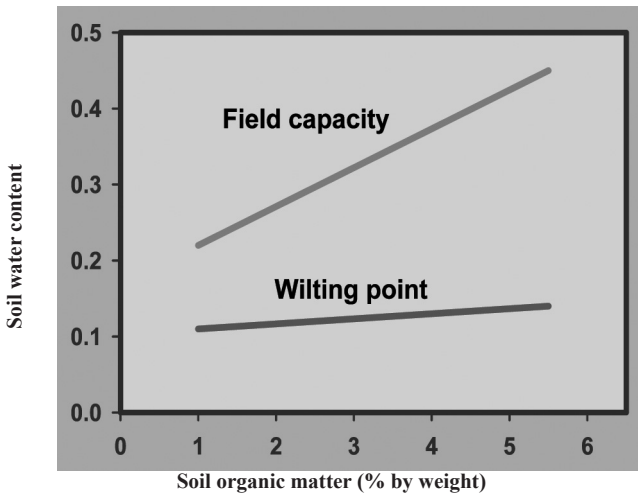


Figure 3. Effect of organic matter on available soil water (adapted from Brady and Weil 2002, reprinted with permission from the Rodale Institute).

The processes that occur at the field level serve both to maintain the system itself and to mediate the cycling of carbon, nutrients, and water on a global scale. The linkages among field system components created by these processes mean that no action within a field happens in isolation. In other words, management targeted at water conservation may also affect soil, living organisms, and energy in the field. This principle also applies to the linkages these cycles create between the field and higher system levels. A field system is not isolated but is nested within a larger complex adaptive system. Activity within the field, therefore, has repercussions in other systems. This concept will be explored more thoroughly below.

Field System Management for Resilience

Human management of a field system is driven by the desire to produce or extract tangible products that benefit human existence, such as food, fiber, medicines, or raw materials. The extent to which a field system meets this demand is often referred to as *productivity*. Historically, the primary concern of the individual field manager who serves as the decision maker in a field system has been the management of internal and external resources to increase output. Such increases in productivity can lead to improvements in family and societal economic conditions and quality of life.

Equally important to these economically tangible products of a field, however, are the economically intangible outcomes of human management of that field. Of primary concern is the impact of management on natural resources, which are fundamental to providing ecosystem services. Ecosystem services are processes by which the natural environment provides resources useful to people, such as clean water, air and a functional soil system. Many of these processes are essential to the function and resilience of the ecosystem itself. Management designed to build resilience—the capacity of the system to absorb and change in response to disturbance while retaining its function, structure, and essential identity—is paramount to maintaining both productivity and ecosystem services from which human communities benefit. Though field-level processes are fun-

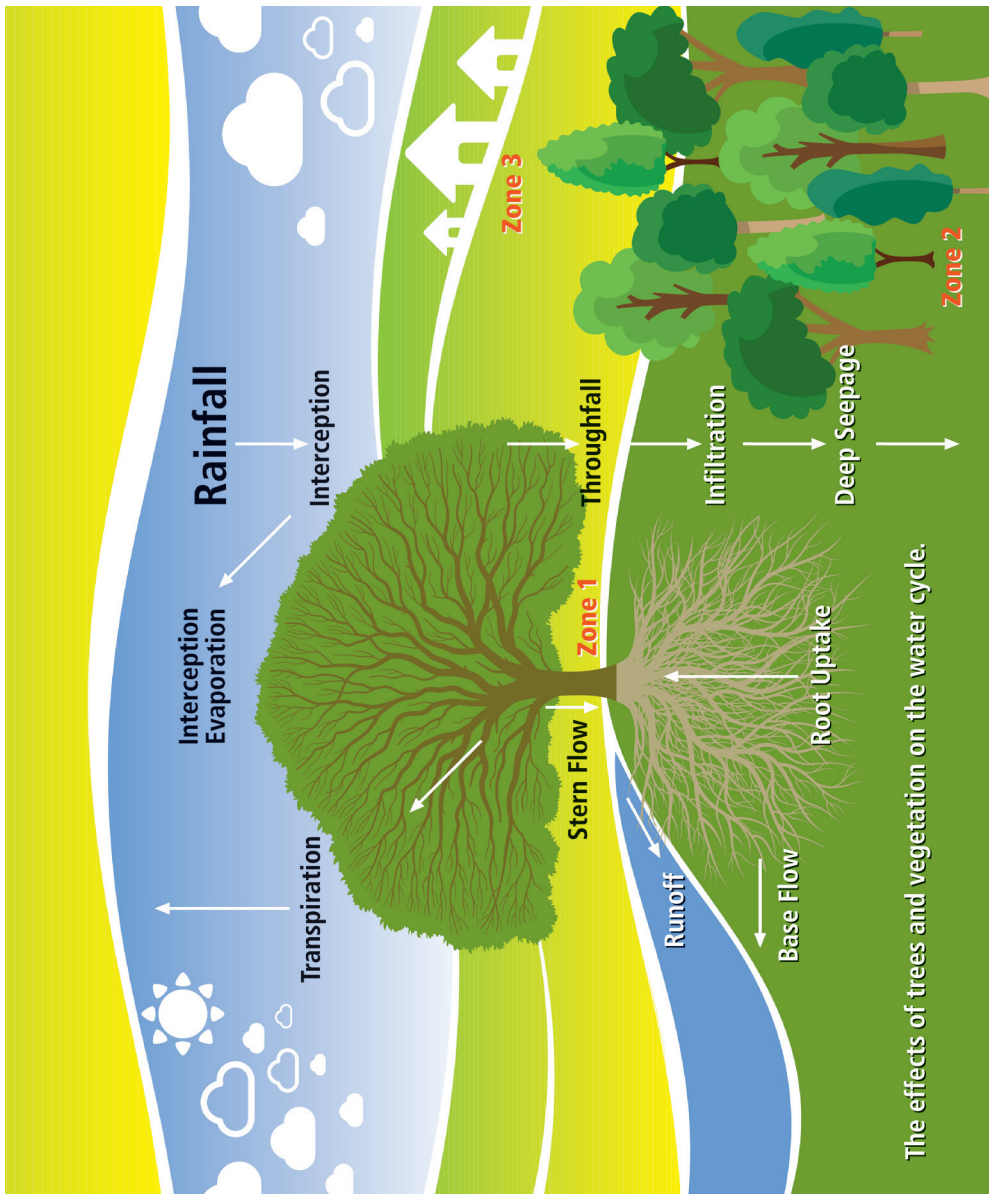


Figure 4. Cycling of water through the field system (reprinted with permission from the Rodale Institute).

damental to the overall resilience of a complex ecosystem, these processes are also influenced by and have an effect on other systems. Several examples help to illustrate these connections.

Soil erosion is an issue of global concern. Within an agricultural field system, erosion results in the loss of nutrient-rich topsoil and decreased agricultural yields (a loss of productivity). Externally, erosion contributes to sedimentation of local and regional water reservoirs, a significant negative influence of field system management on external systems. See the textbox below.

Soil erosion and the water supply: An example from Africa

Northern Ethiopia offers an example of the impact of soil erosion on regional water supplies (Tamene et al. 2006). Numerous micro-dams and reservoirs were constructed across the region from 1996 to 2001, which led to increases in food production, improved access to drinking water for people and livestock, rise in the groundwater level, and issuance of new springs (Tamene et al.). By 1999, rapid loss of water storage capacity due to sedimentation was reported by local management agencies (Gebre-Hawariat and Haile 1999, cited in Tamene et al.). Reduced storage capacity has resulted in the loss of services provided by the micro-dams, including the provision of hydroelectric power. In this region, like many others around the globe, excessive sedimentation has been attributed to topography of the land as well as human management of field systems.

Field system management also plays an important role in global biodiversity. Biodiversity at the field level contributes directly to biodiversity at other system levels. For example, diversity within agricultural fields and field borders contributes to greater diversity at the farm level, providing options for stable yield, increased income, variety in diet, and minimization of risk. Diversity at the field level also contributes to a mosaic structure at higher ecosystem levels that can lead to the creation of multiple habitats for beneficial insect species, wildlife and game populations, and native crop species (Altieri 1994). Field systems often contain important ecological niches for mobile species. Removal of such niches may have significant repercussions at a regional or global level. For example, the conversion of mangrove ecosystems (a field system) to shrimp farms in Southeast Asia and South America has resulted in the removal of spawning and nursery habitat for fish and shellfish. The repercussions are felt by fisherman in other regions and often other countries as reduced or lost adult fish yields (Barbier et al. 1994, cited in Folke et al. 1996).

To view a field system as part of a complex adaptive system is to acknowledge that management practices at the field level can have both positive and negative effects on ecosystem resilience and the capacity of interrelated systems to provide ecosystem services. Promotion of sustainable agriculture and natural resource management must therefore meet the short-term needs of the field manager—productivity—while at the same time addressing long-term considerations for the building of resilience and provision of ecosystem services within the field and beyond. With regard to the latter, natural resource managers such as farmers increasingly have no real isolation from the larger society. In fact, informed communities are exercising a greater stakeholder function and demanding that farmers use methods that will maintain and even improve the overall environment while meeting certain social, labor, energy, and environmental standards for their products.

Adaptive Management of Field Systems for Sustainability

Managing a field system to enhance productivity, integrity and resilience is integral to sustainable community development. Change is a reliable and ubiquitous factor that field managers face in this effort. Adaptive management seeks to develop practices that interpret and respond to feedback within the system brought about by disturbance (Berkes and Folke 1998). Successful adaptive management applies knowledge of ecosystem processes and dynamics to modify and adopt practices appropriate to local environmental and cultural conditions. Adaptive practices also seek to regenerate internal system resources, a key to building system resilience.

Goal: Regenerate Internal Resources

Sustainable management of the field system emphasizes the utilization of its internal resources and strategically uses external inputs to meet the needs of the individual field manager, human communities, the ecological functioning of the field system, and the biosphere as a whole. The term *regenerative* is often used to describe practices that fit these criteria. *Regeneration* is the improvement of the resource base while the base is being used productively. Regenerative practices strengthen the natural resources on which production is based and enable field managers to efficiently use readily available internal resources and reduce reliance on external inputs. In developing countries the latter is critical to promoting subsistence and market agriculture among limited resource agriculturalists due to the lack of access to external inputs.

Each of the principal components of a field system represents an internal resource of the system. In the example of an agricultural plot, soil, water, living organisms, and energy are the internal resources necessary to support productivity and ecosystem services. Regenerating each of these may focus on a particular aspect of a given component. For example, regeneration of soil is largely achieved through management of its organic matter. The latter portion of this chapter focuses on objectives and practices relevant to the regeneration of internal resources in an agricultural field system. The principles of regenerative management of field resources in agroecosystems are a matter of good stewardship practices that enhance soil organic matter, assure clean and abundant water supplies, protect biodiversity, and reduce dependence on external energy inputs.

Enhancing Soil Organic Matter

The rise of high-input agriculture following World War II has promulgated the perception that soil is “a dead substrate holding nutrients for agricultural production” (Martius et al. 2001). This view rationalized reliance on chemical fertilizers and intensive land preparation methods that accelerate soil degradation (Hillel 1991). At the same time that input-intensive agriculture has increased, global soil organic matter levels have been declining, largely due to the conversion of natural areas to agricultural production (Wood et al. 2000). Recent surges in research on management of soil organic matter in developing countries highlight a renewed interest in the potential of SOM to mediate soil degradation, enhance production among limited-resource farmers, and reduce a number of negative effects of agricultural production on associated resources. Research suggests that smallholders in developing countries are also aware of the link between soil organic matter and soil fertility (Murage et al. 2000; Hossain 2001; Quansah 2001). The textbox below provides a summary of the contributions of SOM to field system function. Table 3 (later in this chapter) provides strategies to increase soil organic matter.

Soil organic matter: A key factor in field system health

Soil organic matter makes a number of significant contributions to agroecosystem function, including the following:

- increased capacity of soil to hold water
- enhanced water infiltration
- improved soil aggregation and structure
- increased cation exchange capacity
- enhanced biological cycling of nutrients
- increased heat absorption
- pH buffer capacity
- enhanced chelation
- enhanced adsorption capacity
- reduced damage by soil pathogens

The centrality of functions carried out by SOM in agroecosystems warrants a special focus on practices that increase organic matter in agricultural soils. Because of the influence of SOM on other system components, most practices that aim to increase it will indirectly benefit soil water conservation, nutrient availability, and soil biodiversity, an important concept that will be addressed later in this chapter. A number of these practices also offer direct benefits to secondary aspects of the field system and are considered good tools for adaptive management.

Mulch

A common practice to add soil organic matter is the application of mulch. Mulch may be derived from material imported to the field, cover crops grown in the field, or crop residues left on the soil surface (Erenstein 2003). In humid to sub-humid areas, crop residue biomass is typically sufficient to provide adequate coverage of the soil surface (Erenstein). In arid and semiarid regions, however, crop residue production is generally not sufficient for mulching, and residues are often diverted to other uses such as animal fodder (Erenstein; Tiscareno-Lopez et al. 1999). In these areas, cover cropping may provide an alternative mulch production strategy. Regardless of the composition or origin of mulch, organic material added to the field system provides the substrate on which soil microorganisms act to create humus, as described previously, thus increasing SOM content.

Mulch also contributes to water conservation through two major actions: by adding to organic matter that improves soil aggregation and porosity (Pieri 1989); and as a physical layer covering soil to reduce surface runoff and evaporation (Erenstein 2002). The work of Greb (1983) in the American Great Plains demonstrated that mulch mass was directly related to water availability in semiarid environments. Compared with no mulch, 6,600 kilograms per hectare of dry stubble was sufficient to increase water in the field system by 50% in four sites tested. Gupta and Gupta (1986) reported that on an Indian aridisol, interrow placement of weed mulch at the rate of 6 tons per hectare significantly increased the mean moisture status of the 15 centimeter soil depth by 1.4% and significantly decreased the mean maximum temperature of the 10 cm depth (measured at 2 p.m.) by 3.9°C, resulting in increased plant biomass production. In cases where water availability is a primary constraint to crop yield, mulch application can lead to an immediate increase in

water infiltration and, subsequently, crop yield. Measurable impacts of increased SOM provided by mulch may be observable only in the long run, for consistent mulching tends to stabilize and enhance crop yield (Erenstein 2003).

Short- and long-term effects of residue cover are demonstrated by a soil conservation program first adopted in Guaymango, El Salvador, in 1973. Though burning crop residues had been a common practice in the region, growers reported that they were motivated to end this practice because of the erosion control they observed when surface residues were left intact. After more than 20 years, the El Niño phenomenon provided evidence of the long-term impact of residue conservation on soil moisture. In 1997, farmers in Guaymango who had continuously practiced recommended soil conservation strategies reported achieving near-average yields despite drought conditions (Shaxson and Barber 2003).

Mulch also serves as a means of suppressing weed growth. Mulches limit germination and growth of weed seedlings by altering light, soil moisture, and soil temperature (Teasdale and Mohler 1993). The amount of mulch required for effective weed suppression varies with the type of mulch used. In general, weed suppression improves with increasing mulch thickness and uniformity of distribution. Ligneau and Watt (1995) demonstrated sufficient suppression of annual weed emergence with 3 centimeters of composted materials. For growers using cover crops as mulch, the question of how much biomass is needed for effective weed management is still being studied. Finding the optimal level of cover crop residue may involve on-farm trials of various cover crops to find the mulch system that is most reliable and effective in a particular locality.

Cover Crops

Cover cropping is a beneficial practice applicable to most agroecosystems. The benefits of cover crops include the following:

- protection against soil erosion
- addition of organic matter to the soil
- provision of nutrients (for example, legumes that host nitrogen-fixing bacteria)
- provision of habitat for beneficial insects and other organisms
- moderation of soil temperatures
- conservation of soil water
- biological nitrogen fixation (legume cover crops)

Cover crops may be planted in a field in rotation with food and fiber crops (see “Crop Rotation”) as a living mulch under food and fiber crops, or in fallow fields. As listed in table 1, various species are suitable cover crops that may be used by smallholders in a range of environments. Mulching with cover crops may be possible in dry regions, though mulch production is limited by the short duration of the growing season and extraction of biomass for alternative uses such as fodder for livestock. In general, smallholders in semiarid to arid regions may need to pursue alternative strategies such as intercropping, reduced tillage, compost application, and crop rotation to reduce erosion and enhance SOM (FAO 2004).

Hedgerows

More permanent sources of organic material are available from the planting of trees, shrubs, and grasses as living fences or hedgerows. Such plantings can be cut regularly to provide mulch for cropping areas. It is common to use nitrogen-fixing leguminous trees for this purpose, as many

Table 1. Commonly used cover crops.

Scientific name	Common name(s)	Use	Recommended elevation	Recommended climate*
<i>Avena sativa</i>	Oat	Cereal		Ar, Aw, Bs, Bw, Cf, Cs, Cw, D
<i>Brassica oleracea</i> var. <i>Acephala</i>	Forage kale	Vegetable	Up to 3,000 m	Ar, Aw, Bs, Cf, Cs, Cw, D, E
<i>Cajanus cajan</i>	Pigeon pea	Herbaceous legume (shrubby)	Up to 3,000 m	Ar, Aw, Bs, Cf, Cs, Cw
<i>Canavalia ensiformis</i>	Jack bean Coffee bean	Herbaceous legume	Up to 1,800 m	Ar, Aw, Cf, Cs, Cw, D
<i>Canavalia gladiata</i>	Sword bean	Herbaceous legume	Up to 1,500 m	Ar, Aw
<i>Canavalia maritima</i>	Beach bean Bay bean	Herbaceous legume		Ar, Aw, Bs
<i>Centrosema pubescens</i>	Centro	Herbaceous legume	Up to 1,600 m	Ar, Aw
<i>Clitoria ternatea</i>	Butterfly pea	Herbaceous legume	Up to 1,800 m	Aw, Bs, Cw
<i>Crotalaria juncea</i>	Sunn hemp	Herbaceous legume	Up to 1,500 m	Ar, Aw, Bs, Cf, Cs, Cw
<i>Eleusine coracana</i> var. <i>coracana</i>	Finger millet African millet	Cereal	Up to 2,500 m	Aw, Bs, Bw, Cf, Cs, Cw
<i>Fagopyrum esculentum</i>	Buckwheat	Cereal	Up to 2,000 m	Aw, Bs, Cf, Cs, Cw, D
<i>Glycine max</i>	Soybean	Herbaceous legume	Up to 3,000 m	Aw, Bs, Cs
<i>Glycine wightii</i>	Perennial soybean Glycine	Herbaceous legume	Up to 2,450 m	Ar, Aw, Cf
<i>Indigofera hirsute</i>	Hairy indigo	Herbaceous legume	Up to 1,350 m	Ar, Aw, Cf, Cs, Cw
<i>Lablab purpureus</i>	Lablab bean Hyacinth bean	Herbaceous legume	Up to 2,100 m	Ar, Aw, Bs, Bw, Cf, Cs, Cw, D
<i>Lupinus albus</i>	Sweet lupine White lupine	Herbaceous legume	Up to 740 m	Bs, Cs, D
<i>Lupinus mutabilis</i>	Tarwi Andean lupin	Herbaceous legume	Up to 4,000 m	Aw, Bs, Cf, Cs, Cw, D
<i>Medicago sativa</i>	Alfalfa Lucerne	Herbaceous legume	Up to 4,000 m	Bs, Cf, Cs, Cw, D
<i>Mucuna pruriens</i> var. <i>utilis</i>	Velvet bean	Herbaceous legume	Up to 2,100 m	Ar, Aw, Cf, Cs
<i>Panicum miliaceum</i>	Proso millet Hog millet	Cereal	Up to 3,500 m	Aw, Bs, Bw, Cf, Cs, Cw
<i>Pennisetum glaucum</i> syn. <i>P. americanum</i>	Pearl millet	Cereal	Up to 1,800 m	Ar, Aw, Bs, Bw, Cf, Cs, Cw
<i>Psophocarpus tetragonolobus</i>	Winged bean Goa bean	Vining legume	Up to 2,000 m	Ar, Aw, Cf, Cs, Cw
<i>Pueraria phaseoloides</i>	Tropical kudzu	Herbaceous legume	Up to 2,000 m	Ar, Aw
<i>Setaria italica</i>	Foxtail millet Italian millet	Cereal	Up to 2,000 m	Aw, Bs, Cs
<i>Stylosanthes guianensis</i> var. <i>guianensis</i>	Common stylo Tropical lucerne	Herbaceous legume	Up to 2,200 m	Ar, Aw, Bs, Cf, Cw
<i>Trifolium</i> ssp.	Clover	Herbaceous legume	Varies by species	Varies by species
<i>Vigna umbellata</i>	rice bean	Herbaceous legume	Up to 2,000 m	Ar, Aw, Bs, Cs
<i>Vigna unguiculata</i>	Cowpea Yardlong bean	Herbaceous legume	Up to 2,000 m	Ar, Aw, Bs, Cf, Cs, Cw

Sources: Educational Concerns for Hunger Organization, North Fort Myers, Florida (www.echotech.org), and Ecocrop, a program of the United Nations Food and Agriculture Organization (ecocrop.fao.org).

* Key to climate type: Ar = tropical wet (rainforest, tropical lowlands); Aw = tropical wet and dry (monsoon, savannah); Bs = semiarid; Bw = desert; Cf = subtropical humid; Cs = subtropical dry summer; Cw = subtropical dry winter; D = temperate (all subgroups); E = boreal.

species also contribute to soil fertility and serve as animal fodder (Shaxson 1999). Table 2 provides information on commonly used leguminous trees.

In steep lands, cross-slope planting of trees, grasses, and shrubs is a common tool to mediate soil erosion. In a field system, this type of green hedgerow helps to stabilize soil, slows water run-off, and provides soil cover to minimize erosion (Shaxson 1999). In Vietnam, for instance, hedgerows of *Vetiver* sp. and *Tephrosia* sp. have been shown to reduce dry soil loss in cassava by 83% and 57%, respectively (Dang and Klinnert 2001). Farmer participatory research in the Philippines has demonstrated that high-value contour hedgerows such as asparagus, lemon grass, and pigeon peas can also reduce annual soil loss compared with loss under conventional farmer management. In this experiment, vegetable crops were planted on a 42% slope, and the average amount of soil lost when contour hedgerows were in place was 30% lower than the farmer-managed system without hedgerows (Poudel et al. 2000). Other high-value hedgerows may include fruit and nut trees. These examples demonstrate that sustainable management to both enhance productivity and provide ecosystem services (in this case the prevention of soil erosion) is possible even in marginal areas.

Table 2. Leguminous trees and shrubs commonly used as hedgerows.

Scientific name	Common name(s)	Growth habit	Recommended elevation	Recommended climate*
<i>Albizia lebbek</i>	Women's tongue East Indian walnut	Tree	Up to 1,600 m	Aw, Bs, Cw
<i>Calliandra calothyrsus</i>	Calliandra	Tree	Up to 1,800 m	Ar, Aw
<i>Desmanthus virgatus</i>	Wild tantan Dwarf koa Slender mimosa Bundleflower	Shrub	Up to 2,000 m	Aw, Bs, Bw, Cf, Cw
<i>Desmodium intortum</i>	Greenleaf desmodium	Tree	Up to 2 500 m	Ar, Cf
<i>Erythrina poeppigiana</i>	Coral tree	Tree	Up to 2,000 m	Ar, Aw
<i>Flemingia macrophylla</i>	Wild hops flemingia	Shrub	Up to 2,000 m	Ar, Aw
<i>Gliricidia sepium</i>	Gliricidia Madre de cacao	Tree	Up to 1 600 m	Ar, Aw
<i>Leucaena ssp.</i>	Leucaena	Tree	Varies by species	Ar, Aw, Bs, Cf, Cs, Cw (varies by species)
<i>Robinia pseudoacacia</i>	Black locust False acacia	Tree	Up to 3,300 m	Bs, Cf, Cs, D
<i>Sesbania ssp.</i>	Sesbania	Tree	Varies by species	Ar, Aw, Bs, Cf, Cs (varies by species)
<i>Tephrosia vogelii</i>	Tephrosia Fish bean Fish poison bean	Tree	Up to 2,100 m	Ar, Aw, Cf, Cs, Cw

Sources: Educational Concerns for Hunger Organization, North Fort Myers, Florida (www.echotech.org), and Agroforestry Net, Holualoa, Hawaii (www.agroforestry.net).

* Key to climate type: Ar = tropical wet (rainforest, tropical lowlands); Aw = tropical wet and dry (monsoon, savannah); Bs = semiarid; Bw = desert; Cf = subtropical humid; Cs = subtropical dry summer; Cw = subtropical dry winter; D = temperate (all subgroups).

Compost and Other Organic Amendments

In many areas of the world, field managers rely on synthetic fertilizers to sustain crop production. Though the application of synthetic fertilizers can support crop growth in the short term, this practice can also erode soil carbon content. Over the long term, this results in depletion SOM, compromising both the productive capacity and resilience of a field system. The use of organic amendments, particularly compost, to enhance soil fertility offers a means to increase organic matter and promote sustained soil quality.

The impact of organic amendments on soil microbial activity, increases in which are generally associated with higher rates of decomposition and nutrient transformation, and nitrogen retention in a temperate climate have been demonstrated by research at the Rodale Institute. Studies using tagged nitrogen (N_{15}) to compare nitrogen movement in organic and conventional cropping systems found that application of organic amendments led to higher rates of soil respiration (an indicator of soil microbial activity), increased quantities of nitrogen in soil microbial biomass, and reduced losses of nitrogen (as illustrated in figure 5).

These outcomes underscore the importance of building up quantities of SOM in agricultural field systems. Alternative agriculturists have called this concept “feeding the soil” an important concept in regenerative and sustainable field management.

Composting is a key practice with demonstrated ability to reverse loss of SOM in areas such as the endangered Sahel region that borders the Sahara Desert (Diop, personal communication, 2005). Among organic inputs, research suggests that application of composted, as opposed to raw, manure is an efficient means of increasing soil organic matter. In Senegal, West Africa, McClintock and Diop (2005) reported that field soils amended with compost or manure produced increased growth of millet and corn, and elevated cation exchange capacity and nutrients (potassium, magnesium) compared with non-amended soils. The authors recommended that farmers concentrate on refining the management of conventional compost piles rather than on more labor-intensive methods of composting. In the Rodale farming systems trial in the temperate United States, base SOM levels of 2.0% changed to 2.5%, 2.1%, and 1.9% in systems using composted manure, raw dairy manure, and synthetic chemical fertilizer, respectively, over nine years. Figure 6 provides a graphical representation of these results. Compost may also be derived from crop and household waste. In a study comparing yield response of cabbage with the application of composted crop waste, uncomposted crop waste, and conventional NPK fertilizers, researchers in Uganda observed that yields were highest in the composted crop waste system in two out of three growing seasons (Karungi et al. 2006). See Misra et al. (2003) for further information on composting techniques.

Increasing SOM through compost application provides the opportunity to reduce energy requirements derived from the use and application of conventional fertilizers. This technology not only reduces energy required for crop production through enhanced soil properties, it also reduces the energy required to apply organic materials such as manure. Composting reduces original masses and volumes by 80% to 90%. Through the composting process, potential pests and pathogens can also be eliminated from a field system, further reducing production and energy costs derived from pest management with conventional pesticides. When composting, the labor input can be minimized by using static pile methods and enhanced African pit compost methods. Simple animal draft equipment that can be cheaply constructed by locals is another mechanism for increasing efficiency of organic material use for societal gain.

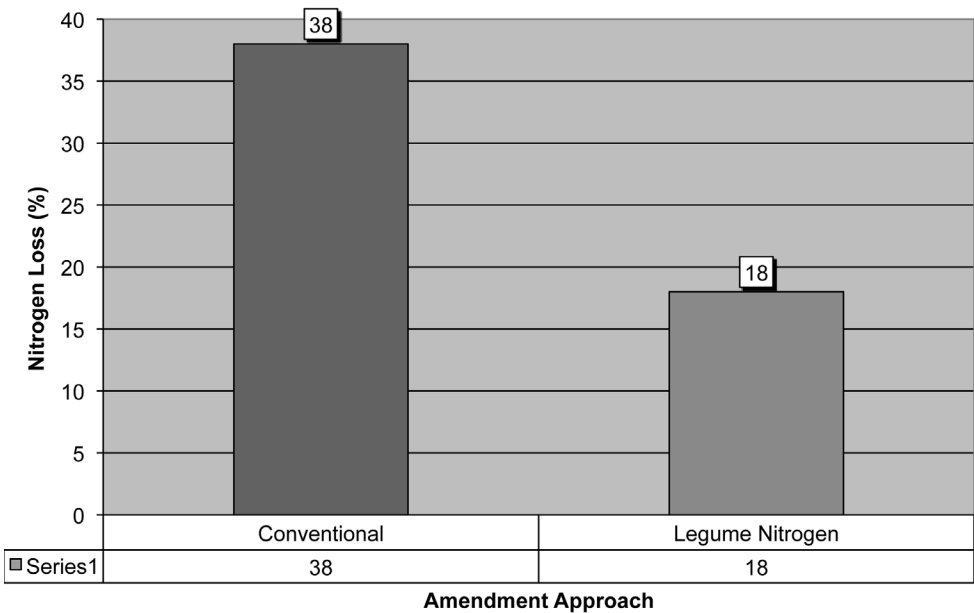


Figure 5. Nitrogen losses measured in Rodale Farming Systems Trial using N₁₅ isotope (reprinted with permission from the Rodale Institute; see Harris et al. 1994 for details).

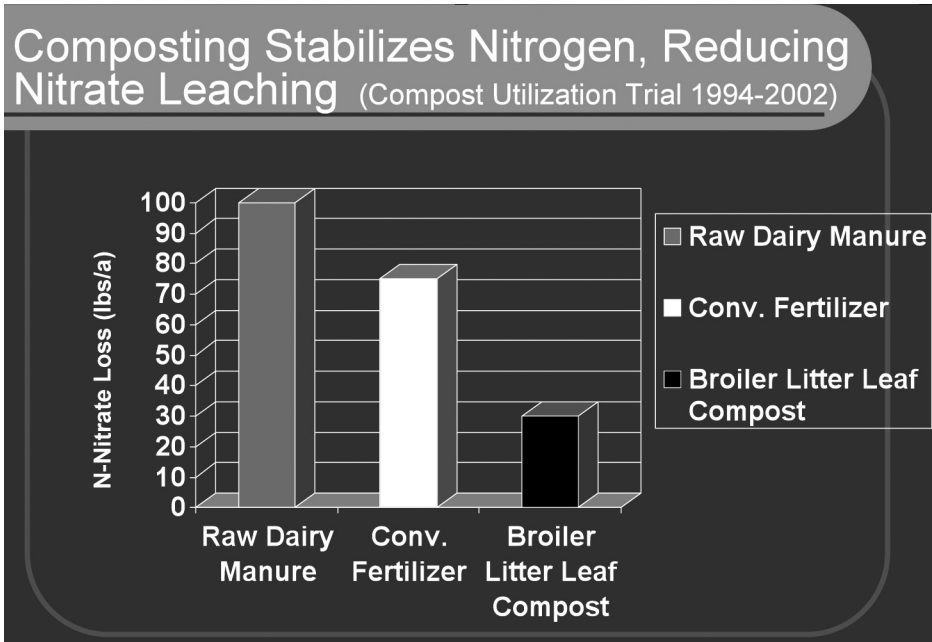


Figure 6. Effect of compost utilization on nitrogen leaching (reprinted with permission from the Rodale Institute; Hepperly et al. 2009).

It should be noted that sustainable management does not require the elimination of synthetic fertility amendments. In cases where synthetic fertilizers are deemed a necessity to support plant growth, proper placement of small amounts are recommended. These should be applied at key stages. Extensive starter fertilizer research shows that 80% of the fertilizer response can be achieved with 20% of the fertilizer effectively placed as a starter. For example, the placement of relatively small amounts of fertilizer at the side and below the seed is critical to avoiding salt toxicity while stimulating optimized nutrient use and early crop stimulation.

Reducing Tillage

Tillage has been employed historically in field systems to facilitate proper placement of seed and to control weeds. Nevertheless, tillage is highly disruptive to field system processes. One of the key processes affected by tillage is the carbon cycle. By turning and mixing organic residues into soil, tillage increases contact between organic materials and soil organisms. This, in turn, speeds the process of decomposition, generating less stable forms of soil humus and releasing higher quantities of carbon dioxide. The net result is decreased soil organic matter. As previously discussed, this can lead to reduction of soil's capacity to hold water. Other negative effects of tillage include loss of habitat for soil organisms, increased susceptibility to erosion, and higher external energy requirements. Because of the link between tillage and poor soil quality, many development organizations promote the adoption of practices that replace or reduce the need for tillage in soil preparation and weeding. These practices are often combined in a production system called conservation agriculture.

Conservation Agriculture

The term *conservation agriculture* is used to describe any farm production strategy that reduces or eliminates the use of tillage. The benefits of reduced or no-tillage include reduced risk of erosion, conservation and augmentation of SOM content, and conservation of soil water.

In many areas of the world, conservation agriculture is promoted as a strategy to replace management systems that contribute to human-induced soil erosion in field systems: excessive tillage, inadequate soil cover, utilization of hillsides and sloped lands for production without proper conservation practices, overgrazing, and slash-and-burn systems. Conservation agriculture is a sustainable field management strategy that can provide immediate and direct reduction of soil losses as well as promote long-term soil quality.

Conservation agriculture is based on three principles: minimal soil disturbance, permanent soil cover, and crop rotations. Management practices utilized in conservation agriculture include reduced or zero tillage, use of mulch (retaining crop residues, no burning), and cover cropping.

The principal biological concept on which conservation agriculture is based is the capacity of organic matter to stabilize and enhance soil structure and function. Tillage disrupts not only the soil's physical structure but also the habitat of soil organisms critical to decomposition, nutrient cycling, and organic matter formation. Therefore, strategies within conservation agriculture aim not only to provide short-term protection of soil structure (for example, by minimizing soil disturbance and covering exposed soil) but also to support the living organisms that promote soil health (FAO 2000). Associated ecosystem services offered by conservation agriculture include improved soil water properties, increased biodiversity, and enhanced carbon cycling. By reducing or eliminating the need for tillage machinery, conservation agriculture also provides a means by which smallholders can reduce external energy inputs.

Although conservation agriculture is prevalent in areas such as Latin America, the practice is lagging on other continents, especially in Africa. Conservation agriculture is still in its infancy in Africa, where it needs to be taught and demonstrated under African environments. It is important to acknowledge that many reduced-tillage systems, particularly those used in industrialized countries, are based on intensive fertilizer and pesticide use. Chemical-intensive conservation agriculture is a one step forward in relation to tillage but several steps back with regard to the known negative effects on natural resources and health from increased use of pesticides and chemical fertilizers. For this reason, it is important that conservation agriculture is recommended and promoted only within a package of sustainable management practices that emphasize both production and natural resource conservation and improvement.

More information on conservation agriculture is available from the Food and Agriculture Organization (FAO) Web site (www.fao.org). FAO Land and Water Bulletin No. 8 (2000) provides a comprehensive review of conservation agriculture practices.

Fallowing

Fallowing represents another tool to increase SOM. Natural fallow periods of sufficient duration (10 to 50 years) such as those used in shifting cultivation systems can restore soil biological, chemical, and physical properties (Greenland and Nye 1959). In any period during which a field is not used for economic crop production, the field can be managed as an improved fallow to restore or enhance soil quality. Herbaceous legumes and trees, also often leguminous, may be planted or encouraged to regenerate in a fallow field to contribute to soil fertility, provide soil cover, augment soil organic matter, and provide other benefits associated with temporal crop diversity (Ganry et al. 2001; Roose and Barthes 2001; Quansah et al. 2001). See “Hedgerows” for additional information on leguminous tree species.

Strategies to Increase Soil Organic Matter

Climate is a key factor determining the optimal strategies for adding organic matter to the field system. For example, in humid to sub-humid regions where biomass production capacity is not limiting, adding crop residues, cover crops, and weed residues to soil are the primary tools used by smallholders to augment soil carbon (Quansah et al. 2001; Hossain 2001; Dang and Klinnert 2001; Manna et al. 2003; Roldan et al. 2003). In semiarid to arid regions, where crop production is limited, farmyard manure and compost application are the most common and effective organic matter additions for soils (Quansah et al. 2001; Ganry et al. 2001; Manna et al. 2003; Bayu et al. 2004). It is important to consider environmental conditions and limitations when selecting practices to enhance soil organic matter. Table 3 provides examples of strategies used to increase soil organic matter in various climates.

Water Conservation

Field system environments are diverse, creating a wide variety of water management priorities. In this section we examine biological principles that govern water conservation and efficient water use in agricultural fields. Water management strategies based on these principles provide smallholders with a number of tools that both enhance field productivity and steward water resources transferred to higher system levels.

Water represents a key link between the field and other systems in the global biosphere. All systems share a limited supply of safe and clean water to meet human needs and support living

Table 3. Strategies to increase soil organic matter.

Strategy	Applications	Examples	References
Compost and manure	<ul style="list-style-type: none"> • Applicable in all climates • 8-10 tons of manure per hectare per season recommended [Bui Dinh Dinh 1995 (Vietnam)] • Prominent in areas where livestock production is prevalent, particularly arid and semiarid savannas 	<ul style="list-style-type: none"> • Farmyard manure (most often a composted mix of animal dung, animal bedding and household wastes) • Raw manure • Improved manure (composted with crop residues) • Quick compost (oil cake, rice bran, and chicken, duck, and/or cow manure) • Pen manure (may be dry, moist, or straw) • Application of leftover excrement slurry following production of biogas from livestock and human excrement 	Hossain 2001 (Bangladesh); Reported in Ganry et al. 2001 (semiarid Africa); Nyombi and Esser 2005 (Uganda); Tamang, 1992 (Nepal); Quasnah et al. 2001 (Ghana); Katyal et al. 2001 (India)
Plant residues: residues of crops and/or weeds left in a field or applied to a field as mulch	<ul style="list-style-type: none"> • Most applicable in humid to sub-humid climates • Residue production may be insufficient in arid and semiarid climates • In many locations, residues often diverted to fuel or livestock fodder 	<ul style="list-style-type: none"> • Rice stubble left in field • Rice straw, sugarcane bagasse applied to crop fields • Corn residue left in field (not tilled) • Weeds slashed and left on fields • Guinea corn and millet stalks used as mulch 	Hossain 2001 (Bangladesh); Whitbread et al. 1999 (Thailand); Taja and van de Zaag 1991 (Philippines); Roldan et al. 2003 (Mexico); Qunsah et al. 2001 (Ghana)
Living fences or hedgerows: trees or grasses pruned and cuttings used as mulch	<ul style="list-style-type: none"> • Applicable in all climates • Recommended in sloped areas to combat erosion 	<ul style="list-style-type: none"> • <i>Calliandra</i>, <i>Flemingia</i>, <i>Gliricidia</i>, <i>Leucaena</i>, <i>Tephrosia</i> ssp. trees as living fences and/or hedgerows • Napiergrass (<i>Pennisetum purpureum</i>), <i>Setaria</i>, <i>Vetiver</i> ssp. grass hedgerows • <i>Erythrina</i>, <i>Gliricidia</i>, <i>Leucaena</i>, <i>Mimosa</i>, <i>Robinia</i>, <i>Sesbania</i> ssp. planted between alleys for crop production (alley-cropping) 	Hossain 2001 (Bangladesh); Konig 1992 (Rwanda); reported in Dang & Klinnert 2001 (Thailand); reported in Dang & Klinnert 2001 (Vietnam); Ganry et al. 2001 (semiarid Africa)
Cover crops	<ul style="list-style-type: none"> • Most applicable in humid to sub-humid climates • Cover crop production be may limited in arid and semiarid climates 	<ul style="list-style-type: none"> • Dhaincha (<i>Sesbania aculeate</i>), sunn hemp (<i>Crotalaria juncea</i>), soybean, mung bean, peanut, winter legume • vetch (<i>Vicia</i> sp.) or ayocote bean (<i>Phaseolus vulgaris</i>) not tilled before corn planting • velvet bean (<i>Mucuna pruriens</i>) cut or uprooted and left on the surface before planting annual crops or in perennial crops such as banana 	Hossain 2001 (Bangladesh); Dang & Klinnert 2001; Roldan et al. 2003 (Mexico); Ganry et al. 2001 (Benin, Ghana, Togo); Nyombi & Esser 2005 (Uganda)
Living mulch: cover crop species grown at the same time as crop species	<ul style="list-style-type: none"> • Most applicable in humid to sub-humid climates 	<ul style="list-style-type: none"> • Grass pea (<i>Lathyrus sativus</i>) planted under taller winter crops such as eggplant 	Hossain 2001 (Bangladesh)
Intercropping: two food crops grown at the same time	<ul style="list-style-type: none"> • Most applicable in humid to sub-humid climates 	<ul style="list-style-type: none"> • Cassava and peanut • Maize and peanut • Litchi and peanut • Coffee and peanut • Tea and peanut 	Reported in Dang & Klinnert 2001 (Vietnam)
Relay cropping: food or cover crops planted when food crop is near harvest	<ul style="list-style-type: none"> • Most applicable in humid to sub-humid climates 	<ul style="list-style-type: none"> • Grass pea planted when aman rice reaches maturity and tilled in after harvest; boro rice then planted 	Hossain 2001 (Bangladesh)
Azolla: nitrogen-fixing aquatic fern used as animal feed	<ul style="list-style-type: none"> • Applicable in flooded rice systems 	<ul style="list-style-type: none"> • Intercropped in flooded rice 	Hossain 2001 (Bangladesh); Dang & Klinnert 2001 (China, India, Vietnam)
Improved fallow	<ul style="list-style-type: none"> • Recommended in semiarid and arid areas • Recommended in livestock areas 	<ul style="list-style-type: none"> • Planting legumes such as <i>Stylosanthes hamata</i>, <i>Dolichos lablab</i>, and <i>Mucuna pruriens</i> in fallow areas • Controlled grazing • Creating plantations of nitrogen-fixing leguminous trees such as <i>Acacia</i> ssp., <i>Albizia lebeck</i>, and <i>Leucaena</i> ssp. during fallow periods (forest fallow) 	Ganry et al. 2001 (semiarid Africa); Quasnah et al. 2001 (Ghana); Bosma et al. 1993 (Mali); reported in Ganry et al. 2001 (semiarid Africa)

organisms that carry out critical ecosystems services such as the recycling of organic matter and redistribution of matter and energy (Danielopol et al. 2003). Human agents in all systems must practice judicious use of water to ensure adequate quantity and quality for the future. Within the field system, soil and crop management can have negative ramifications on the quality of water available to other systems through the diversion of feedback to underground aquifers and the introduction of contaminants such as excess nutrients, organic and inorganic compounds, and sediment.

Conserving Water through Soil Management

Soil physical and biological properties are the primary mediators of water conservation in an agricultural field. In addition to physical systems such as bunds, terraces, contour planting, and planting pits that can be used to conserve water in the field (Shaxson and Barber 2003), soil management strategies can be used as low-input, effective means of increasing water infiltration and reducing surface evaporation to conserve soil water. Rainwater harvesting that diverts farm runoff to temporary storage in tanks or small ponds, or increases in field storage through structures that slow and spread surface water movement, permitting infiltration, is also a valuable tool.

Increasing soil organic matter from 1% to 5% can lead to a fourfold increase in the ability of topsoil to hold water. In other words, 100 kg of dry soil that contains 1% organic matter can hold 30 kg of water, whereas soil with 5% organic matter can hold 195 kg of water (Brady and Weil 2002). Long-term studies at the Rodale Institute in Kutztown, Pennsylvania, provide evidence that practices that increase soil organic matter content improve water use efficiency in agricultural field systems. These studies demonstrated that increasing soil organic carbon from 2% to 2.5% increased corn and soybean yields by 28% to 36% in summer drought years under rain-fed conditions. “Drought-proofing” provided by increased soil organic matter was associated with an increase of 25% to 50% in percolation, or water movement, through the soil profile. As soil organic matter is increased and greater amounts of water infiltrate the soil, water return to underground aquifers and surface water may also increase.

Conserving Water through Crop Management

Water conservation strategies are also linked to crop selection and management. Through appropriate crop selection and management, field managers can reduce water losses through transpiration by crops and weeds, and assure sufficient water availability in the root zone for plant uptake. Strategies to conserve water through crop management should consider two critical aspects of plant physiology: plant species and varieties vary in their ability to use scarce water supplies, and water needs vary by stage of crop development.

Crop selection should be governed by knowledge of local growing conditions such as temperature ranges, water availability, and crop efficiency. In rain-fed systems, there is opportunity to improve water-use efficiency through plant variety selection and breeding. Unfortunately, large breeding programs have historically sought high yield at the expense of dryland adaptation. Local cultivars in particular may exhibit adaptations that support water conservation, such as a waxy cuticle to prevent plant water loss. These genetic resources should be protected and utilized to develop cultivars with a range of desirable qualities. Using a mixture of crops and varieties can also distribute risk posed by limited water availability and provide opportunities for increased productivity under optimal moisture conditions. One example of this is the intercropping of corn, sorghum, and millet.

The first critical stage of plant growth is seed germination. In most situations, delaying planting until rainfall is sufficient for crop germination is optimal to assure sufficient water to support seedling development. Planting should also be timed so that rainfall periods coincide with critical stages of plant development, such as reproductive stages when water loss through evapotranspiration is often higher than the rate observed at other stages of growth. This phenomenon of terminal water deficit during flowering and pod-filling stages has been observed in many crops, including soybean (*Glycine max* L.) and pigeon pea (*Cajanus cajan* [L.] Millsp.) (DeBruyn et al. 1995; Patel et al. 2001). Other critical periods for yield determination are the first 30 days of growth and the periods just before and after pollination.

Irrigation Options for Smallholders

Around the globe, consumption of groundwater is rapidly increasing due to diversion of surface runoff to agriculture and alteration of landscapes for human use (Danielopol et al. 2003). Improved irrigation efficiency is considered a key strategy to slow and possibly reverse this process. Only about 17% of the world's available cropland is irrigated, yet this area produces roughly 40% of the world's food (Postel 1999). The increase in productivity from irrigation has already prevented the conversion of a significant area of natural vegetation, though diversion of water for irrigation has also contributed to regional water shortages. It is estimated that less than 3% of the world's water supply is fresh and suitable for irrigation. Collecting and transporting water to a field is often costly for smallholders. Appropriate timing of irrigation, with regard to both plant development and time of day, can reduce water loss through evaporation and transpiration, and promote optimal plant growth. Monitoring soil moisture with tensiometers, electronic resistance blocks, or with less sophisticated devices can promote more accurate use of limited water supplies without over- or under-irrigating. In this strategy, water is applied only when soil is reaching critical levels of dryness to less than full field capacity to prevent excessive losses and inefficient usage.

By delivering water directly to the plant root zone, micro-irrigation, or localized, systems maximize plant uptake efficiency and reduce water losses to runoff, soil evaporation, deep percolation, and transpiration from weeds (Sijala 2001). Micro-irrigation can reduce the quantity of water needed to meet crop demand, as demonstrated in table 4, and increase crop productivity (Namara et al. 2005). Drip irrigation systems have demonstrated reductions in water use by 30% to 70% and increases of 20% to 90% in crop yields (Postal 1999). Recent development of four kinds of low-pressure gravity drip systems specifically targeted to small farmers has improved prospects for increased implementation of these systems (Postel et al. 2001). They include the following:

Table 4. Comparison of irrigation requirements under well designed and managed drip, sprinkler, and furrow irrigation systems (modified from Sijala 2001).

Crop water demand (mm/day)	Quantity of water required for irrigation (mm/day)		
	Drip method	Sprinkler method	Furrow method
3.0	3.3	4.3	5.0
4.0	4.4	5.7	6.7
5.0	5.6	7.1	8.3
6.0	6.7	8.6	10.0

- bucket systems (20 liter) costing about \$5 and covering an area of 25 square meters
- drum systems (200 liter) costing about \$25 and covering 125 square meters, capable of expansion in 125 square meter increments at about \$14 per increment
- shiftable drip systems costing about \$50 and covering 1,200 square meter (similar to conventional drip systems but with reduced capital costs because they can be shifted)
- stationary microtube systems costing about \$250 and covering 4,000 square meter (these systems consist of plastic lateral lines equipped with micro-tubes and cost about two-thirds less than conventional drip systems)

Despite advantages and availability of low-cost micro-irrigation, a 2005 survey in the Indian states of Maharashtra and Gujarat indicates that the technology has not been widely adopted by poor smallholders, primarily due to cost and educational barriers (Namara et al. 2005). Nevertheless, it has been suggested by Upadhyay (2004) that offering mortgage-free loans to poor landless farmers, usually women, coupled with local micro-finance plans, would allow them to lease land and implement micro-irrigation technologies resulting in cash income and improvement of household nutrition and food security. Micro-irrigation has mobility, and most equipment has multiple-use potential and is transportable.

The treadle pump for manual irrigation is a good example of a low-cost device developed specifically for smallholders. Costing \$12 to \$15, the treadle pump has a benefit-cost ratio of 5, an internal rate of return of 100%, and a payback period of one year (Shah et al. 2000). The pump enables a farmer to irrigate up to 0.3 hectare of crops. More than 1 million of them have been purchased in Bangladesh alone (Frausto 2000).

Reducing Contaminants

The World Commission on Water estimates that more than half of the world's rivers are "seriously depleted and polluted, degrading and poisoning the surrounding ecosystems, threatening the health and livelihoods of the people who depend on them" (United Nations Environment Program 2002). Many of the pollutants found in surface and groundwater supplies originate in managed field systems. As previously discussed, sediment due to erosion is a critical threat to the water supply. Other contaminants include nitrogen and phosphorus from synthetic fertilizers, pesticides, heavy metals, organic pollutants such as nutrients and pathogens from livestock, and pharmaceuticals such as steroids, antibiotics, and other drugs used in animal production. Decisions regarding the use of these materials often fall to the human managers of individual field systems. These managers determine if, when, and how much of an external input will be added to the system or, in the case of livestock, what areas livestock will be restricted to.

Management strategies that reduce fertilizer and pesticide applications will reduce the quantity of pollutants that reach ground and surface water. These strategies may include increasing soil organic matter, as previously discussed, and initiating integrated pest management (IPM). Sustainable management may also include continued use of synthetic fertilizers and pesticides under certain conditions. For this reason, it is critical that adaptive management and local learning on crop nutritional requirements and methods to determine organic and synthetic fertilizer application rates that are neither too high nor too low. Training in IPM practices such as scouting will also promote appropriate safety practices, and timing and application rates of pesticides.

Protecting Biodiversity

The diversity of biological life on Earth has been exploited by humans for thousands of years for the purpose of survival. Biodiversity in agroecosystems is part of the complete range of biodiversity that humans depend on for food and fiber. Though often considered only in higher system levels, biodiversity is an important aspect of regenerative and sustainable management of field systems (see text box below). Figure 7 illustrates primary components and functions of biodiversity in field systems.

Biodiversity and plant breeding: Maintaining genetic resources

An important aspect of biodiversity conservation is the maintenance of local crop and animal genetic resources. Field managers play a central role in this activity as the primary decision makers regarding which crops and animals should be introduced to a field system and which individuals should be used to provide seed or stock for future generations. A necessary step in promoting sustainable management of genetic resources is the creation of institutions that strive to connect field managers to international research centers, catalog local knowledge and genetic resources, and engage field managers in the process of cultivar selection, multiplication, and distribution.

In recent years, international agricultural research centers and other research institutions have established participatory planting breeding programs aimed at improving smallholder adoption of improved varieties and maintaining beneficial cultivar diversity (Probst 2004). The aim of such programs is to ensure that the needs of farmers are met by research programs while promoting development and biodiversity (Vernooy and Stanley 2003). Participatory planting breeding combines farmer training based on local knowledge and environmental conditions with plant breeding programs targeted at overcoming local challenges to production. This approach gives farmers greater input into their own livelihoods and offers scientists access to new sources of knowledge and genetic material that can be utilized globally. The involvement of farmers in seed multiplication and distribution also encourages adoption by their peers, a key to widespread, successful scaling out of new innovations and technologies.

Conserving Crop and Animal Genetic Resources

The genetic diversity of crops and livestock represents an important component of biodiversity in managed field systems. Genes that control the physiological adaptation of plants and animals are the primary source of an organism's ability to respond to diverse abiotic and biotic stresses in the field environment. The potential yield of a specific crop variety, for example, is determined by its genetic makeup, as is its ability to reach this potential in a specific field system environment. Similarly, genes determine an animal's tolerance to insects and pathogens, ultimately dictating whether the animal thrives in the presence of these pests.

Crops and animals selected for certain environment and management conditions are likely to possess genes that allow them to reach optimum growth potential in that environment and develop internal protection mechanisms against common pests. For this reason, local crop cultivars and animal breeds are a good choice for a field system, for natural adaptations favor yield stability without requiring a high level of external inputs. Also, protection of local genetic resources

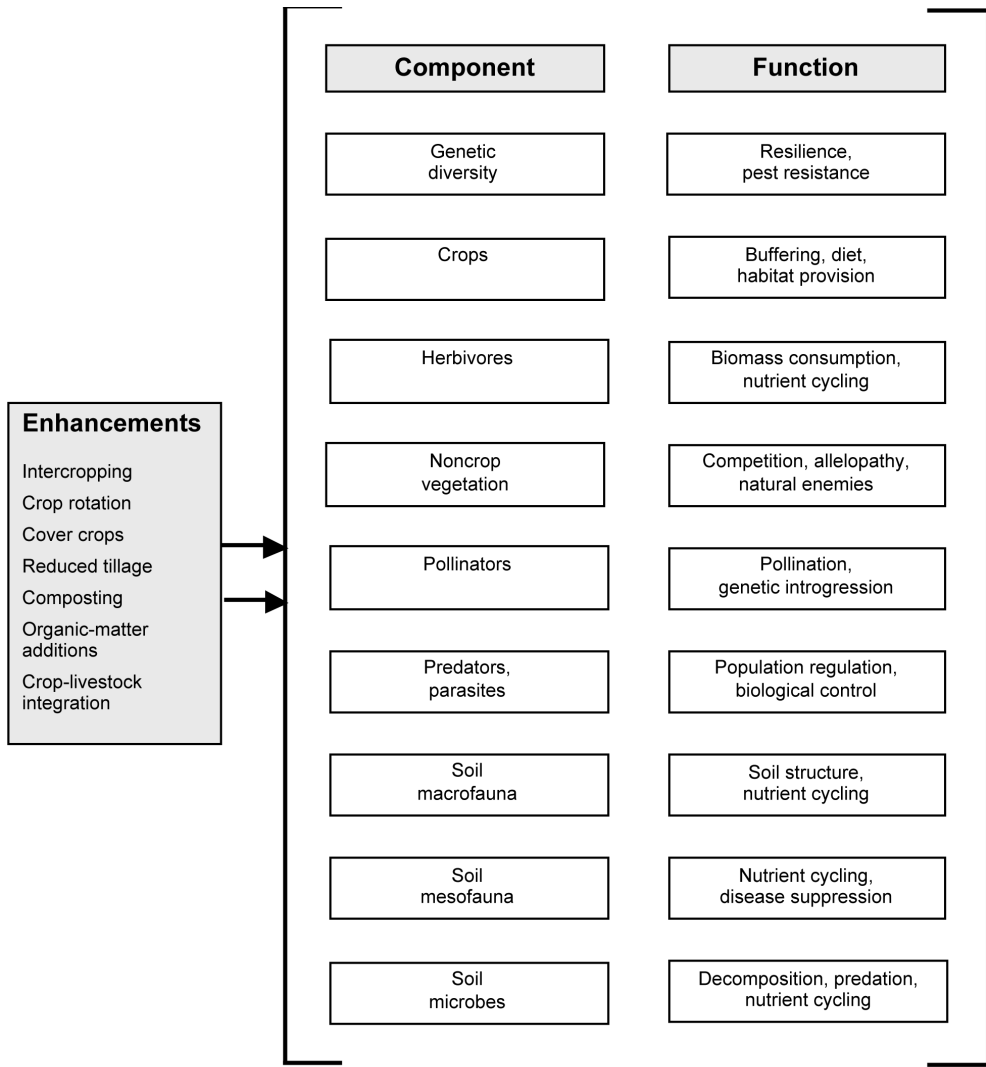


Figure 7. Agroecosystem biodiversity (adapted from Altieri 1999).

maintains the stock of potentially beneficial cultivars that field managers and breeders may use to improve production, confer protection against a specific pest in other locations, and exploit beneficial relationships among various components of a field system.

Enhancing Crop Diversity

Increased crop diversity represents a central strategy in sustainable management of an agricultural field. Introducing crop diversity will enhance diversity of other living organisms within the system and lead to secondary benefits such as improved nutrient availability (as contributed by soil biodiversity), pollination (by animal populations), and pest management (provided by soil biota and insect predators). Crop diversity also provides a buffer against crop failure or changes in agricultural markets. Though increased yield is cited most often as the primary indicator of

improved production, increased crop diversity should also be considered a central objective of sustainable management. Finally, crop diversity can provide benefits to human agents interacting with the field system by offering a broad range of nutritional options for subsistence farmers. Tropical American indigenous civilizations, for example, used corn, beans, peppers, and squash as their principal field mixture both to benefit the ecological processes of the system and to create a rich and balanced diet.

From an agronomic standpoint, crop diversity confers biotic and abiotic stress avoidance, ultimately contributing to enhanced crop production (Clergue et al. 2005). The biotic stresses mediated by crop diversity include insects, weeds, diseases, and nematodes. Potato late blight (the disease that led to the Great Irish Famine of the 1840s) and Southern corn leaf blight (which threatened US crops in the 1970s) are good examples of how reliance on a single species can result in catastrophic epidemics that may have been avoided through diversity. Crop diversity can also provide a buffer against yield losses in a single crop due to environmental stresses such as extreme variation in temperature and rainfall. Diverse cropping systems exploit the broad range of ecological niches in a field during a specific growing season, enabling field managers to maintain yield stability and achieve other production goals from year to year.

Species and cultivars are the cropping system components that define crop diversity in a field system. Crop diversity has both temporal and spatial components. Different crops existing within the same field at the same time are an expression of spatial diversity. Polycultures—mixed stands of species and cultivars—are an important component of cropping systems used historically by smallholders (Altieri 1999; Haugeraud and Collinson 1991). Land equivalent ratio comparisons frequently reveal the increased efficiency of polycultures over monocultures (Schulthess et al. 2004; Hiebsch and McCollum 1987). Temporal diversity is represented by different crop species existing in the same field at different times (seasons or years). This is commonly the case with crop rotation.

Crop diversity supports biodiversity among field inhabitants critical for pollination and crop protection from pests, functions essential to field-level productivity. An estimated 75% of the world's major crops depend on pollination by bees, other insects, hummingbirds, and bats (Cassman and Wood 2005). Diversity of food sources and habitats supported by crop and soil organism diversity attracts pollinators that drive sexual reproduction. Pollination rate has a direct impact on the yield of numerous crops and helps maintain genetic diversity of crop plants (Clergue et al. 2005). Crop diversity also supports large, diverse populations of insects, arthropods, and bird predators that hold insect pest populations in check (Clergue et al. 2005) and promote stability in insect populations to minimize severe yield losses to a single pest outbreak (Altieri 1999). Research also suggests that greater diversity within a community confers resistance to, but does not always prevent, invasion by alien species (Shea and Chesson 2002).

Intercropping

Intercropping—combining two or more rows of crops in the same field—is widely practiced in Africa, Asia, and Latin America as a management strategy to introduce diversity and reduce risk. Increased diversity, in turn, performs several functions. Olasantan (2001) found that intercropping cassava with a high-density planting of okra (50,000 plants per hectare) reduced weed growth by 25% to 45% due to increased shading. Legumes planted with a cash crop can provide nitrogen needed by the cash crop, resulting in a reduced need for external nitrogen addition (Borin and Frankow-Lindberg 2005). Intercropped systems may also be composed of mixed cultivars of a single species. In East Africa, farmers report planting both early and late maturing maize cultivars

to manage potential environmental stresses as well as meet different end use needs, such as home consumption and commercial sale (Haugeraud and Collinson 1990).

Crop Rotation

Crop rotation is a means of introducing temporal diversity that promotes crop protection and benefits soil nutrient cycling, water conservation, and output. On the same piece of land, growing a crop following one of a different species can also disrupt the life and reproductive cycles of pests such as weeds, insects, pathogens, and nematodes. There are two crop rotation strategies. In a *seasonal rotation*, a sequence of two or more crops is grown in a field in a single year; this same sequence is often repeated the following year. Farmers in Ethiopia, for example, grow potatoes or a cereal such as wheat during the period of long rains and, in the same year, grow another cereal such as maize during the period of short rains.

In an *annual rotation*, the crop grown in a field varies from year to year; an annual rotation may be as simple as yearly alternating between two crops or involve multiple crops grown in sequence over several years. Many farmers in Africa use an annual rotation in fields where millet is grown:

- year 1—millet
- year 2—cowpea
- year 3—millet
- year 4—cowpea

In this example, both millet and cowpea are important crops for home consumption and sale. Inclusion of a nitrogen-fixing legume such as cowpea in rotation with other cash crops can also boost overall productivity of the crop system.

Crop rotations including a legume are used in many rice production systems across Asia. A recent study in India demonstrated that including the legume mung bean (*Vigna mungo* L.) in the traditional Asian rice-wheat cropping system resulted in higher productivity, gross income, and net return than rice-wheat alone (Sharma and Sharma 2005). The sequence of this rotation is as follows:

- spring—mung bean
- summer—rice
- winter—wheat

Other rotations commonly used in Asia include the following:

- spring rice—summer rice—winter soybean (or other winter legume)
- spring mung bean (or soybean)—summer rice—winter maize
- spring peanut—summer rice—winter sweet potato

In these examples, the legume can be used for human consumption; however, it is not necessary that all crops in a rotation have a direct human benefit.

Though used for human consumption only on a limited basis, mucuna or velvet bean [*Mucuna pruriens* (L.) DC. var. *Utilis* (Wright) Bruck] is used worldwide in rotation with cash crops. In Central America the velvet bean is referred to “frijol de abono” (fertilizer bean), for it can fix more than 200 kg N per hectare annually, well over the quantity needed by corn. In western Kenya, mucuna grown following an intercrop of maize (*Zea mays* L.) and common bean (*Phaseolus vulgaris* L.) can lead to an increase in the yield of the subsequent maize crop as well as provide herbage for animal fodder (Nyambati et al., 2006). Also, *Mucuna* ssp and other legume species such as *Canavalia* ssp. can inhibit weed growth and suppress some species of plant parasitic nematodes (Camaal-Moldonado et al. 2001; Arim et al. 2006). Intercropping of grains and legumes is a regenerative practice with the potential to increase both the organic matter of soil and grain yields.

Promoting Soil Biodiversity

Soil supports a variety of living organisms that play an important role in field system function, resilience, and regeneration. For example, soil bacteria such as *Rhizobium* and *Azotobacter* and blue-green algae are responsible for the fixation of atmospheric nitrogen. Exploitation of free-living nitrogen fixers and those associated with leguminous crops is a key strategy to reduce reliance on costly external sources of N to support crop growth. Other bacteria in soil serve to mediate the impact of pests such as insects, non-beneficial nematodes, weeds, and diseases on field systems by serving as biological control agents (Kennedy 1999). Another class of microflora, mycorrhizae, is a fungal species symbiotically associated with plant root systems. These combinations can enhance nutrient uptake and water use efficiency of crop plants.

Macrofauna such as earthworms, termites, centipedes, and millipedes directly and indirectly affect decomposition and nutrient cycling through activities that mix, transport, and break apart litter; initial decomposition of resistant materials such as cellulose and chitin polymers; and provision of a food source for microbial populations in the form of castings. Soil arthropods play an important role in the regulation of agricultural pests such as insect and seed predators. Soil organisms also include antagonists that inhibit soil pathogens. Suppression of disease in environments favorable to the growth of certain pathogens is often observed in fertile soils with high levels of organic matter. These soils support diverse and large microbial populations such as actinomycetes and bacteria that may confer disease suppression (Altieri 1999). The critical functions carried out by soil organisms, summarized in table 5, underscore the necessity of management practices that enhance soil biodiversity.

Field management has a significant impact on soil biodiversity and activity. Practices that lead to increases in soil organic matter, such as mulching, cover cropping, and composting, all of which have been discussed in this chapter, support diverse soil populations. In contrast, tillage can significantly reduce soil microbial diversity (Lupwayi et al. 1998; Wander et al. 1995; Hassink et al.

Table 5. Functions carried out by soil organisms (biota) (adapted from Bot and Beites 2005).

Function	Organisms involved
Maintenance of soil structure	Macroorganisms (invertebrates) that turn soil; mycorrhizae, other microorganisms
Gas exchange, carbon sequestration	Soil microorganisms
Soil detoxification	Soil microorganisms
Nutrient cycling	Soil microorganisms; some litter- and soil-feeding invertebrates
Decomposition of organic matter	Litter-feeding invertebrates, fungi, bacteria, actinomycetes and other microorganisms
Suppression of pests, parasites, diseases	Mycorrhizae and other fungi, nematodes, bacteria and other microorganisms, earthworms, various invertebrate predators
Sources of food and medicines	Various insects, earthworms, vertebrates, microorganisms and their byproducts
Symbiotic and asymbiotic relationships with plants and their roots	Rhizobia, mycorrhizae, actinomycetes, diazotrophic bacteria, other rhizosphere microorganisms, ants
Plant growth regulation (positive and negative)	Rhizobia, mycorrhizae, actinomycetes, pathogens, phytoparasitic nematodes, rhizophagous insects, biocontrol

1991). Zhang et al. (2006) reported that fungal contribution to the microbial community increased with a decrease in tillage and that reducing human disturbance may facilitate the development of microbial communities that favor carbon retention in agricultural soils. By creating a homogenous soil environment, tillage eliminates habitats formed through the natural process of soil stratification and, therefore, the soil microorganisms exploiting these niches (Altieri 1999). Plowing can also physically break up fungal mycelium, resulting in reduced populations and activity. Reduced tillage practices that leave mulch or residues avoid or eliminate physical disruption and provide a variety of habitat and food sources that support diverse populations. These surface mulches also provide organic materials that are broken down by soil micro- and macro-organisms, adding to the organic matter pool.

Reducing Dependence on External Energy Inputs

Many field managers now rely on nonrenewable fossil fuels to meet external energy requirements in managed fields. Such reliance on a finite resource can limit the sustainable development of agricultural and natural resources. As fossil fuels become more expensive, field managers, particularly smallholders, must utilize alternative management strategies to reduce external energy demand. Regenerative practices are those that reduce external energy demand by efficient use of internal resources to provide ecosystem services. The term *low-input agriculture* is often used to refer to production systems that use combination of internal resources to replace and/or eliminate the need for external energy resources.

Energy Dynamics in Low-Input Agriculture

David Pimentel of Cornell University and co-workers have conducted several studies of energy-use efficiency in low- and high-input agricultural systems. In Mexico, for example, low-input corn production resulted in a low yield level of about 2,000 kg per hectare but had an energy output to energy input ratio of 12:1. In contrast, a high-input system in Minnesota resulted in a yield of 6,500 kg per hectare but had an energy output to energy input ratio of 2.9:1 (Pimentel et al. 1973). This comparison indicates that low-input systems can be more energy efficient than conventional high-input systems. More recently, Pimentel and Pimentel (2005) have estimated output to input ratios of an “industrialized” and an “improved sustainability” intensive maize system at 2.8:1 and 4.8:1, respectively. They suggest that these energy efficiency improvements of intensive production systems favored for higher yields and lower land area demands are the result of integration of low-input strategies such as crop rotation, livestock integration, cover cropping, and reduced tillage.

Alternative Sources of Fertility to Enhance Energy Efficiency

Of all agricultural practices, nitrogen fertilization with ammoniated fertilizer is the most energy intensive, representing up to 30% of the fossil fuel requirement for conventional maize production (Pimentel et al. 1973). Alternative strategies to meet nitrogen requirements include the application of manure (see “Compost and Other Organic Amendments” for more information) and integration of nitrogen-fixing legumes through crop rotation, intercropping, and cover cropping. Legumes provide several cost-saving strategies by reducing the external energy required to generate plant-available nitrogen and reducing or eliminating the need to purchase external sources of nitrogen such as chemical fertilizers. In the Rodale Institute’s farming systems trial in the temperate United States, the fossil fuel requirement for legume-based organic production of corn and

soybeans is 33% lower than the requirement for conventionally produced corn and soybeans. The legume-based systems have demonstrated equivalent yield and quality for both crops.

Integrating Crops and Livestock

Although the numbers of large specialized livestock farms have increased dramatically in developed countries since World War II, mixed crop-livestock farms still predominate in developing countries. These systems occupy about 2.5 billion hectares and globally account for 54% of meat and 90% of milk supply (CAST 1999). Crop-livestock systems employ a diversity of complementary resources, including crop residues, forage grasses and legumes, and manure. If managed properly, the system may substantially increase the efficiency of nutrient recycling. In the case of limited-resource smallholders, the integration of livestock in cropping systems is highly desirable because it adds flexibility and stability, both financial and physical, by buffering the system against climatic stresses and market fluctuations. Furthermore, livestock are easily marketable and provide a relatively high level of return per labor unit as well as manure, a valuable byproduct that can be used as fertilizer.

From a field-level perspective, ruminant livestock can take advantage of crop residues in the utilization and conversion of these fibrous, human-inedible materials to food, fiber, and other useful products as well as through their digestion and redistribution as manure. As mentioned by Latham (1997), management of crop residues is one of the most important issues of crop-livestock systems in the semiarid tropics; however it is not an issue with a simple technical solution. It requires that the farm household consider the risks and tradeoffs involved.

Many of the attributes of crops and livestock that are considered complimentary are crucial to the economic and ecological stability of the field system. Manure is probably the most obvious because of its role as a source of organic fertilizer. Because a large proportion (60% to 90%) of the nutrients that ruminant animals consume at the field level from pasture and crop residues is recycled in the dung and urine, the management of grazing patterns and the collection and redistribution of excreta is critical to crop production in many areas.

Furthermore, ruminant excreta can be a source for biogas generation for household use. Biogas generation for cooking and lighting can be a valuable resource in areas where water is not a limiting factor and temperatures remain between 20°C and 40°C most of the time. The excreta from a few cows collected and sealed in a digester could produce 2 to 3 cubic meters of methane daily, enough for a family of six to use in lieu of firewood or kerosene (FAO 2001). Moreover, the spent slurry from the digester remains a valuable fertilizer material for crop or pasture production. A variety of mixed crop-livestock systems have proved successful in many different environments. They may involve ruminants such as cattle, sheep, and goats; monogastrics such as pigs, chickens, and turkeys; and various combinations of crops and trees, depending on climate and available resources. Crop production also may be heavily dependent on animal traction for land preparation and cultivation and transport for market access. Economically, livestock also represent an additional source of income beyond crop production. It is imperative that farmers involved in integrated crop-livestock systems think holistically about the system, realizing that maximization of an individual system component such as crop yield may not result in the optimization of the system as a whole (figure 8).

As mentioned previously, there are many potential benefits from an integrated crop-livestock system at the field level. Nevertheless, tradeoffs are necessary to implement the system (table 6). For example, the field manager must have expertise in both crop and animal husbandry, and achieving economies of scale is difficult in this situation (Van Keulen and Schiere 2004).

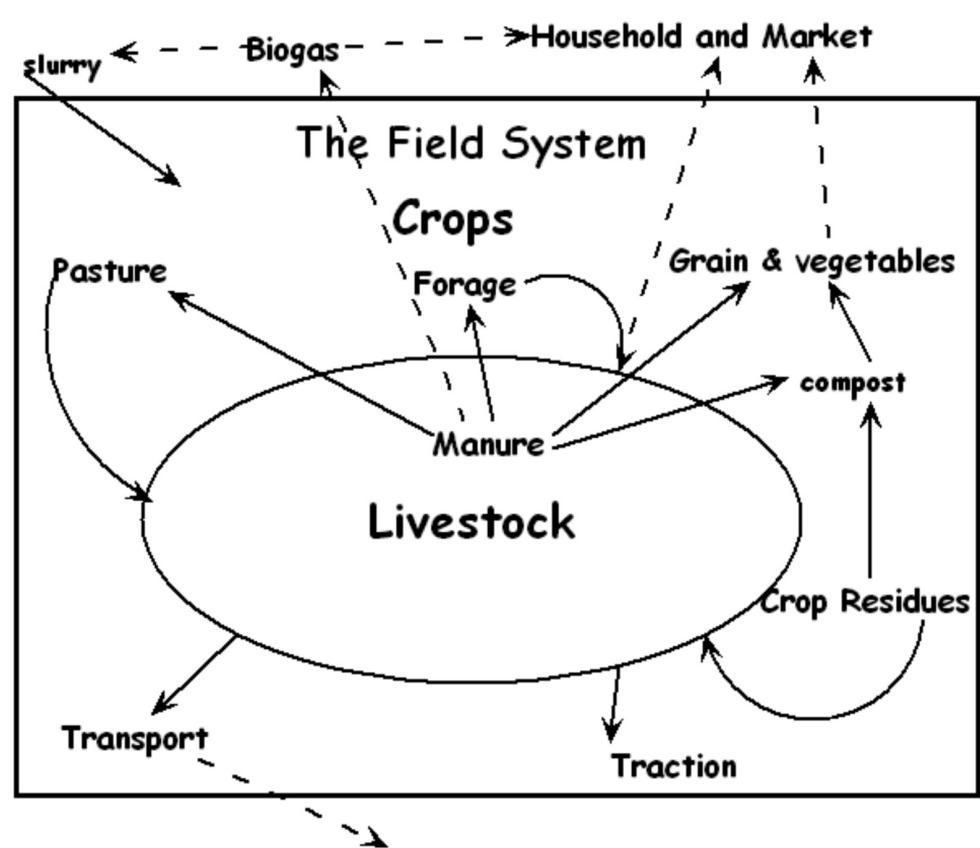


Figure 8. Crop-livestock integration in the field system.

Table 6. Benefits and challenges of crop-livestock systems (Van Keulen and Schiere 2004).

Benefits	Challenges
Buffered against fluctuations in trade and price	Requires double expertise
Buffered against climate fluctuation	Fewer economies of scale
Erosion control through perennial forages	Erosion hazard due to overgrazing
Higher nutrient recycling due to more direct soil-crop-animal manure relations	Nutrient losses through competitive uses for residues
Diversified income source	Continual labor requirement
Draught power allowing larger cultivated area, more flexible residue management	Capital required
Source of security and savings	Social function, potential cause of conflict

Note: Some of these issues could occur both in the left and right hand columns due to local context.

Overgrazing could cause compaction and erosion. Competition for crop residues by other uses such as fuel, building materials, or off-farm sales could diminish or eliminate nutrient recycling.

Management of pests such as diseases, insects, nematodes, and weeds that interrupt farm systems' function and production relies on the integration of practices that exploit complementary interactions of field system components. This approach is referred to as integrated pest management or IPM. Due to the number of resource materials available on IPM, this book will not provide an exhaustive discussion of this concept. It will, however, highlight several key practices used in IPM systems that provide cross-cutting benefits and enhance field system resilience. As with all adaptive management strategies, IPM is most effective when the practices employed are adapted for local environmental and cultural conditions.

Cultivar selection is a cornerstone of IPM. Using the rich diversity of plant and animal genetic resources available in the biosphere, both scientists and smallholders have identified plant cultivars that demonstrate resistance to specific pests. For example, use of resistant cultivars has been identified as a key strategy for effective integrated management of diseases in major crops such as wheat, potato, peanut, sorghum, and maize (Mehta et al. 1992; Pande et al. 2001; Ellis-Jones et al. 2004; Marley et al. 2004; Nyankanga et al. 2004). Similarly, the exploitation of host plants resistant to specific insect pests has been a central component of IPM programs for numerous world crops, including sorghum, rice, and cowpea. Introducing resistance to insects and diseases is a focus of many international breeding programs.

Crop cultivars vary in their abilities to compete with and adapt to weeds. There are several characteristics that a cultivar may exhibit that enhance competitive ability with weeds. For many row and horticultural crops, rapid growth and early canopy closure can result in the suppression of weeds. For this reason, using transplants when possible for horticultural crop production is advantageous. Use of transplants will increase production costs, so the economic benefit of using transplants must be weighed against cost. The physical structure of a cultivar may also affect competitive ability. Tall grain crops, for example, are generally more competitive with weeds because they intercept light. A large leaf area index and high biomass production can also contribute to a cultivar's competitive abilities. Local varieties often have these desirable traits that may not be prioritized for commercial seed varieties from centralized breeding programs.

IPM also relies on knowledge of the targeted pest. An organism cannot survive in an ecological system without resources for food and habitat provision, including locations for reproduction. When field managers eliminate these basic necessities from the system, the targeted pest population will be reduced. Strategies to deprive pest populations include delayed planting to avoid pest emergence, cultivation, and crop rotation. IPM may also include exploitation of pest antagonists such as soil pathogens, natural enemies, and biofumigants. Strategies to enhance these beneficial populations are those that promote biodiversity within the system, the direct and indirect benefits of which were discussed previously.

Another consideration in IPM is the extent to which management of pest populations is essential to eliminate interference with production goals. For example, the goal of eradicating weeds is unrealistic and unneeded. Most crops have a "critical weed-free period" during which competition from weeds is yield-limiting; the presence of weeds during growth phases outside this critical period is not detrimental to yield. In most situations, the critical period is in the first one-third of the crop growth cycle. With crops such as beans and corn, this means that controlling weeds for the first 40 days is sufficient to prevent severe losses. Weeding is not necessary through the entire period of crop growth. Similarly, field managers may use thresholds to determine the critical population size at which control of weed and insect populations is essential to avoid crop damage. The

threshold concept recognizes that the presence of some weeds and insects can be tolerated with little negative effect on crop output.

Another system component to consider in developing an IPM plan is soil fertility. Recent research and reviews of past studies indicate a link between soil fertility management strategies and insect pest populations, for soil fertility management can influence the resistance of crops to insect pests (Altieri and Nicholls 2003). For example, numerous studies have documented increased damage and/or growth of insect pests on crops that receive synthetic nitrogen fertilizer (Scriber 1984). This increase is thought to be caused by high concentrations of foliar N, particularly following fertilizer application. In contrast, use of organic N does not lead to high foliar N concentrations or N pulses and has been cited as a factor leading to lower abundance of insect species in organically managed crops (Lampkin 1990). Though the relationship between soil fertility and insect pests is not well understood, current available knowledge suggests that strategies to enhance soil quality and organic matter will have positive impact on insect pest management.

In addition to benefiting ecological components of the field system, IPM can also have a positive impact on the human agents in the field system. Smallholders in developing countries commonly devote more than 50% of their labor time to weeding, a task often done by women (Ellis-Jones et al. 1993; Akobundu 1996). IPM empowers field managers to optimize use of limited labor resources and reallocate labor to other critical field and household tasks.

Conclusions

The field system represents the fundamental unit nested in farms, landscapes, watersheds, and ecosystems. Agricultural fields are governed by the ecological processes of photosynthesis and respiration that transform solar energy and regulate nutrient and mineral cycles. Field systems contain biotic and abiotic elements that are necessary to convert solar energy into plant tissue and subsequently to animal products. Guided by human interventions, field systems produce food, forage, fiber, fuel, and building materials. The production efficiency of these commodities drives human economies and to a large extent determines quality of life for human populations. The capability of field systems to conserve natural resources and provide ecosystem services is dependent on the knowledge and skill of field managers, land tenure issues, and wise governance. These issues and more will be explored in the chapters that follow.

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