8 Soil

Soil is a complex, living, changing, and dynamic component of the agroecosystem. It is subject to alteration, and can either be degraded or wisely managed. In much of present-day agriculture, with the availability of an array of mechanical and chemical technologies for rapid soil modification, soil is all too often viewed primarily as a growth medium, something from which to extract a harvest. Farmers often take the soil for granted, and pay little attention to the complex ecological processes that take place below the surface. The premise of this chapter, in contrast, is that a thorough understanding of the ecology of the soil system is a key part of designing and managing sustainable agroecosystems in which the long-term fertility of the soil is maintained.

The word *soil*, in its broadest sense, refers to that portion of the earth's crust where plants are anchored; this includes everything from the deep soils of a river bottomland to a crevice in a rock with a bit of dust and plant debris. More specifically, the soil is that weathered superficial layer of the earth that is mixed with living organisms and the products of their metabolic activities and decay (Odum and Barrett, 2004). Soil includes material derived from rocks and organic and inorganic substances derived from living organisms, and the air and water occupying the spaces between soil particles.

From an agricultural perspective, an "ideal" soil is made up of 45% minerals, 5% organic matter, and 50% space, with the "space" filled half with water and half with air. It is hard to find anything that we can call a "typical" soil, since each site or location has unique properties that ultimately determine the final outcome of the soil formation process.

PROCESSES OF SOIL FORMATION AND DEVELOPMENT

Biological processes combine with physical and chemical processes in each particular climatic region and location to form soil. Once formed, soil changes and develops due to these and other biological, physical, and chemical processes. With variations in slope, climate, and type of vegetative cover, many different soils can form in close juxtaposition with one another, even though the parent material may be fairly similar.

Natural processes of soil formation and development take considerable time. For example, it is estimated that only about 0.5 to 1.5 t of topsoil per acre is formed annually in areas of corn and wheat production in the central Midwest region of the U.S. (Daily, 1995). In contrast, about 5 to 6 t of soil per acre are estimated to erode from conventionally farmed land in these areas, with soil losses often exceeding 15 to 20 t/acre in some years (NRCS, 2005).

Formation of Regolith

As a whole, the layer of unconsolidated material between the soil surface and the solid bedrock of the earth below is called the *regolith*. The most basic element of the regolith is its mineral component, made up of soil particles formed from the breakdown of the bedrock or parent material. At any particular location, these soil particles may have been derived from the bedrock below, or they may have been transported from elsewhere. Where a soil's mineral particles have been formed in place from the bedrock below, the soil is a residual soil. Where the mineral particles have been carried from some other location by wind, water, gravity, or ice, the soil is a *transported soil*.

Physical Weathering

The weathering of rock and rock minerals is the original source of mineral soil particles, whether the particles remain in a location or are moved elsewhere. The combined forces of water, wind, temperature, and gravity slowly peel and flake rock away, accompanied by the gradual decomposition of the minerals themselves. Water can seep into cracks and crevices in rock, and with heating and cooling causing alternating swelling and contracting, rock begins to fragment. In addition, the carbon dioxide contained in the water that seeps into cracks can form carbonic acid, pulling elements such as calcium and magnesium from the minerals of the rock and forming carbonates, and in the process weakening the crystalline structure of the rock and making it more susceptible to further physical weathering. Finer particles mix with larger particles, promoted by the physical movement created by the combined forces of gravity, temperature change, and alternating wetting and drying. Even the abrasive forces of rocks against each other during this movement can form smaller particles. Eventually the unconsolidated regolith takes form.

Depending on local conditions and geological history, the regolith can be recently formed, lightly weathered, and made up of mostly primary minerals, or it may have been subjected to intensive weathering and be made up of more resistant materials such as quartz.

Transport

As rock is broken down into smaller and looser materials, it can remain in place and eventually form residual soils, but a more likely fate is for it to be carried some distance and deposited. The forces of wind, water movement, gravity, and glacial ice movement can all transport weathered soil particles. Transported soils have different classifications depending on the manner in which their particles were transported. Soil is called

- Colluvium, where it has been transported by gravity
- Alluvium, where it has been transported by the movement of water
- Glacial soil, where it has been transported by the movement of glaciers
- Eolian soil, where it has been transported by wind

Biotic Processes

Sooner or later, depending on the consistency of the regolith, plants establish themselves on the weathered material. They send roots down that draw nutrients from mineral matter, store them for a while in plant matter, but eventually return them to the soil surface. Deep roots further break down the regolith, capture nutrients that have leached from the upper surface, and add them to the soil surface in an organic form. Plant residue then serves as an important source of energy for the bacteria, fungi, earthworms, and other soil organisms that establish in the area.

Organic matter is broken down into simpler forms through decomposition and mineralization. Macroorganisms in the soil — centipedes, millipedes, earthworms, mites, grasshoppers, and others — consume freshly deposited plant debris and convert it to partially decomposed material, either in the form of excreta or their own dead bodies. This material is then further decomposed by microorganisms, mostly bacteria and fungi, into an array of compounds such as carbohydrates, lignins, fats, resins, waxes, and proteins. Mineralization eventually breaks these complex compounds down into simple products such as carbon dioxide, water, salts, and minerals.

The fraction of organic matter left in the soil as a result of decomposition and mineralization is called *humus*. It has a certain lifetime in the soil, after which it is broken down itself. New humus, however, is constantly replacing old humus, and the equilibrium point between the two is an important factor in soil management.

Chemical Weathering

While the regolith is forming and living organisms begin to have their impacts on it, chemical weathering is occurring as well. Chemical weathering includes natural chemical processes that aid in the breakdown of parent materials, the conversion of materials from one form to another in the soil, and the movement of materials within the soil. Four different chemical processes are of primary importance in soil formation and development: hydration, hydrolysis, solution, and oxidation.

Hydration is the addition of water molecules to a mineral's chemical structure. It is an important cause of crystal swelling and fracturing. *Hydrolysis* occurs when various cations of the original crystalline structure of silicate minerals are replaced by hydrogen ions, causing decomposition. In regolith with low pH, the greater concentration of H^+ accelerates hydrolysis. The release of organic acids as a byproduct of the metabolic activities of living organisms, or from decomposition of dead organic matter, can add to this process as well. *Solution* occurs when parent materials with a high concentration of easily soluble minerals (such as nitrates or chlorides) go into solution in water. Limestone is particularly susceptible to solution in the presence of water, high in carbonic acid; in extreme cases the solution of limestone leads to the formation of limestone caves in areas of underground water flow. Finally, *oxidation* is the conversion of elements such as iron from their original reduced form into an oxidized form in the presence of water or air. Softening of the crystalline structure usually accompanies this process.

Once minerals are released from the consolidated parent material, another chemical process that is of great importance is the formation of secondary minerals — the most important being clay minerals. Clay mineralogy is a very complex field of study, but it is important to understand some basic aspects of clay formation, since they have such dramatic impacts on plant growth and development.

Clay minerals are very small particles in the soil, but they affect everything from water retention to nutrient availability, as will be discussed elsewhere. They are formed by complex processes in which silicate minerals are chemically modified and reorganized. Depending on the combination of climatic conditions and parent material, the secondary minerals that are formed are of two basic types: *silicate clays* that are predominantly made up of microscopic aluminum silicate plates with different arrangements and the presence or absence of other elements such as iron and magnesium; and *hydroxide clays* that lack a definite crystalline structure and are made up of hydrated iron and aluminum oxides in which many of the silicon ions have been replaced.

Eventually, the clays found in any soil will be a mixture of many subtypes of these two basic types of secondary clay minerals, although one or a few subtypes

may predominate. When silicate clays dominate, there are abundant sites for absorbing cations, giving the soil a relatively high productive potential. When hydroxide clays dominate — as in many humid tropical regions — fewer cation sites are available, making the soil more difficult to farm because of its poor ability to exchange nutrient cations.

Organic matter, either from plant residues or the activities of living organisms, has important impacts on all of these chemical weathering processes of parent material and greatly accelerates the formation of the regolith. However, it is the array of biological and chemical interactions that go on once rock and minerals have been converted to small soil particles that are of the greatest agricultural interest.

SOIL HORIZONS

Over time, the localized chemical, physical, and biological processes in the regolith lead to the development of observable layers in the soil, called *horizons*. Together, the horizons in a particular location give each soil a distinctive *soil profile*. Each horizon of the soil profile has a distinct combination of characteristics.

The Soil Profile

In general terms, a soil profile is made up of four major horizons: the organic, or O horizon, and three mineral horizons. The O horizon lies at the soil surface; immediately below it is the A horizon, where organic matter accumulates and where soil particle structure can be granular, crumb like, or platy. Under the A horizon is the B horizon, where materials leached from the A horizon can accumulate in the form of silicates, clay, iron, aluminum, or humus, and soil structure can be blocky, prismatic, or columnar. Finally there is the C horizon, made up of weathered parent material, either derived from the local parent material below or from material transported at some earlier time to that location. Some material leached or deposited from the A and B horizons can be found here, such as carbonates of calcium and magnesium, especially in areas of low rainfall. Depending on the depth of the upper four horizons, an R horizon made up of consolidated bedrock may also be included as part of the soil profile.

Since the separations between each horizon are rarely distinct, the horizons described above actually form a continuum in the soil profile. A typical soil profile is presented in schematic form in Figure 8.1. The depth, characteristics, and differentiation of each horizon of each soil profile is the result of the combined impacts of the properties of the soil material (its color, organic matter content, and chemical and physical traits), the type of vegetative cover, and the climate.

The processes that differentiate soil horizons function in different ways depending on regional and local conditions. These differences result in four basic types of soil development, which are summarized in Table 8.1. The process of calcification is most characteristic of areas of grassland vegetation in subhumid-to-arid and temperate-to-tropical climates of the world. Podzolization is most characteristic of humid, temperate areas of the world

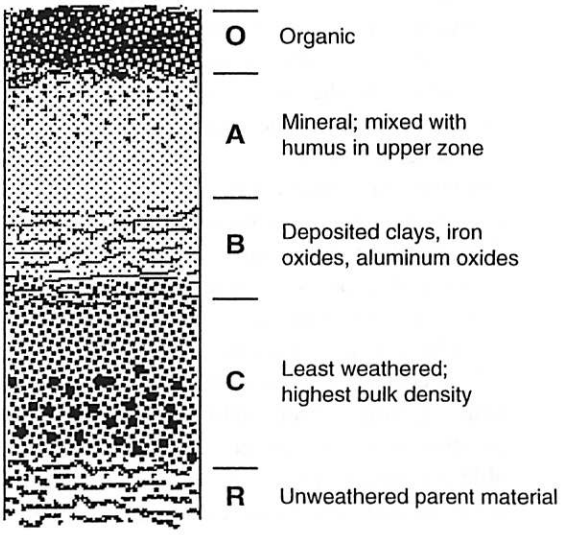

FIGURE 8.1 Generalized soil profile.

TABLE 8.1
Four Types of Soil Development

Development Process	Moisture	Temperature	Typical Vegetation	Resulting Characteristics
Gleization	High	Cold	Tundra	Compact horizons, little biological activity
Podzolization	High	Cool to warm	Needle-leaf forest, deciduous forest	Light-colored A horizon; yellow-brown B horizon high in iron and aluminum
Laterization	High	Warm to hot	Rainforest	Weathered to great depth; indistinct horizons; low in plant nutrients
Calcification	Low	Cool to hot	Praire, steppe, desert	Thick A horizon rich in calcium, nitrogen, and organic matter (except in deserts)

where forests have been the dominant vegetative cover for a long time. Laterization takes place on older and heavily weathered soils of the humid subtropical and tropical forested regions of the world, and gleization is most common on soils where water stays at or near the surface for a good part of the year. But depending on localized conditions of slope, drainage, vegetation, depth to bedrock, etc., combinations of these processes can be found. On the whole, soil formation and development is an ecological process, where soil affects the vegetation, and the vegetation affects the soil.

Importance of the Organic Horizon

In natural ecosystems, the O horizon is the most biologically active part of the profile and the most important ecologically. It plays a significant role in the life and distribution of plants and animals, the maintenance of soil fertility, and in many soil-development processes. Macro- and microorganisms responsible for decomposition are most active in this layer and in the upper part of the A horizon. Significantly, the O horizon is usually greatly reduced or even absent from cultivated soils.

The combination of local climate and vegetation type contributes to the conditions that promote activity in this layer; yet at the same time, the quality of the layer has profound influence on what kinds of organisms prosper. Bacteria, for example, favor nearly neutral or slightly alkaline conditions, whereas fungi favor more acid conditions. Soil-dwelling mites and collembola are more important under acid conditions, whereas earthworms and termites tend to predominate at or above neutrality.

The complex process of soil particle aggregation, which creates what is called the crumb structure of the soil, is greatly influenced by humus formed during decomposition in the organic soil layer. In addition, many valuable soil fertility processes, discussed later in this chapter, are related closely to the ecological characteristics of this important layer.

SOIL CHARACTERISTICS

In order to develop and maintain a healthy soil system, as well as make sound judgments about particular soil management strategies, it is important to understand some of the most essential properties of soils as they affect crop response.

Texture

Soil texture is defined as the percentage, by weight, of the total mineral soil that falls into various particle size classes. These size classes are gravel, sand, silt, and clay (Table 8.2). Particles greater than 2.0 mm in diameter are classified as gravel. Sand is easily visible by the naked eye, and feels gritty when rubbed between the fingers. Its low surface-to-volume ratio makes it porous to water and less able to adsorb and hold nutrient cations. Silt, although finer than sand, still is grainy in appearance and feel, but more actively holds water and nutrient ions. Clay particles are difficult to see separately with the naked eye, and look and feel like flour. Clay particles are colloidal in that they can form a suspension in water and are active sites for the adhesion of nutrient ions or water molecules. As a result, clay controls the most important soil properties, including plasticity and ion exchange between soil particles and water in the soil. A soil very high in clay content, however, can have problems with water drainage, and when dry can exhibit cracking.

TABLE 8.2
Soil Texture Classifications

Category	Diameter Range[a] (mm)
Very coarse sand	2.00–1.00
Coarse sand	1.00–0.50
Medium sand	0.50–0.25
Fine sand	0.25–0.10
Very fine sand	0.10–0.05
Silt	0.05–0.002
Clay	<0.002

[a] According to the US Dept. of Agriculture system.

Most soils are a mixture of texture classes, and based on the percentage of each class, soils are named as shown in Figure 8.2. From an agricultural perspective, sand gives a soil good drainage and contributes to ease of cultivation, but a sandy soil also dries easily and looses nutrients to leaching. Clay, at the other extreme, tends not to drain well and can become easily compacted and difficult to work, yet is good at holding soil moisture and nutrients.

What soil texture is best, depends on the crops grown in it. Potatoes, for example, do best in a sandy, well-drained soil, which helps prevent rotting of the tubers and makes harvest easier. Paddy rice does best on heavy soils high in clay content due to this crop's particular adaptations to the wet environment. A clay loam soil may be best overall in a drier environment, whereas a sandy loam might be better in a wet one. The addition of organic matter changes the relationships of the particles in mixtures, as we will see below.

Structure

In addition to the aspects of texture described above, soils possess a macrostructure formed by the ways individual particles are held together in clusters of different shapes and sizes called aggregates (Figure 8.3). Soil aggregates tend to become larger with increasing depth in the soil. Soil texture is one important determinant of

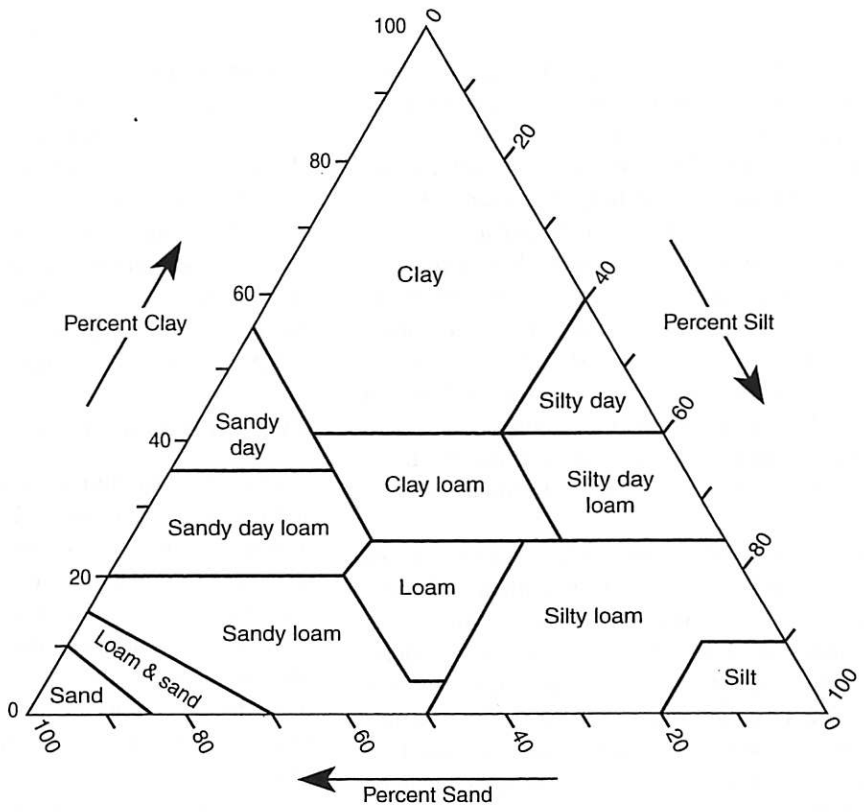

FIGURE 8.2 Soil textural names. The best type of soil is determined by the crop and local conditions; generally, however, soils containing relatively equal amounts of clay, sand, and silt — called loams — are best for agricultural purposes (From USDA diagram).

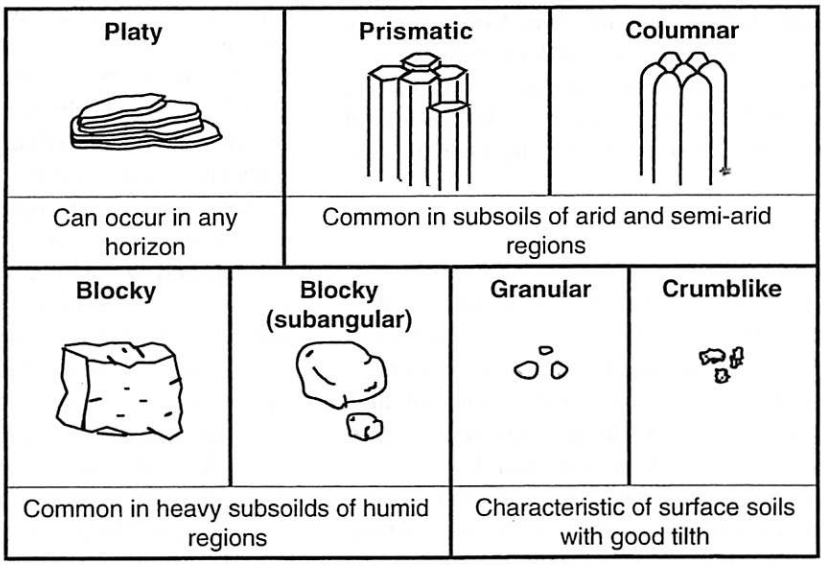

FIGURE 8.3 Patterns of soil aggregation (Modified from Brady, N. C., and R. R. Weil. 1996. 11th ed. Prentice Hall: Upper Saddle River, New Jersey).

structure, but structure is usually more dependent on soil organic matter content, the plants growing in the soil, the presence of soil organisms, and the soil's chemical status. Structure of the crumb or granular type is of the most benefit for agriculture, since good "crumb structure" improves soil porosity and ease of tillage, which together are known as tilth. When a lump of soil is crushed in the hand, and easily breaks into the crumb or granular structure noted in Figure 8.3, good crumb structure is present.

From an agroecological perspective, good crumb structure is of considerable significance. Soil particles that are bound together resist wind and water erosion, especially during any time of the year when vegetative cover is minimal. Good structure also helps maintain low *bulk density*, defined as the weight of solids per unit volume of soil. Soil with a low bulk density has a higher percentage of pore space (higher porosity), more aeration, better water percolation (permeability), and more water storage capacity. Obviously, such a soil is easier to till and allows plant roots to penetrate more easily. Excessive cultivation accelerates breakdown of soil organic matter and increases the potential for compaction, causing bulk density to go up and many of the advantages of good crumb structure to be lost.

The formation of soil aggregates has essentially two components: the attraction between individual soil particles, the degree of which is very dependent on soil texture, and the cementing of these attracted groups of particles by organic matter. The first component cannot be very easily manipulated by the farmer, at least in any practical manner, but the second can be very much impacted by farming practices. Thus good crumb structure can be maintained, degraded, or improved.

For example, excessive tillage with heavy equipment while the soil is too wet can lead to the formation of large blocky clods of soil that can dry on the surface and later be broken apart only with great difficulty. Compaction, or the loss of pore spaces and a rise in bulk density, is an indication of the loss of crumb structure, and can be caused by the weight of farm machinery, by the loss of organic matter from excessive tillage, or by a combination of the two.

Color

Soil color plays its most important role in the identification of soil types, but at the same time it can tell us much about the history of a soil's development and management. Dark-colored soils are generally an indication of high organic matter content, especially in temperate regions. Red and yellow soils generally indicate high levels of iron oxides, formed under conditions of good aeration and drainage, but these colors can also be derived directly from the parent material. Gray or yellow-brown colors can be indicators of poor drainage; these colors form when iron is reduced to a ferrous form rather than oxidized to the ferric form in the presence of abundant oxygen. Whitish light-colored soils often indicate the presence of quartz, carbonates, or gypsum. Standardized color charts are used to determine a soil's color.

Hence, a soil's color can be an indicator of certain kinds of soil conditions that a farmer might want to look for or avoid, depending on the kinds of crops or cropping systems that might be used. More specific analysis of soil structure and chemistry is necessary to complete the picture, but color is a good beginning. In addition, soil color can influence the interaction of the soil with other factors of the environment. For example, it may be an advantage to have a lighter-colored, sandy soil on the surface in some tropical farming systems in order to reflect the sun's rays and keep the soil cooler; conversely, a darker soil surface in areas with cold winters will help the soil temperature rise earlier in the spring, dry the soil sooner, and permit soil preparation for planting at an earlier date.

Cation-Exchange Capacity (CEC)

Plants obtain the mineral nutrients described in Chapter 2 and Chapter 3 from the soil in the form of dissolved ions, whose solubility is determined by their electrostatic attraction to molecules of water. Some important mineral nutrients, such as potassium and calcium, are in the form of positively charged ions; others, such as nitrate and phosphate, are in the form of negatively charged ions. If these dissolved ions are not taken up immediately through plant roots or fungi, they risk being leached out of the soil solution.

Clay and humus particles, separately or in aggregates that form platelike structures known as micelles, have negatively charged surfaces that hold the smaller, more mobile positively charged ions in the soil. The number of sites on the micelles available for binding positively charged ions (cations) determines what is called soil CEC, which is measured in milliequivalents of cations per 100 g of dry soil. The higher the CEC the better the soil's ability to hold and exchange cations, prevent leaching of nutrients, and provide plants with adequate nutrition.

CEC varies from soil to soil, depending on the structure of the clay/humus complex, the type of micelle present, and the amount of organic matter incorporated into the soil. Multisided polyhedrons form lattices that vary in their sites of attraction and flexibility in relation to moisture content. Cations cling to the negatively charged outer surfaces of the micelles and humates with differing degrees of attraction. The most tenacious cations — such as hydrogen ions added by rain, positively charged acids from decomposing organic matter, and acids given off by root metabolism — can displace other important nutrient cations such as K^+ or Ca^{2+}. Organic matter in the form of humus is many times more effective than clay in increasing CEC since it has a much more extensive surface area-to-volume ratio (hence more adsorption sites) and because it is colloidal in nature. Farming practices that reduce soil organic matter content can also reduce this important component of soil fertility maintenance.

Negative ions that are important for plant growth and development, such as nitrate, phosphate, and sulfate, are more commonly adsorbed to clay micelles by means of

ion "bridges." Under acid conditions these bridges form by association of additional hydrogen ions with functional groups such as the hydroxyl group (OH). An important example is the binding of nitrate (NO_3^-) with OH_2^+ formed following the dissociation of water molecules under acid conditions. Because soil acidity influences electrical charge on micelle surfaces and controls whether other ions are displaced from soil micelles, it greatly affects the retention of ions in the soil and the short-term availability of nutrients, both of which are key components of soil fertility.

Soil Acidity and pH

Any experienced gardener or farmer is aware of the importance of a soil's pH, or acid–base balance. The typical pH range of soils is between very acid (a pH of 3) and strongly alkaline (a pH of 8). Any soil over a pH of 7 (neutral) is considered basic, and those less than pH 6.6 are considered acid. Few plants, especially agricultural crops, grow well outside the pH range of 5 to 8. Legumes are particularly sensitive to low pH due to the impacts acid soils have on the microbial symbiont in nitrogen fixation. Bacteria in general are negatively impacted by low pH. Soil acidity is well known for its effects on nutrient availability as well, but the effects are less due to direct toxicity on the plant than they are to the plant's impaired ability to absorb specific nutrients at either very low or very high pH. It becomes important, then, to find ways to maintain soil pH in the optimal range.

Many soils increase in acidity through natural processes. Soil acidification is a result of the loss of bases by leaching of water moving downward through the soil profile, the uptake of nutrient ions by plants and their removal through harvest or grazing, and the production of organic acids by plant roots and microorganisms. Soils that are poorly buffered against these input or removal processes will tend to increase in acidity.

Salinity and Alkalinity

It is common for the soils of arid and semiarid regions of the world to accumulate salts, in either a soluble or insoluble form. Salts released by the weathering of parent material, combined with those added in limited rainfall, are not removed by leaching. In areas of low rainfall and high evaporation rates, dissolved salts such as Na^+ and Cl^- are common, combined with others such as Ca^{2+}, Mg^{2+}, K^+, HCO_3^-, and NO_3^-. Irrigation can add even more salts to the soil, especially in areas with a high evaporation potential (Chapter 9), where added salts migrate to the surface of the soil by capillary movement during evaporation. In addition, many inorganic fertilizers, such as ammonium nitrate, can increase salinity as well because they are in the form of salts.

Soils with a high concentration of neutral salt (e.g., NaCl or Na_2SO_4) are called saline. In cases where sodium is combined with weak anions (such as HCO_3^-), alkaline soils develop, which have a pH generally greater than 8.5. Soils with high levels of neutral salts are a problem for plants due to osmotic imbalances. Alkaline soils are a problem because of excess OH^- ions and difficulty in nutrient uptake and plant development. In some regions, saline-alkaline conditions occur when both forms of salt are present. Proper irrigation and soil water management becomes a key part of dealing with these conditions.

SOIL NUTRIENTS

Since plants obtain their nutrients from the soil, the supply of nutrients in the soil becomes a major determinant of an agroecosystem's productivity. Many nutrient analysis methodologies have been developed for determining the levels of various nutrients in the soil. When a particular nutrient is not present in sufficient quantity, it is called a *limiting nutrient* and must be added. Fertilization technologies have grown and evolved to meet this need. It must be kept in mind, however, that the presence of a nutrient does not necessarily mean it is *available* to plants. A variety of factors — including pH, CEC, and soil texture — determine the actual availability of nutrients.

Because of the loss or export of nutrients out of the soil due to harvest, leaching, or volatilization, fertilizers must continually be added in large amounts to most agroecosystems. But the cost of fertilizers as an input is increasing, and leached fertilizer pollutes ground and surface water supplies; therefore, an understanding of how nutrients can be cycled more efficiently in agroecosystems becomes essential for long-term sustainability.

As described in Chapter 2, the major plant nutrients are carbon, nitrogen, oxygen, phosphorus, potassium, and sulfur. Each of these nutrients is part of a different biogeochemical cycle and relates to management of soil in a unique way. The management of carbon will be discussed below in terms of organic matter; nitrogen in the soil will be included in a discussion of mutualisms and the ecological role of nitrogen-fixing bacteria and legumes in Chapter 16. Here, as an example of an important soil nutrient, we will examine the nutrient phosphorus. Because the efficient recycling of phosphorus depends principally on what happens in the soil, it can teach us a lot about sustainable nutrient management (Figure 8.4).

Unlike carbon and nitrogen, whose principal reservoirs are in the atmosphere, the principal reservoir of phosphorus is in the soil. It occurs naturally in the environment as a form of phosphate. Phosphates can occur in the soil solution as inorganic phosphate ions (especially as PO_4^{3-}) or as part of dissolved organic compounds. But the primary source of phosphate is the weathering of

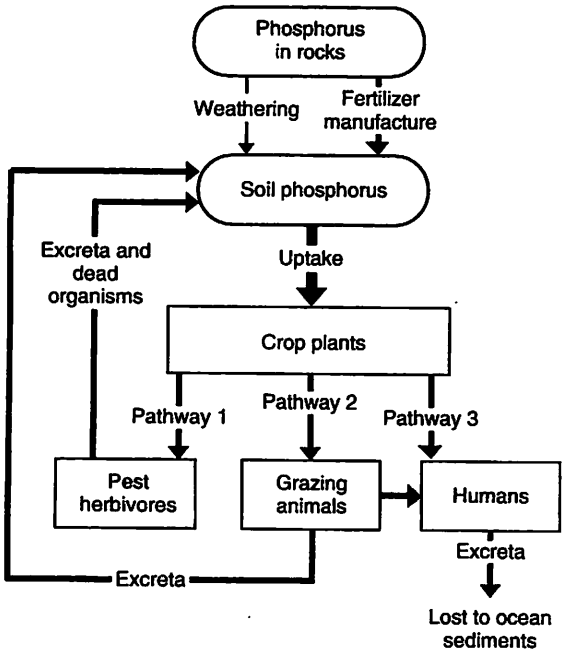

FIGURE 8.4 Pathways of phosphorus cycling in agroecosystems.

parent material; therefore, the input of phosphorus into the soil and the phosphorus cycle in agroecosystems is limited by the relatively slow rate of this geologic process.

Inorganic soluble phosphate ions are absorbed by plant roots and incorporated into plant biomass. The phosphorus in this biomass can be sent along one of three different pathways, depending on how the biomass is consumed. As shown in Figure 8.4, consumption of plant biomass by pest herbivores, by grazing animals, or by humans who harvest the biomass comprises the three pathways. Phosphorus in the first pathway is returned to the soil as excreta, where it decomposes and enters the soil solution. Phosphorus in the second pathway can be recycled in the same way, but if the grazing animal goes to market, some phosphorus goes with it. In the third pathway, there is little chance of the phosphorus returning to the soil from which it was extracted (except in much of China, where human excreta is used as fertilizer).

Much of the phosphorus consumed by humans in the form of plant biomass or the flesh of grazing animals is essentially lost from the system. An example of what may happen to phosphorus in the third (human consumption) pathway may serve to illustrate the problem: phosphate is mined from phosphate-rich marine deposits that have been geologically uplifted and exposed in Florida, processed into soluble fertilizer or crushed into rock powder, and shipped to farms in Iowa where it is applied to the soil for the production of soybeans. A part of the phosphorus, in the form of phosphates, is taken up by the plant and sequestered in the beans that are harvested and sent to California, where they are turned into tofu. Following consumption of the tofu, most of the liberated phosphate finds its way into local sewer systems, and eventually ends up returning to the sea 3000 mi from where it originated. Since the time necessary to build up sufficient sediments of phosphate-rich rock and to go through the geological process of uplifting is very much beyond the realm of the human time frame, and since the known easily-available phosphate reserves are quite limited, current practices of phosphate fertilizer management in many modern agroecosystems can be said to be unsustainable.

For sustainable management of phosphorus to occur, phosphate needs to pass quickly through the soil component of the cycle and back to plants for it not to be fixed in sediments or washed to sea. Ways must be found to better keep phosphorus in an organic form, either in standing biomass or in soil organic matter, and to ensure that as soon as phosphorus is liberated from this organic form, it is quickly reabsorbed by soil microorganisms or plant roots.

An additional component of sustainable management of soil phosphorus has to do with the formation of insoluble phosphorus compounds in the soil. Phosphates in the soil solution often react chemically (especially with iron and aluminum) to form insoluble compounds, or become trapped in clay micelles out of reach of most biological recovery. Low pH in the soil exacerbates the problem of phosphate fixation in an insoluble form. At the same time, however, these processes provide a strong mechanism for retaining phosphorus in the soils of the agroecosystem; phosphate fertilizers added to the soil are retained almost completely. Some agricultural soils in California show very high levels of total (through not easily available) phosphorus after several decades of farming. So leakage of phosphorus from agroecosystems can be quite small, but the unavailability of phosphorus from the soil component of the system once it is fixed requires further addition of available phosphorus in the form of fertilizer. Of course, biological means of liberating this "stored" phosphorus might contribute better to sustainability. These means have a lot to do with the management of soil organic matter.

SOIL ORGANIC MATTER

In natural ecosystems, the organic matter content of the A horizon can range up to 15 or 20% or more, but in most soils it averages 1 to 5%. In the absence of human intervention, organic matter content of the soil depends mostly on climate and vegetative cover; generally, more organic matter is found under the conditions of cool and moist climates. We also know that there is a very close correlation between the amount of organic matter in the soil and both carbon and nitrogen content. A close estimate of soil organic matter content can be obtained by either multiplying total carbon content by 2 or total nitrogen content by 20.

Soil organic matter is comprised of diverse, heterogeneous components. Its living material includes roots, microorganisms, and soil fauna; its nonliving material includes surface litter, dead roots, microbial metabolites,

and humic substances (humus). The nonliving component is by far the greater proportion.

Interaction between the living and nonliving organic matter is constant. The complex carbon compounds in fresh plant litter are rapidly metabolized or decomposed, undergoing a process known as humification that eventually imparts a darker color to the soil as it produces humic residues, or humus. Humic residues consist of condensed aromatic polymers that are normally relatively resistant to further breakdown, and normally are capable of becoming stabilized in soil. The organic matter fraction that becomes stabilized, though, eventually undergoes mineralization, releasing mineral nutrients that can be taken up by plant roots. An equilibrium is reached between humification and mineralization, but this equilibrium is subject to shifts depending on farming practices.

During its life in the soil, organic matter plays many very important roles, all of which are of importance to sustainable agriculture (Magdoff and Weil, 2004). Apart from providing the more obvious source of nutrients for plant growth, organic matter builds, promotes, protects, and maintains the soil ecosystem. As we have already discussed, soil organic matter is a key component of good soil structure, increases water and nutrient retention, is the food source for soil microorganisms, and provides important mechanical protection of the soil surface. Depending on the cropping practices used, however, these traits can be rapidly altered — for the better as well as for the worse. Of all of the characteristics of soil, the factor that we can manipulate the most is soil organic matter.

Once a soil is put under cultivation, the original organic matter levels begin to decline unless specific steps are taken to maintain them. After an initial rapid decline, the drop slows. Several kinds of changes occur in the soil as a consequence of the loss of organic matter. Crumb structure is lost, bulk density begins to rise, soil porosity suffers, and biological activity declines. Soil compaction and the development of a hardened soil layer at the average depth of cultivation, called a plow pan, can become problems as well.

The extent to which organic content declines in soil under cultivation is dependent on the crop and cropping practices. Some examples follow.

In one study, the organic matter content of the upper 25 cm of soil in two agroecosystems used for intensive vegetable production in coastal central California were compared with each other and to an unfarmed grassland control. One system had been farmed for 25 years using organic farming practices; the other for 40 years under conventional practices. The study showed that the organic matter content had been reduced from 9.869 to 8.705 kg/m^3 in the organic system and to 9.088 kg/m^3 in the conventional system (Waldon, 1994). Even with the higher inputs of organic matter in the form of composts and winter cover crops in the organic system, cultivation and cropping significantly reduced soil organic matter even more than in the conventional system.

In another case, after 15 years of continual production of grains such as corn and rice, organic matter in the initial 15 cm of a heavy alluvial clay in the humid lowlands of tropical Tabasco, Mexico, had lowered to less than 2%, as compared to an organic matter content of more than 4% in an adjacent area of uncut tropical forest (Gliessman and Amador, 1980). A tree-covered cacao plantation on the same soil type was able to maintain the soil organic matter in the same layer at 3.5%, demonstrating the negative impact of soil disturbance on organic matter in cropping systems and the role of vegetative cover in retaining it.

A study comparing soils after 75 years of organic and conventional wheat production in eastern Washington found that organic matter was not only maintained in the organic system, but also actually increased over time, while production levels for the organic farmer were near equal to the conventional (Reganold et al., 1987). We can see from these three examples that crop type, input management, local environment, and cultivation practices all help determine the long-term impacts of farming on soil organic matter.

SOIL MANAGEMENT

In present-day farming systems, soil is treated as if it were mainly a medium for holding the plant up. When soil is managed for sustainable production and emphasis is placed on the role of soil organic matter, however, the role of soil is greatly expanded.

Many farmers feel that if a high yield is obtained from the land, then this is evidence of a productive soil. However, if the perspective is agroecological and the goal is to maintain and promote all of the soil-forming and soil-protecting processes involving organic matter, then a productive soil is not necessarily a fertile soil. The processes in the soil that enable us to produce a crop take on greater importance in sustainable agriculture. Fertilizers can be added to raise production, but only through an understanding of nutrient cycles and soil ecological processes — especially soil organic matter dynamics — can soil fertility be maintained or restored.

Management of Soil Organic Matter

The first step in developing soil organic matter is to maintain constant inputs of new organic matter to replace that, which is lost through harvest and decomposition. If the agroecosystem were more similar to a natural ecosystem, a diversity of plant species would be present in addition to the crop or crops being grown for harvest. Many agroforestry systems (Chapter 17), especially in tropical agriculture, have a large number of plants, many of them

noncrop species, whose primary role is biomass production and the return of organic matter to the soil. But present-day agriculture, with its focus on the market, has reduced plant diversity so greatly that very little organic matter is returned to the soil.

Crop Residue

An important source of organic matter is crop residue. Many farmers are experimenting with better ways of returning to the soil the parts of the crop that are not destined for human or animal use. A major concern has been how to deal with potential pest or disease organisms that residue may harbor and pass on to a subsequent crop. Proper timing of incorporation of the residue into the soil, rotating crops, and composting the residue away from the field and then returning the finished compost are possible ways of overcoming this problem. Research on these and other management strategies are helping transform crop residue from a problematic by-product into a valuable part of soil organic matter management (Franzluebbers, 2004) (Figure 8.5).

Cover Crops

Cover cropping, where a plant cover is grown specifically to produce plant matter for incorporation, as a "green manure" into the soil, is another important source of organic matter. Cover crop plants are usually grown in rotation with a crop or during a time of the year that the crop can't be grown. When legumes are used as cover crops, either alone or in combination with nonlegume species, the quality of the biomass can be greatly improved. The resultant biomass can be incorporated into the soil, or left on the surface as a protective mulch until it decomposes.

In research done at UC Santa Cruz (Gliessman, 1987), a local variety of fava bean called bellbean (*Vicia faba*) was grown as a cover crop in combination with either cerealrye or barley during the winter wet season fallow period. It was shown that the total dry matter produced in the grass/legume mixtures was almost double that of the legume alone. After 3 years of cover crop use, organic matter levels in soils under mixed covers improved as much as 8.8%. Interestingly, soils under the legume-only cover actually dropped slightly in organic matter content

FIGURE 8.5 Burning of crop residue in Taiwan. Burning is a common method of removing crop residue. Although it returns some nutrients to the soil and helps control pests and diseases, burning can cause significant air pollution and prevents crop residue from being incorporated into the soil as organic matter. When crop residue is seen as a valuable and useful resource for maintaining soil organic matter, techniques for incorporating it into the soil can be developed as alternatives to burning.

after three years, probably because the lower C/N ratio of the incorporated organic matter caused more rapid microbial breakdown.

A more recent innovation in the cover-cropping approach is the use of a living mulch, where a noncrop species is planted between the rows of the crop during the cropping cycle. Living mulches have become especially popular in vineyard, orchard, and tree crop systems. Research has focused on ways of minimizing negative interactions between cover crop and crop species, especially living mulches in annual crops. Studies are also finding that living mulches can provide and conserve nitrogen for grain crops, reduce soil erosion, reduce weed pressure, and increase soil organic matter content (Hartwig and Ammon, 2002).

Manure

It is a long-standing practice, both in conventional and in alternative farming systems, to add animal manures to the soil to improve organic matter content. The application of animal manure is an important tool for an integrated nutrient management strategy because applications can simultaneously increase soil organic matter and supply nutrients for crop growth (Seiter and Horwath, 2004). Dairies and feedlot operations produce large amounts of animal wastes that are converted to a useful resource when returned to fields, but as we have already noted in Chapter 1, there are many problems involved in containing, storing, transporting, and applying such large quantities of animal manures. Small, integrated farm operations can more easily use animal manures that accumulate in stables or pens for intensive vegetable production or use on other crops (Chapter 19). The use of silkworm droppings in Chinese agriculture is yet another example of the use of animal manures.

At any scale, the direct application of animal manures can have many drawbacks, however. Smell and flies are often associated with direct manure application. Nitrogen loss through ammonification can be quite high. Runoff of nitrates and other soluble materials can be a problem. And once fresh manures are incorporated into the soil, there often is a waiting period for decomposition and stabilization before planting can take place. To avoid these problems, current organic certification standards in the U.S. require that fresh or raw animal manures be composted under specific conditions before they are applied (Figure 8.6).

FIGURE 8.6 Manure spreader used on a dairy farm near Cody, Wyoming. Aged manure is returned to fields in which feed is grown for the farm's dairy cows.

Composts

Compost amendment of soil is an attractive way to add organic matter for a variety of reasons. The particle-size distribution of compost favors uniform field application; the ratio of carbon to nitrogen is optimal; compost is usually free of weed seeds; and soil diseases are often suppressed by compost addition (Chen et al., 2004). Many different sources of organic materials, from manures to agricultural by-products to lawn clippings, are being converted into useful soil amendments through the composting process (Figure 8.7). Under controlled conditions, raw organic matter goes through the first stages of decomposition and humification, so that when it is added to the soil, it has stabilized considerably and can contribute more effectively to the soil fertility-building process. In this way, wastes — including materials that would otherwise go to already bulging landfills — are being converted into resources (Table 8.3).

Vermicompost, or compost produced through the action of worms, is also becoming a popular source of soil organic matter, especially for smaller-scale farm and garden systems. Fresh, wet organic matter, especially food waste, is consumed by worms specifically known for their composting ability (redworms such as *Eisenia foetida* are especially good), and systems have been developed, where a small household vermicomposting chamber can produce up to 25 kg of worm castings a month. These castings are known for their high levels of phosphate, nitrogen, and other nutrients, and also contain polysaccharides that glue soil particles together and aid in soil organic matter development. Cuban researchers have recently developed farm-scale vermicomposting systems that are designed to replace difficult-to-obtain imported fertilizers. Further development of larger-scale systems could aid greatly in improved soil management.

Table 8.3
Organic Waste Materials Employed in the Production of Compost

Agricultural By-Products	Manures
Alfalfa leaf meal	Feedlot beef cattle manure
Apple and grape pomace	Dairy cattle manure
Blood meal	Broiler chicken litter
Bone meal	Laying chicken litter
Cottonseed meal	Turkey litter
Feather meal	Swine manure
Almond and walnut hulls	Horse manure
Coffee pulp	Sheep manure
Cocao pulp	Goat manure
Soybean cakes	
Rice hulls	
Green garden and yard wastes	

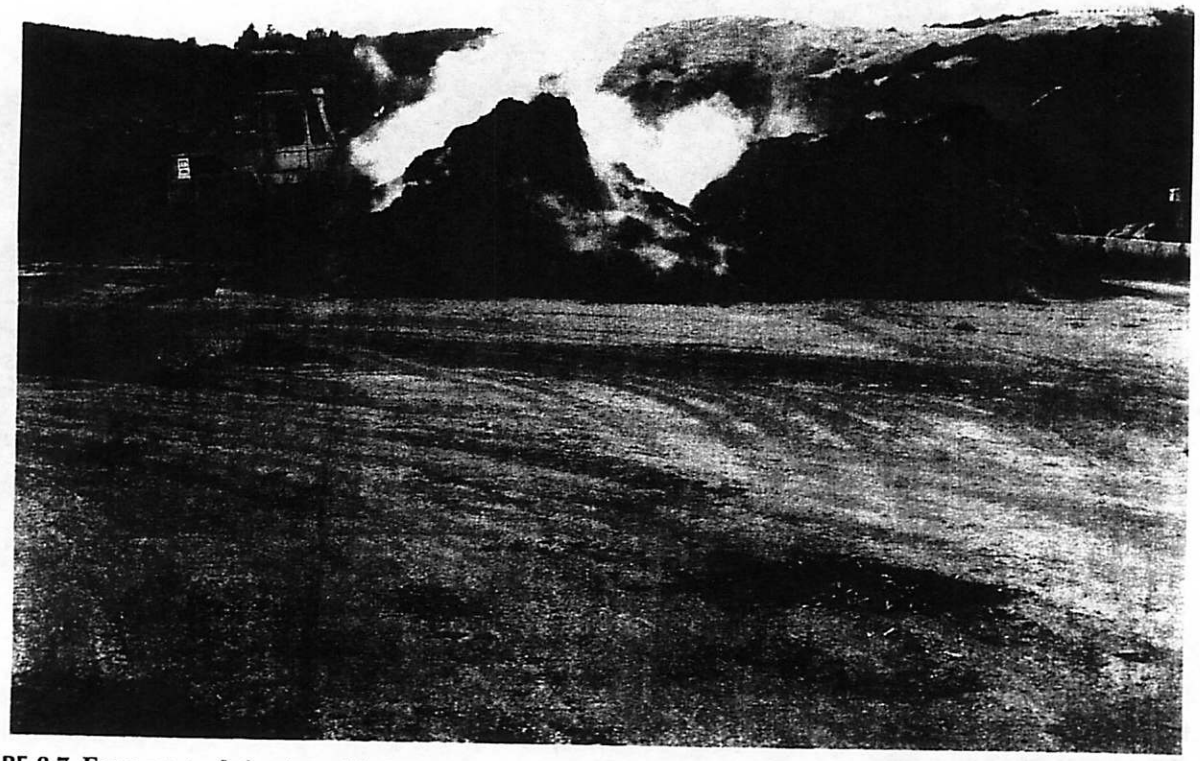

FIGURE 8.7 Farm wastes being turned into compost on a farm on the central coast of California. The breakdown of vegetative matter by microorganisms releases significant amounts of energy in the form of heat.

Other Soil Amendments

A range of other types of organic soil amendments can be used as well. Humates, kelp, fishmeal, animal by-products, mined guano, and others are on the market. Each one has specific applications, advantages and disadvantages, and optimal scales of use. Each organic matter source needs to be examined for short-term crop response, but more importantly for possible long-term contributions to soil organic matter development and maintenance.

Sewage

A final source of organic matter — underutilized except in a few parts of the world — is sewage. To complete nutrient cycles, nutrients that leave the farm should ultimately come back to the farm. If they can come back in an organic form, then they will also add to the soil-building process.

Solid material removed from wastewater during treatment, known as sewage sludge, has been spread on the land for decades. As a percentage of dry weight, sewage sludge can contain 6 to 9% nitrogen, 3 to 7% phosphorus, and up to 1% potassium. It can be applied as dried cake or granules, with water content of 40 to 70%, or as a liquid slurry that is 80–90% water. Sewage sludge is widely used on turf grass, degraded rangeland, and even on the ground below fruit trees. The liquid portion of treated sewage, known as effluent, has been applied to land for a long time in Europe and selected sites in the U.S. Some cities operate, what are called, sewage farms where effluent is used to produce crops, usually animal feeds and forages, that partially offset the cost of disposal, where in other cases, it is used for irrigating golf courses, highway landscaping, and even forests.

There is much to learn, however, about how to treat sewage so that pathogens are dealt with properly. Collection, treatment, and transport all need to be examined with an eye toward the goal of linking waste management with sustainable agriculture. The fact that many sewage systems around the world do not separate human from industrial wastes, contaminating the resultant sludge with toxic amounts of heavy metals, complicates the process immensely.

Nevertheless, sewage will undoubtedly become a more important resource in the future as a source of organic matter, nutrients, and water for crop production. Many small-scale and traditional practices for turning sewage into a useful resource can serve as an important basis for future research on this important link to sustainability.

Tillage Systems

The conventional wisdom in agriculture is that soil must be cultivated to control weeds, incorporate organic matter, and allow root growth. Despite its potential benefits, however, cultivation can degrade soil structure and organic matter content, and cause the soil to lose some of the elements of productivity. For this reason, paying attention to how the soil is cultivated must be an integral part of soil organic matter management.

Many different patterns of soil tillage exist, but the main pattern employed in conventional agriculture is a three-stage process involving a deep plowing that turns the soil, a secondary tilling for preparation of a seed bed, and finally postplanting cultivations (often combined with herbicide use) for controlling weeds. Soil erosion, loss of good soil structure, and nutrient leaching are well-known problems associated with this pattern of tillage. Despite these problems, most conventional farming systems, especially those producing annual grains and vegetables, are dependent on extensive and repeated tillage.

At the other extreme, there are many traditional farming systems in which no tillage is used at all. In swidden agriculture, traditional farmers clear land using slash and burn techniques and then poke the soil with a planting stick to sow seeds. Such systems, which have the longest history of sustained management, respect the need for a fallow period to control weedy vegetation and to allow natural soil building processes to replace removed nutrients. Many agroforestry systems, such as coffee or cacao under shade, depend on the tree component of the system to provide soil cover and nutrient cycling, and only receive occasional surface weeding. Permanent pasture is rarely cultivated either.

Alternative tillage techniques, many of them borrowed from traditional farming practices, have been developed for and tested in conventional annual crop systems. These have demonstrated that annual crop systems do not have to remain dependent on extensive and repeated tillage and that reduced tillage can help improve soil quality and fertility (Franzluebbers, 2004).

Using the technique of *zero tillage*, soil cultivation is limited to the actual seedbed and is done at the time of seed planting. In some cases, special equipment is used that allows planting directly into the crop residue left from the previous crop. Other steps, such as fertilization and weed control, can be completed at the same time as planting. Unfortunately, many zero tillage systems have developed a great dependence on herbicides, which may create other ecological problems.

In order to reduce herbicide use, a number of *reduced tillage* systems have been developed. One in particular that has been quite successful for corn and soybean production is *ridge tillage*. After an initial plowing and formation of planting beds or ridges, the only cultivation that occurs is seed planting and weed management with specially designed tillers that cultivate the surface of the soil only. Some ridge till systems can go through many years of repeated planting without deep tillage, and the reduced soil disturbance helps preserve soil organic matter and structure. The Thompson Farm in Boone County, Iowa,

REDUCED TILLAGE ON THE THOMPSON FARM

Farmers who want to reduce the frequency and intensity of cultivation and soil disturbance face a major quandary: how to cultivate less without simultaneously increasing herbicide use? Decades ago, Dick Thompson, a farmer in Boone, Iowa, realized this was a false choice — it should be possible to reduce both tillage and herbicide use and yet still control weeds effectively. Dick reasoned that while cultivation killed weeds, it also created the ideal disturbed environment for their regrowth. The solution must involve cultivating less, and doing so in a way that aided crops but deterred weeds.

Through extensive experimentation and tinkering, Dick has developed a modified ridge tillage system that, combined with other farming practices, produces the desired result: the Thompson Farm uses virtually no herbicides, the soil is tilled much less frequently and intensively than conventional wisdom would dictate, and weeds are not a problem. In addition, the Thompsons generate about $147 more profit per acre than their conventional neighbors, and their soil contains about twice as much organic matter.

The ridge tillage works like this: in the spring, special planters shave a little soil — and the weeds and cover crop growing in it — off the top of each ridge, burying plant residue, weed seeds, and previously applied compost in the inter-row zone. There, the allelopathic effect of the residue suppresses weed germination. Later, a rotary hoe lifts soil up around the crops planted in the weed-free area in the middle of the ridges. Weeds are controlled by this process until the crop is developed enough to suppress weeds itself.

The Thompson's modified ridge tillage system is the centerpiece of their farming operation — or at least the part that differs most from conventional practice — but it is only one part of a broader management system with many components.

- *Rotations.* Whereas many conventional farms in Iowa grow corn continuously, the Thompsons always rotate their crops. One rotation they've used with success is the five-year sequence of corn–soybeans–corn–oats–hay. Rotating crops avoids problems with soil pests and helps maintain soil fertility. The rotation has a direct connection with the ridge-till system as well: after the four years of row crops planted on minimally tilled ridgetops, the ridges are flattened for the final crop of hay, which is a mixture of grasses and legumes. This crop is cut multiple times to help control weeds. During this ridgeless period, the field is cultivated conventionally, with incorporation of manure deep into the soil where its fertility is most needed by crops. Then the ridges are re-formed for the corn that begins the cycle again.
- *Cover crops.* During winter, the soil in the fields is always covered by a cover crop. At first, the Thompsons used winter rye and hairy vetch, but after much experimentation, they found that grains worked best as cover crops. They now plant oats ahead of corn, and rye ahead of soybeans. At the point in the rotation when hay will be followed by corn, however, they plant a cover crop of rye. In addition to reducing erosion and nitrate leaching, these cover crops suppress weed growth allelopathically. The weeds that do grow with the cover crop are treated as part of the cover vegetation — they help provide cover, suppress later-germinating weeds, and contribute organic matter to the soil after cultivation.
- *Livestock integration.* The Thompsons raise both beef cattle and hogs, and all their manure — composted aerobically in special containers — goes into the fields as organic fertilizer. To complete the nutrient cycling, the livestock are fed hay and crop residue from the crop fields.

Combined, these principles result in both profitability and sustainability, making the Thompson Farm an excellent model. Every year, hundreds of visitors — ranging from college professors to organic farmers — tour the farm to learn alternative practices for soil management, erosion control, weed management, and reduced tillage.

featured in the Case Study, is a well-known example of a successful diversified farm operation that has as its centerpiece the use of a modified ridge tillage program (Practical Farmers of Iowa, 2002).

The challenge for research on reduced tillage systems is how to find ways to reduce tillage without increasing input costs elsewhere in the system, especially those involving the use of chemicals or fossil fuels.

Sustainable Soil Management

When soil is understood to be a living, dynamic system — an ecosystem — management for sustainability becomes

an integrated, whole-system process. Focusing on the processes that promote the maintenance of a healthy, dynamic, and productive system becomes paramount. Fertility management is based on our understanding of nutrient cycles, organic matter development, and the balance between the living and nonliving components of the soil. The application of our understanding of the ecological processes that maintain the structure and function of the soil ecosystem over time takes on the greatest importance. And since the soil ecosystem is a complex, dynamic, and ever-changing set of components and processes, our understanding of this complexity must increase.

Good soil management is an important part of attaining overall sustainability of agroecosystems. Many of the indicators of sustainability discussed in Chapter 21 relate directly to soil.

FOOD FOR THOUGHT

1. Organic matter is considered to be one of the most important components of a healthy soil ecosystem, but most agricultural activities (i.e., plowing, burning, cultivation, harvest) remove, reduce, or degrade organic matter. What are some of the most practical ways of maintaining this valuable resource in the soil?
2. What are the key factors that determine how long a degraded soil will take to be restored to a condition similar to its previous healthy condition?
3. What is the difference between dirt and soil?
4. It has recently been proposed that we develop some indicators of "soil health" in order to determine the sustainability of different farming practices. What indicators do you think should be used to evaluate the health of the soil?
5. Why is it important for farmers to learn how to use the concept of the soil ecosystem?

INTERNET RESOURCES

www.pedosphere.com
An on-line soil science magazine.

Natural Resources Conservation Service: Soil Quality
soils.usda.gov/sqi
The Soil Quality portion of the NRCS Soils website, with information about soil management practices, soil biology, and soil quality assessment.

National Sustainable Agriculture Information Service: Sustainable Soil Management
www.attra.org/attra-pub/soilmgmt.html#Resources
Contains a wealth of information about the biology and chemistry of soil and the relationships between soil management and sustainability.

Rodale Research Foundation
www.newfarm.org
A wealth of examples of alternative farm management practices, especially of soils.

US Department of Agriculture, Natural Resources Conservation Service
soils.usda.gov
The NRCS soils website, providing extensive science-based soil information, including soil surveys from across the nation.

RECOMMENDED READING

Brady, N.C. and R.R. Weil. 2001. *The Nature and Properties of Soils.* 13th ed. Prentice Hall: Upper Saddle River, New Jersey. One of the most complete reference books on soil as a natural resource; highlights the many interactions between soil and other components of the ecosystem. The recognized primer of soil science.

Frissel, M.J. (ed.) 1978. *Cycling of Mineral Nutrients in Agricultural Ecosystems.* Elsevier: Amsterdam. A pioneering work on the need for an ecological approach to the study of nutrient use in agriculture.

Jenny, H. 1994. *Factors of Soil Formation.* Reprint edition of the 1941 original. Dover Publications: Toronto, Canada. The classic textbook on soil and the soil formation process; emphasizes the soil as a complex system that changes through time.

Juo, A.S.R. and K. Franzluebbers. 2003. *Tropical Soils: Properties and Management for Sustainable Agriculture.* Oxford University Press USA: Cary, NC. A text that uses an agroecological approach to describe the tropical soil environments of sub-Saharan Africa, Southeast Asia, and South and Central America, focusing on production and management systems unique to each region.

Magdoff, F. and H. van Es. 2000. *Building Soils for Better Crops.* 2nd ed. Sustainable Agriculture Network Handbook Series. Sustainable Agriculture Publications: Burlington, Vermont. Very farmer-friendly and practical information that explains how ecological soil management boosts soil fertility and yields, while reducing pest pressures and environmental impacts.

Magdoff, F. and R.R. Weil. 2004. *Soil Organic Matter in Sustainable Agriculture.* Advances in Agroecology Series. CRC Press: Boca Raton, Florida. This book provides the essential scientific background to understand soil organic matter and develop improved soil and crop management systems.

Paddock, J., N. Paddock, and C. Bly. 1986. *Soil and Survival: Land Stewardship and the Future of American Agriculture.* Sierra Club Books: San Francisco. An important work on the need for linking sound soil management with sustainability in American agriculture.