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Soil System Management in Temperate Regions

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The view of soils as principally support media for plants, rather than as complex systems driven by life processes, dominates most thinking about temperate zone agriculture. To a large extent, the success of the last century's Green Revolution was based on new technologies that provided, via inputs external to the system, certain ecological services traditionally supplied by soil — nutrient supply and pest suppression in particular. The result has been an agricultural enterprise that too often values soil largely as a porous medium which supports plants and drains excess rainfall. Not well appreciated are the crucial roles of soil for creating fertility and for buffering the environmental impacts of agricultural production. Nor is enough credit given to the roles that soil systems play as fundamental, interactive components within larger agricultural ecosystems. As a result, the actual and potential contributions of soils to the productivity of intensively managed systems, particularly in temperate regions which rely heavily on exogenous inputs, are undervalued.

Figure 3.1 illustrates how soils are dynamic, living systems that are integral parts of larger ecosystems. Soil subsystems participate fully in the processes that are common to ecosystems as a whole — energy flow; the movement and transformations of water, carbon, and nutrients; and the trophic dynamics that regulate biodiversity and other community characteristics. From a functional standpoint, soil can be regarded essentially in terms of habitat, providing a home to a wide variety of organisms that together provide services critically important to crop productivity and environmental quality: pest protection, pathogen control, nutrient and water availability, water filtration, carbon storage, erosion control, and plant support, among others.

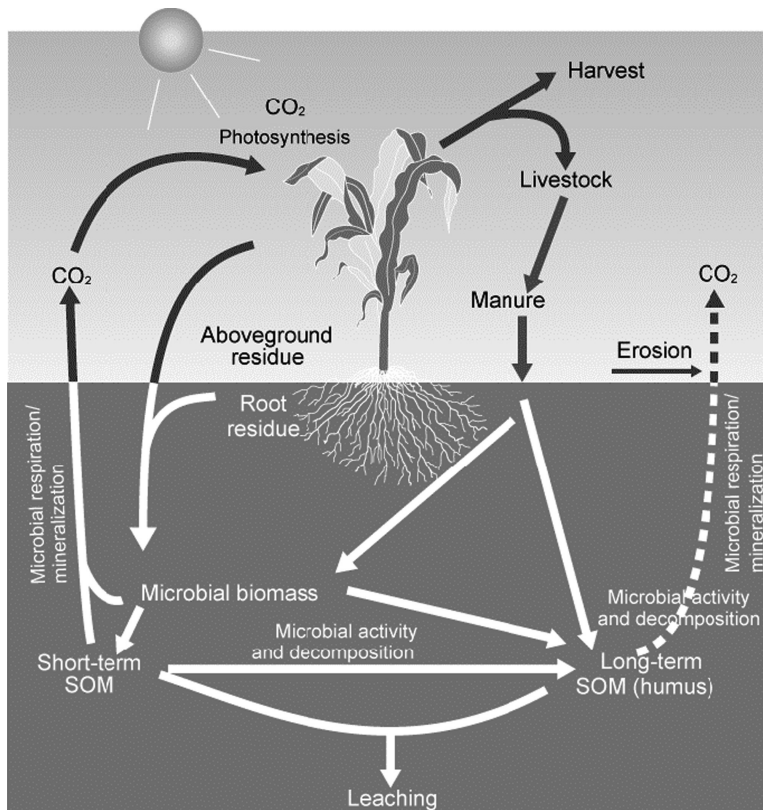


FIGURE 3.1

A maize ecosystem diagram illustrating aspects of the carbon cycle, one of many system-level processes that occur in ecosystems. (From Cavigelli, M.A., Deming, S.R., Probyn, L.K., and Harwood, R.R., Eds., in *Michigan Field Crop Ecology: Managing Biological Processes for Productivity and Environmental Quality*, Michigan State University Extension Bulletin E-2646, East Lansing, MI, 1998. With permission.)

Are these services in greater demand in temperate than in other soil systems? No. Nor are they more expendable. Rather, 20th-century chemical and mechanical technologies have allowed many of these services to be diminished if not supplanted entirely in management systems dominated by external inputs of energy, nutrients, and pesticides. Although this dominance of input-intensive methods is more common today in temperate regions, it can be found in tropical areas as well (Robertson and Harwood, 2001). In fact, as mechanized, intensive agriculture has moved into the tropics, for example, large-scale soybean production in Brazil, there are the same kinds of problems, though rates of change may differ. The challenge in both temperate and tropical regions is similar: how to maintain, enhance, and restore the contributions of soil biology to the fertility and sustainability of agricultural ecosystems.

3.1 Temperate Region Soil Differences

All generalizations about soil systems have significant exceptions, but two generalizations that differentiate temperate from tropical soils are quite tenable. First, because temperate soils are seasonally cold, during a significant portion of the year, plant growth and soil

biological activity are low or nil due to suboptimal or freezing soil temperatures. Seasonality with its temperature fluctuations results in important changes in the chemical and physical soil environment. Freeze–thaw cycles accelerate rock weathering and the breakdown of soil aggregates, for example, and chemical as well as biological reactions that affect mineral weathering, chemical solubility, and other soil chemical properties occur more slowly in winter months. As discussed below, this seasonality provides both challenges and opportunities for effectively managing soil fertility.

A second generalization concerns soil mineralogy and its impact on soil chemistry. Agricultural soils in temperate regions are more likely to be geologically young in comparison to large regions of the tropics. Some tropical soils are also young, especially those developed from geologically recent volcanic and alluvial deposits, but most are not, and this has important implications for soil fertility. In young soils, such as those recently glaciated or formed from windblown loess, primary minerals have weathered little, and the electrical charge system (which confers ion exchange capacity) is largely permanent, with base cations such as Ca^{+2} , K^+ , and Mg^{+2} common. In older soils, weathering will have removed most of the 2:1 layer-silicate clays, and electrical charges result mainly from the protonation and deprotonation of surface hydroxyl groups (Uehara and Gillman, 1981).

The ion exchange capacity of older tropical soils therefore depends very much on soil pH. When pH is low, cation exchange will be negligible, and many ions important for plant growth will be in low supply and easily washed from the soil by percolating rainfall. In contrast, the charge system of younger soils is more durable because it mostly results from the crystal lattice structure of 2:1 layer-silicate clays and is thus more impervious to changes in soil pH and soil solution composition. Although all soils contain both permanent and variable charge surfaces, most are dominated by one or the other charge system, and this has a significant impact on nutrient mobility and availability (Sollins et al., 1998). In general, the permanent charge system that dominates most temperate region soils provides these soils with greater chemical and structural resistance to the deleterious effects of chronic disturbance that is typical of mechanized agriculture.

One sometimes reads of other temperate vs. tropical soil differences such as regional differences in soil organic matter (SOM) or soil biodiversity. These are not differences that are regionally inherent. Many tropical soils can have native SOM stores equal to those in temperate regions, so such generalizations do not hold up (Sanchez et al., 1982; Greenland et al., 1992). Likewise, it is difficult to generalize about soil biodiversity because we know so little about it. We know, for example, that 1 g of soil can contain $>10^9$ microbes representing >4000 different, mostly unidentified species (Torsvik et al., 1990), while a liter of soil can contain hundreds of different species of soil fauna (Coleman and Crossley, 2003). On average, about 20% of the organic matter in arable soils is living biomass (Paul and Clark, 1996), yet very little of this can at present be identified by species. In neither temperate nor tropical soils do we know $>1\%$ of the soil biota (Tiedje et al., 1999), so generalizations are hard to substantiate. Moreover, the relationship of this biodiversity to ecosystem functioning is in any case not yet documented. So, scientists and practitioners are both operating with little certain knowledge about the specific organisms present in soil.

3.2 Challenges to Soil Fertility and Management

The inherent fertility of many temperate-region soils is high. In comparison to highly weathered tropical soils, many soils in temperate regions can withstand years of crop

production following their conversion from natural vegetation. Eventually, however, soil nutrient stocks decline and soil structure degrades, and most temperate-region cropping systems now owe much of their present productivity to external subsidies, which enhance or compensate for lost ecological services. To bring soil to its full fertility and to sustain this depends on the satisfactory resolution of two major challenges: the restoration and maintenance of SOM, including its all-important living fraction; and the development of nutrient-efficient, and especially nitrogen-efficient, cropping systems. Other challenges are also important — erosion control; water conservation; nutrient losses to groundwater, surface waters and the atmosphere; and pathogen suppression, among others — but in most landscapes they remain secondary. This chapter focuses on these two major challenges, considering secondary challenges within the context of these two chief concerns.

3.2.1 Soil Organic Matter Restoration and Conservation

The loss of SOM, sometimes referred to simply as soil carbon loss, is common to almost all field-crop production systems. The principal cause of SOM loss is accelerated microbial activity as agronomic activities in general, and cultivation in particular, stimulates microbial respiration of soil organic carbon, the foundation of organic matter. This rapid turnover of SOM is the foundation of soil fertility in low-input cropping systems, since as microbes consume carbon they release nitrogen and other nutrients to the soil solution where nutrients become available to plants. Typically 40–60% of a soil's organic carbon stores are lost in the 40–60 years following the initial cultivation of a temperate region soil (Figure 3.2). This occurs even more quickly with cultivation in the tropics. Restoring lost SOM and tempering its turnover is thus a major goal of biologically-based agriculture (Robertson and Harwood, 2001).

The reasons for accelerated microbial activity are complex and related to a number of factors. Chief among them is the breakdown of soil aggregates, small particles of soil (0.05–8 mm) that protect carbon molecules from rapid microbial consumption. Carbon particles inside aggregates exist in an environment very different from the bulk soil environment: certain soil organisms may not be present, and the activity of those that are present is likely be restricted by low oxygen availability. Oxygen diffuses very slowly into

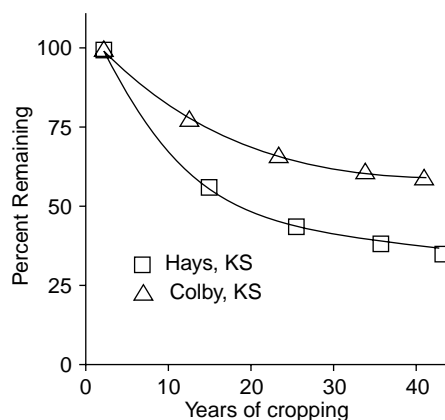


FIGURE 3.2

Soil carbon loss following cultivation at two temperate region sites, Hays and Colby counties, Kansas, U.S.A. (From Haas, H.J., Evans, C.E., and Miles, E.F., in *Nitrogen and Carbon Changes in Great Plains Soils as Influenced by Cropping and Soil Treatments*, USDA Technical Bulletin 1164, Washington, DC, 1957. With permission.)

aggregates, with the result that the oxygen consumed by microorganisms is not quickly replaced, and the interiors of aggregates thus tend to be anaerobic to a much greater degree than bulk soil.

Cultivation breaks apart aggregates, especially the larger ones, exposing trapped organic carbon to aerobic microbes that easily respire it to CO₂. Much of the increase in atmospheric CO₂ starting early in the 19th century was the result of pioneer cultivation (Wilson, 1978). This stimulated microbial activity and the turnover of active organic matter pools formerly in aggregates. The basis for soil carbon sequestration as a CO₂ mitigation strategy is recovery of this lost soil carbon (Lal et al., 2004). While this recovery will contribute to greenhouse gas abatement, it will also improve soil productivity and increase microbial biomass and nutrient availability.

Aggregation remains low following cultivation because the microbial processes that stabilize soils are disrupted at the same time that aggregates are more exposed to physically destabilizing processes. Microbial production of polysaccharides, humic substances, and aliphatic compounds that promote particle binding and aggregate stabilization invariably decrease following the start of cultivation. Additionally, extensive networks of fungal hyphae that enmesh soil particles and provide a framework for aggregate stabilization are shattered by tillage. These hyphae are also sensitive to changes in residue placement following agricultural conversion (Jansa et al., 2003).

Increases in the physical forces that destabilize aggregates following cultivation are mostly related to changes in soil water dynamics. Cultivated soils are bare much of the year. During these periods, raindrop impacts result in greater disruption of aggregates at the soil surface, and without transpiration these soils will be wetter for more of the year. Generally, with increasing water content, aggregate structure decreases and dispersed clay increases (Perfect et al., 1990). Bare soils are also more exposed to freezing, which has particularly damaging effects on soil structure since as soil water freezes and expands, it moves into pores and fracture planes between particles, driving them apart. Structural breakdown of cultivated soils leads quickly to wind and water erosion, to substantial and permanent losses of soil carbon, and ultimately to reduced productivity.

Usually not all carbon is lost from soil even after decades or centuries of plowing. However, what remains is carbon that is relatively unavailable to microbes because it is chemically resistant to microbial decomposition or tightly bound to clay particles (Kiem and Kögel-Knaber, 2003) — what soil biologists call slow or passive carbon — plus whatever carbon has been recently added as crop residue (Figure 3.3). These fractions provide a very different soil habitat than before, bereft of many of the benefits of abundant SOM and biota. There is less water-holding capacity, less porosity and aeration, lower infiltration, and a diminished buffer of biologically available nutrients. Moreover, organic matter itself — even in permanent-charge soils — provides significant cation exchange capacity, which helps to hold biologically important cations against leaching loss.

Soils impoverished in carbon will thus be impoverished in biological activity and in the fertility that this activity confers. Soil nitrogen turnover — the nitrogen-supplying power of the soil — is lower whenever microbial populations are diminished, and there are consequently fewer invertebrates such as earthworms, ground-dwelling beetles, and nonparasitic nematodes. Many of these organisms, discussed in Part II, are needed to promote crop growth by providing services such as decomposing litter, creating soil pores and aggregates, and consuming root-feeding insects, parasites, and plant pathogens (Coleman and Crossley, 2003).

In summary, soil systems that are low in SOM and soil biota, whether for either management or for natural reasons, will be lower in fertility, and for this reason they require substantial external inputs to maintain crop productivity. Restoration and

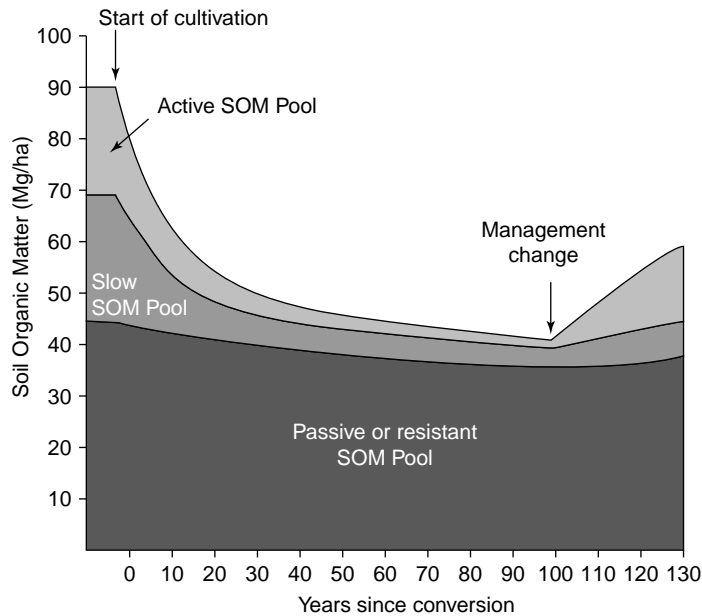


FIGURE 3.3

Changes in soil organic matter fractions following cultivation of a soil profile under native vegetation. (After Brady, N.C. and Weil, R.R., in *The Nature and Properties of Soils*, 12th ed., Prentice Hall, Upper Saddle River, NJ, 2002, 523. With permission.)

maintenance of SOM in both residual and living forms is thus a crucially important management challenge.

3.2.2 High Nutrient-Use Efficiency

Most cropping systems use and export nutrients at prodigious rates. Some nutrient loss, such as that exported in yield, is unavoidable. Other losses, however, such as nutrients lost via hydrologic and gaseous pathways, are inadvertent. All exported nutrients that can limit crop performance must be replaced for a cropping system to remain productive, from external sources or from within the soil system. Maintaining this nutrient availability in both time and place to match plant needs is one of the toughest of agronomic challenges.

For certain plant nutrients such as calcium and magnesium, most temperate-region soils can maintain a steady supply with little depletion even in the face of significant export. This is because the mineral stores of these nutrients are high in most young soils. For other nutrients, however, particularly nitrogen, phosphorus, and potassium (N, P, and K), the ability of a soil to fully resupply losses is eventually lost. When this occurs, modern cropping systems rely on fertilizers to make up the difference. Nitrogen deficits are especially severe because nitrogen losses can occur via so many different pathways, and it is nitrogen that typically limits the productivity of even natural ecosystems that are not harvested.

The two main strategies for improving nutrient availability in cropped ecosystems are to increase inputs and to reduce losses. Inputs are commonly increased via organic or synthetic fertilizer additions, or specifically for nitrogen, by N_2 fixation (see Chapter 12). Losses can be reduced, on the other hand, by increasing system-wide nutrient-use efficiency. Nitrogen is a case in point. A highly productive maize crop with a yield of

10 tons of grain removes about 260 kg N ha^{-1} (Olson and Kurtz, 1982) or around 5.2 tons of nitrogen over 20 years of cropping. In uncultivated arable soils, organic nitrogen stores can be as high as 10 tons of nitrogen ha^{-1} on average. Continuous cropping of maize thus has the potential to remove, within 20 years, an amount of nitrogen equivalent to 50% of the nitrogen stock in the native SOM, demonstrating the potential for rapid soil nitrogen depletion. Because nitrogen is the most common limiting nutrient in temperate region ecosystems, restoring lost nitrogen is a crucial agronomic goal. Preventing as much nitrogen as possible from inadvertently leaving the system is equally important, from both an agronomic and environmental standpoint.

Improving a cropping system's nutrient-use efficiency requires matching soil nutrient release — whether from organic or inorganic sources — with the demand for nutrients by plants. This matching has to occur both temporally and spatially. In diverse native plant communities and many cropped perennial systems, soil microbial activity will almost always coincide with periods when there is at least some plant need. In native communities, the presence of diverse species having different life cycles means that at least some plants will be actively photosynthesizing whenever temperature and moisture permit. In the annual monocultures typical of temperate-region agriculture, on the other hand, such synchrony is rare.

Most grain crops, for example, are in the ecosystem for only 90–100 days, and only during 30–40 days at midsummer will they be accumulating biomass at a significant rate. In maize, for example, nitrogen uptake rates can reach the astonishing rate of $4 \text{ kg N ha}^{-1} \text{ day}^{-1}$ (contrast this with inputs of nitrogen to the soil from precipitation of $10 \text{ kg ha}^{-1} \text{ year}^{-1}$). This high rate is sustained for only 3–4 weeks, however, and it falls to nil within the following 2–3 weeks (Olson and Kurtz, 1982). The much longer periods during which atmospheric nitrogen deposition occurs and soil temperature and moisture are sufficient to support microbial nitrogen mineralization do not match crops' peak nutrient demand. This asynchrony creates a huge potential for nutrient loss and for low system-wide nutrient-use efficiency (Figure 3.4).

Spatial symmetry can be as important as temporal synchrony for ensuring that nutrient availability and uptake are well matched (Robertson, 1997). Row crop management, unfortunately, does not often result in well-matched spatial arrangements of plants and

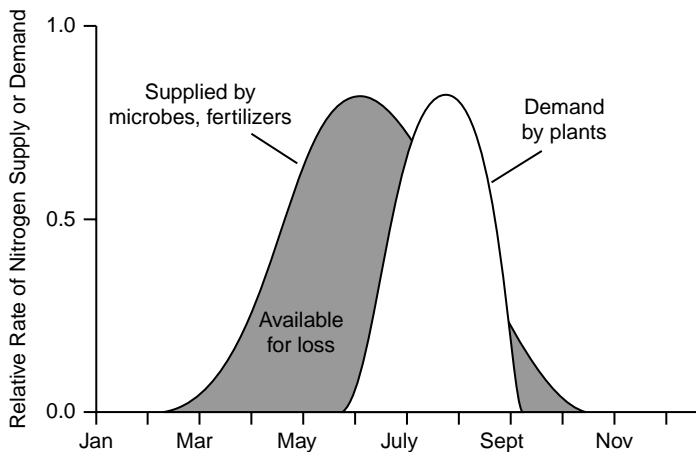


FIGURE 3.4

Asynchrony between nitrogen supply and nitrogen plant demand in a temperate cropping system can lead to periods of nitrogen vulnerability to loss. (From Robertson, G.P., in *Ecology in Agriculture*, Academic Press, New York, 1997. With permission.)

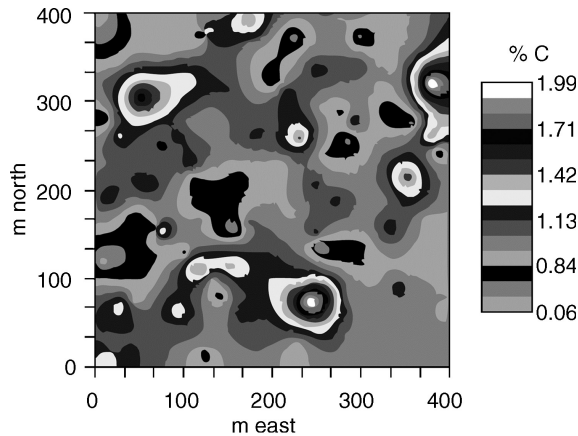


FIGURE 3.5

The variability of soil organic carbon across a $400 \times 400 \text{ m}^2$ soybean field in southwest Michigan. (From CAST, *Climate Change and Greenhouse Gas Mitigation: Challenges and Opportunities for Agriculture*, Council for Agricultural Science and Technology, Ames, IA, 2004, With permission.)

resources within a field, and this mismatch also reduces system-wide nutrient-use efficiency. Row vs. between-row differences in soil-nutrient availability have been recognized for decades (e.g., [Linn and Doran, 1984](#)), and a number of management strategies, discussed later, can be derived from knowledge about how to increase the water and nutrient-use efficiencies of row crops.

Spatial heterogeneity at larger scales is also emerging as a management issue. Available evidence suggests that soil nitrogen availability is highly variable in natural communities, with variable patches of soil fertility at scales that can affect individual plants (e.g., [Robertson et al., 1988](#)). This variability persists after conversion to agriculture ([Robertson et al., 1993](#)), so that field-scale soil variability as shown in [Figure 3.5](#) becomes a major factor in most cropping systems. High nutrient-use efficiency from both the spatial and temporal perspectives is thus an important goal of agronomists, and one whose achievement depends on adept combinations of soil and plant management decisions.

3.3 Solutions to the Major Soil System Challenges in Temperate Regions

3.3.1 Restoration of Soil Organic Matter

Decades of research have demonstrated that SOM can be restored and maintained at relatively high levels in most arable soils. Most importantly, those biologically active SOM fractions most rapidly lost following cultivation — such as light-fraction (LF) or particulate organic matter (POM) — can be regenerated. LF has a rapid turnover time of 2–3 years because it is relatively free of mineral material and humification and has high concentrations of carbon and nitrogen ([Wander et al., 1994](#)). LF is thus an ideal source of energy and nutrients for microorganisms, and its decomposition releases plant nutrients to the soil solution. Restoring LF and other active SOM pools through strategic crop and soil management thus has the potential to stabilize cropping systems and reduce dependencies on external inputs.

At the simplest level, SOM change is simply the difference between organic carbon added to soil and organic carbon lost via the biological oxidation of SOM carbon to CO₂ carbon. There are thus two ways to build SOM in cropping systems: (1) increase soil carbon inputs via crop residues, cover crops, and soil amendments such as compost and manure, and (2) decrease soil carbon loss by slowing decomposition and (where important) soil erosion.

Carbon inputs to soil are influenced by nearly every facet of agricultural practice (Paustian et al., 1995). These include crop type and productivity, the frequency and duration of fallow periods, and fertilizer and residue management. Organic amendments such as manure, compost, and sewage wastes provide additional management interventions.

High crop productivity based on associated residue inputs does not in itself guarantee higher SOM pools (Paul et al., 1997). Relationships between residue inputs and SOM are complicated by changes in enzyme dynamics and decomposition processes following N-fertilization and other agricultural practices (Fontaine et al., 2003; Waldrop et al., 2004). In the U.S.A.'s corn belt, for example, even though aboveground residues in a maize ecosystem may exceed by a factor of two the amount of litterfall in the forest or native prairie that the agricultural system replaced, SOM levels in the maize system persist at about 50% of the levels in native forest even when maize residues are not exported from the soil system.

This said, substantial residue inputs are still a prerequisite for building organic matter stores in soil. Removing all aboveground residues — as is the case for corn silage, wheat straw production, or biobased fuel production, for example — removes a major source for SOM accumulation. With other factors held equal, in fact, field experiments have generally found a close linear relationship between the rates of residue carbon return and the SOM levels found in temperate agricultural soils (e.g., Rasmussen et al., 1980). Organic amendments also provide a direct and effective means for building SOM. For example, in a long-term continuous wheat experiment at Rothamsted, U.K., plots receiving farmyard manure (35 tons ha⁻¹ annually) over a 100-year period effectively doubled their SOM levels (Jenkinson, 1982).

Decomposition rates of crop residues and SOM are principally influenced by climate, by the chemical composition or quality of the residue, and by soil disturbance. In general, decomposition occurs faster in warmer, moister (but not saturated) soils, and with management that exposes the soil's surface to greater solar radiation or that uses spring tillage to accelerate soil drying and warming following a winter snow cover so as to promote decomposition. Draining wetland soils for agriculture achieves essentially the same result.

Decomposition is also affected by litter quality. Plant tissues lower in nitrogen and higher in structural compounds such as cellulose, suberin, and lignin decompose more slowly than tissues that are higher in sugars, protein, and nitrogen: for example, soybean leaves decompose much faster than do wheat straw or maize stalks. Few microbes are able to degrade the complex chemical structure of lignin, whereas simple organic compounds can be respired by most soil organisms.

It follows that SOM is likely to accumulate faster with the addition of more structurally complex materials (for example, Figure 3.6), although these relationships may be complicated by interactions between decomposition products and soil physical processes. For example, the rapid production of polysaccharides associated with the decomposition of legumes can facilitate aggregate formation and increased physical protection of SOM. More research is needed, however, to determine how plant and microbial communities interact to control decomposition and, in particular, the formation of particular biochemicals which stabilize SOM in agricultural soils. Manure tends to be more complex

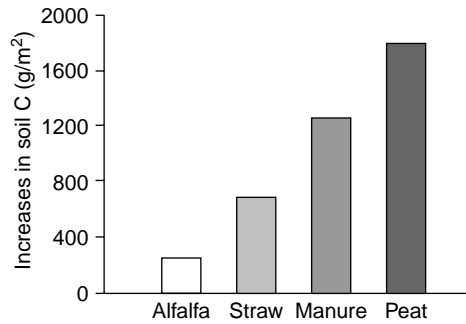


FIGURE 3.6

Soil carbon increases over 20 years following the addition of carbon sources differing in a structural complexity or quality to a sandy soil in Canada. Residues were added at the rate of $500 \text{ g m}^{-2} \text{ year}^{-1}$. (From Paustian, K., Elliot, E.T., Collins, H.P., Cole, C.V., and Paul, E.A., *Aust. J. Exp. Agric.*, 35, 929–939, 1995; after Sowden, F.J. and Atkinson, H.J., *Can. J. Soil Sci.*, 48, 323–330, 1968. With permission.)

structurally than are uncomposted crop residues because it has already been exposed to microbial attack in the animal gut.

No-till soil management, discussed in Chapter 22 and Chapter 24, and other forms of tillage management that are less destructive than moldboard plowing help to conserve SOM in cultivated soils by helping to maintain soil aggregate stability. Conservation tillage can also conserve SOM by reducing erosion in landscapes subject to wind and water erosion (Lal et al., 2004). Cover crops that maintain plant cover during periods when the primary crop is not present — late fall, winter, and early spring, for example — can also reduce the potential for soil erosion and add additional vegetative residue to the SOM pool.

Restoring SOM in cropping systems can thus be achieved best through some combination of increased organic matter inputs, no-till or other conservation tillage practice, and cover cropping. While any organic matter inputs will help to build SOM, the most effective will be those that are slow to decompose, such as low-nitrogen, high-lignin crop residues or compost and manure. Rotational complexity may also help to restore SOM when one or more crops in the rotation have higher lignin contents, more residue, or a longer growing season than others.

3.3.2 Improving Nutrient Efficiency

Making nutrients available mostly when and where they are needed by the crop improves nutrient-use efficiency. Temporal synchrony is achieved by applying inputs as close as possible to the time required for crop growth. Applying mobile fertilizers, such as nitrogen, in split applications, e.g., 20% at planting and the rest just before the period of greatest crop growth, is common in many temperate systems, although — egregiously — fall application of anhydrous ammonia is still common for maize production in some regions of the Midwestern U.S.A.

Likewise, encouraging decomposition of the previous crop's residue early in a crop's growing season is also beneficial. Spring rather than fall tillage will keep more nutrients in active SOM pools where they are better protected from overwinter leaching and gaseous losses and will serve to stimulate decomposition (and nutrient release) prior to crop growth. Rotary hoeing or some other type of shallow cultivation well into the growing season can stimulate microbial activity just prior to major crop growth. Winter cover crops — particularly fast-decomposing high-nitrogen crops such as legumes — also help to provide active-fraction SOM when the crop most needs it (see Figure 3.4). Cover crops

can additionally help to capture nutrients released to the soil solution when the main crop is not present; plants active in the fall and spring when microbes are actively oxidizing SOM can temporarily immobilize nutrients that would otherwise be vulnerable to overwinter or springtime losses from the ecosystem.

Other aspects of crop management that may influence microbial communities and decomposition are nitrogen fertilization, inputs of labile carbon compounds, and irrigation. Many studies have demonstrated that nitrogen or organic matter additions may result in a change in the mineralization of native SOM (Fontaine et al., 2003). This is referred to as the priming effect: a strong change in the turnover of SOM in response to a soil amendment (Kuzyakov et al., 2000). Priming effects may play a critical role in controlling carbon balance and nitrogen turnover in ecosystems. However, our ability to exploit the underlying microbial processes to manage soil fertility is currently limited (De Neve et al., 2004). This is primarily because environmental controls over priming responses are very complex and include interactions between nutrient availability, litter quality, soil texture, and other factors. Despite these challenges, this should remain an area of active research because the potential benefits are great from being able to manipulate SOM turnover and nutrient mineralization when and where it is most needed with relatively modest additions of nitrogen or carbon to the soil.

Spatial synchrony or coincidence can be achieved at two levels. At the row vs. between-row level, inputs such as fertilizers can be applied in bands next to or over the tops of rows using drip irrigation, fertilizer banding, or foliar feeding; or organic amendments or crop residues can be mounded into rows using techniques such as ridge tillage. Ridge tillage, a popular soil management technique for many low-input farmers in the Midwestern U.S.A. (NRC, 1989), minimizes spatial asymmetry by periodically mounding the between-row A_p horizon into semi-permanent ridges on to which the crop is planted. This concentrates the labile organic matter and soil biotic activity within rows, achieving the same effect as fertilizer banding.

At the larger field scale, variability can be addressed by using site-specific application technologies. Many harvest-combines today are sold with global positioning system (GPS) equipment to permit highly-resolved yield mapping. With proper application equipment, these maps can then be used to tailor fertilizer applications to the productive capacity of any given area of the mapped field. Rather than fertilizing an entire field with a single, high rate of application, the highest rates can be applied only where productivity, and therefore plant nutrient uptake, will be high, reducing nutrient losses from low-productivity areas. In effect, this method uses plants in the field as bioassays for the nitrogen made available by soil microbes; it provides additional nitrogen fertilizer in proportion to the plants' abilities to take it up.

In most temperate regions, the current cost of fertilizer is low relative to the marginal increase in productivity that can be gained from applying it at high rates. So from the producer's standpoint, it rarely pays to reduce the inputs of limiting nutrients that are inexpensive, e.g., nitrogen. Thus, socioeconomic influences condition decisions about achieving crop nutrient-use efficiency (Robertson and Swinton, 2005). In many if not most cases we cannot expect improved ecosystem nutrient-use efficiency until policy and other issues affecting farmer decision-making are appropriately resolved (Robertson et al., 2004).

3.4 Discussion

Soil fertility in both temperate and tropical regions is the net result of a complex interplay between the biotic and abiotic components of agricultural ecosystems. The abiotic

environment includes both physical and chemical attributes, which can differ between temperate vs. tropical regions, though often less than terminology implies. Important differences are that temperate-region soil systems are usually exposed to a seasonal cold or frozen period; further, temperate region soils are in general developed on geologically younger soils and therefore dominated by a permanent-charge mineralogy. The biological environment includes enormously complex food webs and a truly amazing diversity of microbes and invertebrates. As yet, we still know little about the patterns and importance of this diversity in either temperate or tropical regions, and even less about how to manage it, but this should change rapidly in the coming decades.

The major agronomic challenges related to temperate-region soil system fertility management are SOM restoration and the improvement of ecosystem-level nutrient-use efficiency. Both issues are addressable with current knowledge and technology, and both require active management of the soil biota, either directly or indirectly. To date, methods to manage the soil biota directly through priming or other strategies are often more theoretical than practical in production-oriented systems. A better understanding of the various scientific issues that can illuminate these processes and dynamics is much needed. However, effective utilization of such knowledge will require more attention to social science variables and more integration across disciplines than is currently found in scientific studies or farmer practice.

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