
5 Managing Soils as Systems within Temperate-Region Landscapes

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The view of soils as physical media whose purpose is to support plants, rather than as complex biophysical systems in their own right, still dominates the approaches to soil management in intensive cropping systems worldwide, and especially in the highly productive row-crop systems of temperate regions. This is true despite recognition that soil biology is the basis for successful regenerative agriculture (Robertson and Harwood, 2013) and a growing concern with soil health that properly considers the complex biophysical nature of soil systems (Doran and Parkin, 1994; Lehmann et al., 2020). The predominance of agronomic strategies that pay little attention to life in the soil derives in large part from the success of the 20th-century Green Revolution, which coupled improved crop varieties with technologies that provided via exogenous agrochemical inputs many of the ecological services that were traditionally supplied by soil systems themselves, such as plant nutrients and disease suppression.

The result has been an agricultural enterprise that too often values soil largely as a porous medium that supports plants, holds nutrients, and drains excess rainfall. Not as well appreciated are the crucial roles of soil systems with their vast web of soil biota 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 of larger ecosystems. As a result, the actual and potential contributions of soils to the productivity of intensively managed systems, which rely heavily on exogenous inputs, are often undervalued.

Figure 5.1 illustrates how soils are dynamic, living systems that are integral parts of larger ecosystems, both managed and natural. Soil subsystems participate fully in the processes that are common to ecosystems as a whole: energy flow (examined in Chapter 8); the movement and multiple transformations of water, carbon, and nutrients; and the

trophic dynamics that engage all players in the ecosystem's food web (Chapter 7). From a functional standpoint, soil systems provide habitat for a wide variety of organisms that together provide ecosystem services critically important for crop productivity and environmental quality: pest and disease suppression; the supply of nitrogen, phosphorus, and other essential nutrients; water availability and filtration; carbon storage; erosion control; and plant support, among many others. Managing soil systems to enhance the delivery of these services is an important strategy for producing ecosystem services and not just food (Robertson et al., 2014; Tamburini et al., 2020).

Are these services more essential in temperate regions than in others? No; nor are they more expendable. Rather, modern chemical and mechanical technologies have allowed many of these services to be diminished if not entirely supplanted in intensively managed farming systems worldwide, typically dominated by external inputs of energy, plant nutrients, and biocides. Although these methods may be more common today in temperate regions, they are increasingly found in the tropics, for example, in the huge swaths of South America that are now planted with soybeans and sugarcane. 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.

5.1 TEMPERATE-REGION SOILS

Two generalizations illustrate characteristics of temperate-region soils that significantly differentiate them from tropical soils. First, because temperate soils are seasonally cold during a significant portion of the year, plant growth and soil biological activity in them are low or nil. This seasonality results in important changes in the chemical and

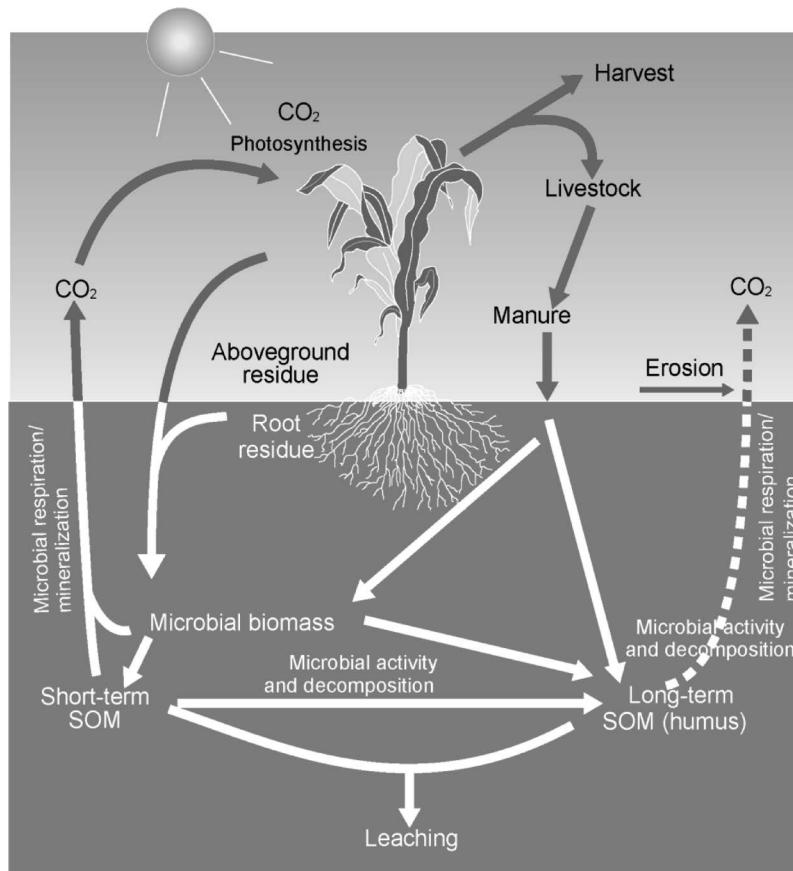


FIGURE 5.1 A maize ecosystem diagram illustrating aspects of the carbon cycle, one of many system-level processes that occur in ecosystems. (From Cavigelli et al., 1998.)

physical aspects of the soil environment. Cycles of freezing and thawing accelerate rock weathering and the breakdown of soil aggregates. They also influence chemical as well as biological reactions that affect mineral weathering, chemical solubility, and other soil chemical properties that occur more slowly in winter months. Additionally, soil freezing kills many of the insects and other pests that migrate seasonally from lower latitudes. As discussed below, this seasonality provides both challenges and opportunities for effective management of soil fertility.

Second, agricultural soils in temperate regions tend to be geologically young in comparison to large regions of the tropics. Although many tropical soils are also young, for example, those developed on recent volcanic and alluvial deposits, most tropical soils are not young, and this has important implications for soil fertility. In geologically young soils such as those recently glaciated or formed from windblown loess, the primary minerals are not much weathered, and their electrical charge system (which confers cation exchange capacity) is largely stable, with important basic cations such as calcium (Ca^{2+}), potassium (K^+), and magnesium (Mg^{2+}) tightly conserved (Chapter 21). In older soils, the process known as weathering will have removed most of the cations from clays that confer permanent charge.

Thus, the ion exchange capacity of older tropical soils depends largely 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 temperate soils is more durable, and thus, it is more impervious to changes in the soil pH and to the composition of the soil solution. Although all soils contain both permanent and variable-charge surfaces (e.g., organic matter can express a variable charge), most soils are dominated by one or the other charge system, and this has a significant impact on nutrient mobility and availability (Sollins et al., 1988). In general, the permanent charge system that dominates most temperate-region soils provides these soils with greater chemical and structural resistance to the damaging effects of chronic disturbance that is associated with mechanized agriculture.

Other generalizations are more questionable. For example, one sometimes reads of other differences between temperate versus tropical soils in terms of soil organic carbon or organic matter content, microbial biomass, and biodiversity. Regional differences appear within both biomes, so few cross-biome generalizations hold up. Despite higher temperatures, for example, many tropical soils have levels

of native soil organic matter (SOM) that are equal to those in temperate regions (Greenland et al., 1992).

Likewise, it is difficult to generalize about soil biodiversity. About 1.2% of organic matter in arable soils is living biomass that contains immense diversity (Xu et al., 2013). A single gram of soil typically includes thousands of different microbial species and 4–20 billion cells (Bardgett and van der Putten, 2014), with hundreds of fungal species whose hyphae may extend hundreds of meters just within that gram of soil (Peay et al., 2016). Moreover, this microbial diversity is in addition to dozens to hundreds of species of other taxa, including nematodes, isopods, earthworms, and collembolans (Coleman et al., 2003; Bardgett and van der Putten, 2014).

It is thus not possible to state with any certainty that temperate and tropical soils differ with respect to soil biodiversity, and even less so with respect to microbial functions and responses to environmental conditions (Crowther et al., 2019). New methodologies, including trait-based approaches, are clarifying these patterns (or their absence) as they elucidate how different microbial groups contribute to critical soil processes, including SOM turnover and trace gas emissions (Malik et al., 2020).

5.2 CHALLENGES FOR SOIL SYSTEM FERTILITY AND MANAGEMENT

The inherent fertility of many temperate-region soils in mesic (nonarid) climates is high. In comparison to highly weathered tropical soils, many soils in temperate regions can support 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 productivity to external subsidies that 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 the all-important living fraction that regulates soil ecosystem function (Tiessen et al., 1994), 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. In this chapter, we focus on these two major challenges, considering secondary challenges within the context of these two chief concerns.

5.2.1 SOIL ORGANIC MATTER RESTORATION AND CONSERVATION

Typically, 40–60% of a soil's stores of organic matter are lost in the 40–60 years following conversion to agricultural production (Figure 5.2). Site-specific losses depend on

ecosystem conditions such as temperature, water availability, and soil type, as well as on agroecosystem management practices. Restoring lost SOM and tempering its turnover is thus a major goal of biologically based agriculture (Robertson and Harwood, 2013). Management strategies to restore SOM generally involve increasing the quantity and quality of plant-residue inputs and increasing the proportion of plant-residue inputs that are converted to SOM.

There is now strong evidence that the majority of SOM is built from microbial residues formed when microbes metabolize crop residues and SOM (Miltner et al., 2012). Microbial by-products, including cell walls and metabolites, form persistent SOM when these by-products become associated with soil mineral surfaces that limit microbial access to SOM (Grandy and Neff, 2008). SOM will thus accumulate when microbial biomass is large, active, and produced efficiently, i.e., when a higher proportion of microbial substrate is converted into microbial biomass rather than lost from the soil as carbon dioxide (Kallenbach et al., 2016).

The importance of microbial residues as a principal source of soil carbon accumulation suggests that agricultural management strategies that support a larger microbial community and more efficient conversion of plant inputs into microbial biomass will be an important driver for building stable soil carbon (Cotrufo et al., 2019). Increasing cropping system diversity, especially with the use of cover crops and perennial crops, consistently increases SOM (McDaniel et al., 2014). These practices encourage a larger microbial community and more efficient transfer of plant carbon into microbial biomass and ultimately into stable SOM pools (Tiemann et al., 2015).

Roots, rather than aboveground plant litter or crop residue, are the dominant source of microbial carbon substrates in the soil, and most stable SOM appears to be root-derived (Rasse et al., 2005). Microorganisms process and incorporate root carbon into biomass approximately twice as fast as aboveground plant residues (Austin et al., 2017). In addition

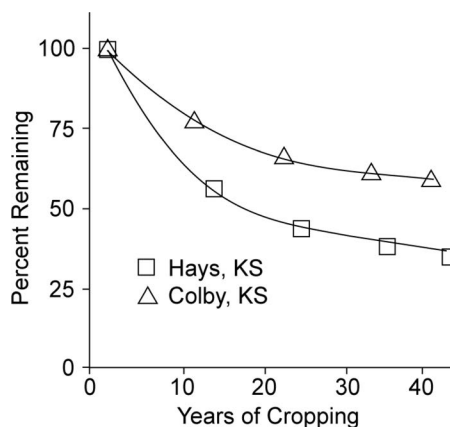


FIGURE 5.2 Soil carbon loss following cultivation at two temperate-region sites, Hays and Colby counties, Kansas, United States. (From Haas et al., 1957.)

to root residues, root exudates may also play a key role in determining the fate of SOM through their influence on microbial communities. Root exudates are low-molecular-weight organic compounds, primarily sugars, organic acids, and amino acids released by plant roots. Low-molecular-weight exudates are considered to be a sizeable portion of total root carbon entering most soils (Boddy et al., 2007), and they greatly affect microbial population size, activity, and community structure.

Roots also affect SOM accumulation by altering the soil physical environment. As roots forage for nutrients and then decompose, they create channels and pores of different diameters, each a microhabitat with different water and oxygen characteristics. Resulting differences in microbial activities create opportunities for the stabilization of microbial carbon on mineral surfaces at different rates in pores of different diameters (Kravchenko et al., 2019). That soils with more diverse root assemblages appear to accumulate more stable carbon further underscores the association between crop diversity and SOM conservation.

Increasing the diversity of crop residue inputs, enhancing root inputs, and using diverse cover crops all help to support an active microbial community that builds and conserves SOM. At the same time, these practices protect the soil against erosion, which reduces the stocks of SOM in many soils.

Reducing tillage disturbance in agroecosystems also supports SOM accumulation. Tillage disrupts the physical structure of soil and increases the accessibility of SOM to decomposers. SOM is primarily stabilized by physical protection on mineral surfaces and by occlusion within the small pores of soil aggregates. Soil aggregates are small clusters (0.05–8 mm) of soil particles that protect carbon molecules from rapid microbial consumption. Aggregates form from the action of primarily low-molecular-weight, microbially derived compounds that glue particles together. In the process of aggregate formation, SOM becomes entrapped within aggregate pores, where decomposition is suppressed by reduced oxygen, less nutrient availability, and lower microbial activity.

Cultivation exposes soil aggregates to more frequent wet-dry and freeze-thaw cycles that break apart aggregates, especially the larger ones, thereby exposing trapped organic carbon to aerobic microbes that easily respire it as carbon dioxide (CO₂) (e.g., Grandy and Robertson, 2006). Reducing tillage can reverse this process, restoring soil structure and physically protecting SOM (Chapter 23). Coupling tillage reduction with greater crop rotation diversity by using cover crops and perennial crops like forage grasses can restore half or more of the SOM that has been lost following agricultural conversion.

The relatively stable SOM that remains following agricultural conversion is relatively unavailable to microbes because it is chemically resistant to microbial decomposition or tightly bound on clay mineral surfaces (Kiem and Kogel-Knaber, 2003). Soils long cultivated without cover crops or complex rotations are comprised principally of

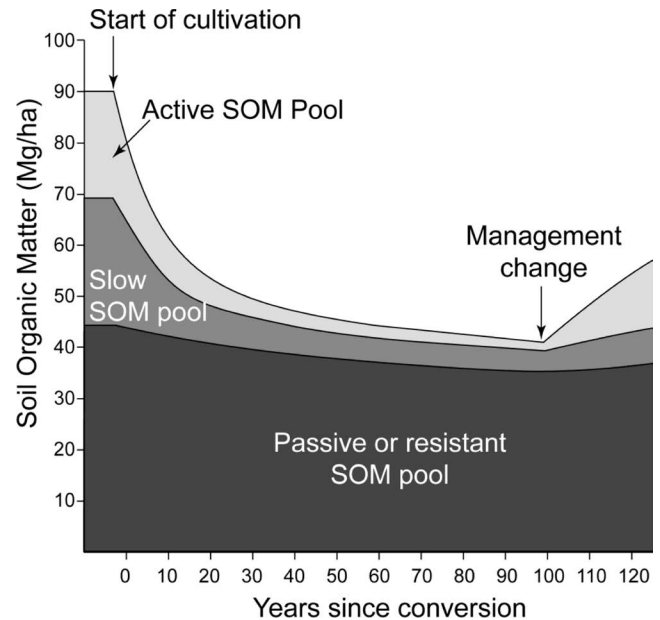


FIGURE 5.3 Changes in soil organic matter fractions following cultivation of a soil profile under native vegetation. (After Brady and Weil, 2002: 523.)

this resistant or passive SOM pool, having lost much of the SOM in more biologically active pools (Figure 5.3). These impoverished soils possess lower biological activity and reduced fertility.

Soil nitrogen turnover – the nitrogen-supplying capacity of the soil – is correspondingly lower whenever microbial populations are diminished and where 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 et al., 2003).

In summary, soil systems that are low in SOM and soil biological activity, whether because of their management or for natural reasons, will be lower in fertility (Maron et al., 2018). For this reason, they require substantial external inputs to maintain crop productivity. Restoration and maintenance of SOM in both residual and living forms are thus crucially important management challenges with high payoff.

5.2.2 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, collateral damage, so to speak. All exported nutrients that can limit crop performance must be replaced, either

by external inputs or from within the soil–plant system, for a cropping system to remain productive. Maintaining this nutrient availability in both time and place so as to precisely 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 even in the face of significant export. This is because the mineral stores of these nutrients are high in most geologically 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 many different pathways (Robertson and Groffman, 2015), 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, and specifically for nitrogen, by biological N_2 fixation (Chapter 13). Losses can be reduced, on the other hand, by increasing system-wide nutrient-use efficiency. Nitrogen is a case in point. A maize crop with a yield of 12 t of grain ha^{-1} with a nitrogen content of $\sim 1.8\%$ will remove about 216 kg N ha^{-1} per year, or around 5.4 t of nitrogen over 25 years of cropping. In uncultivated arable soils, organic nitrogen stored in SOM can average as much as 10 t N ha^{-1} . Continuous cropping of maize thus has the potential to remove, within 25 years, more than 50% of the nitrogen stock in the soil's native organic matter, demonstrating the potential for rapid soil nitrogen depletion. Because nitrogen is the most common limiting nutrient in temperate ecosystems, restoring lost nitrogen is a crucial management objective. Preventing as much nitrogen as possible from inadvertently leaving the system is equally important, from both an agronomic and environmental standpoint (Robertson and Vitousek, 2009).

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 must occur both temporally and spatially. In diverse native plant communities, soil microbial activity will almost always coincide with periods when there is at least some plant need. In such communities with diverse vegetation, the presence of diverse species with different life histories means that at least some plants will be actively photosynthesizing whenever temperature and moisture permit. This will also be the case in many perennial cropping systems. In the annual monocultures typical of much temperate-region agriculture, on the other hand, such synchrony of nutrient supply and demand is rare, although it can be partially achieved with cover crops.

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.

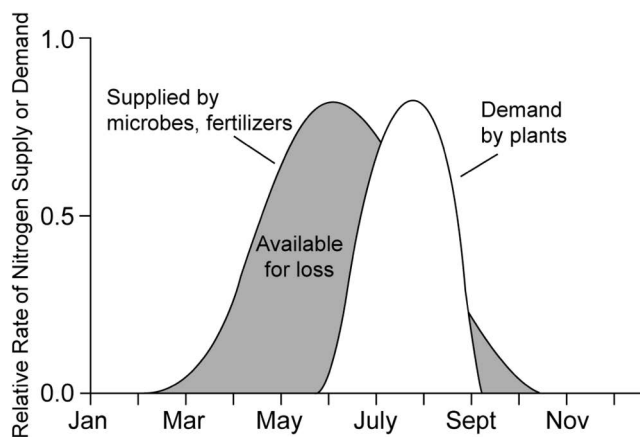


FIGURE 5.4 Asynchrony between nitrogen supply and nitrogen plant demand in a temperate cropping system can lead to periods of nitrogen vulnerability to loss. (From Robertson, 1997.)

In maize, for example, nitrogen uptake rates can reach the astonishing rate of >4 kg N ha^{-1} per day, much, much greater than natural inputs of nitrogen from precipitation of 10 kg ha^{-1} annually. This high rate of nitrogen uptake 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 when soil temperature and moisture are sufficient to support microbial nitrogen mineralization do not match the crops' peak nutrient demand. This asynchrony creates a huge potential for nutrient loss and for low system-wide nutrient-use efficiency (Figure 5.4).

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 resources within a field, and this mismatch also reduces system-wide nutrient-use efficiency. Row versus 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 below, 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 key management issue. Available evidence suggests that the plant-obtainable soil nitrogen 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 such as that shown in Figure 5.5 becomes a major factor affecting most cropping systems. This is reflected in patterns of within-field crop productivity documented for large areas of the US Midwest (Basso et al., 2019). Achieving high nutrient-use efficiency from both spatial and temporal perspectives is thus an important goal of soil system

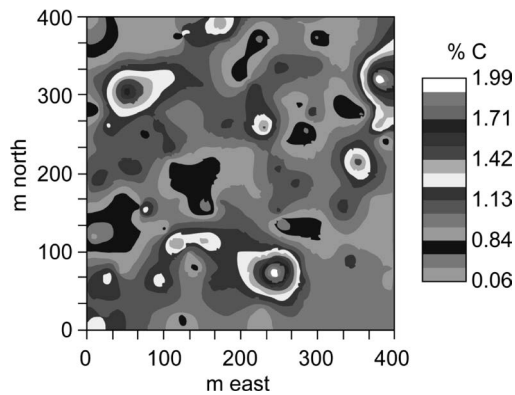


FIGURE 5.5 The variability of soil organic matter (expressed as % carbon) across a 400 × 400 m² soybean field in southwest Michigan. (From CAST, 2004.)

managers, and one for which success depends on adept combinations of soil and plant management decisions.

5.3 SOLUTIONS TO THESE CHALLENGES IN TEMPERATE REGIONS

5.3.1 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, the biologically active SOM fractions most rapidly lost following cultivation can be regenerated. Light or particulate SOM fractions are among the most rapidly lost. Light-fraction SOM has a rapid turnover time of 2–3 years because it is relatively free of mineral material and has high concentrations of carbon (Wander et al., 1994). Light-fraction SOM is thus an ideal source of energy and nutrients for microorganisms, and its decomposition releases plant nutrients into the soil solution. Restoring light-fraction and other active SOM pools through strategic crop and soil management thus has the potential to increase agroecosystem resilience and reduce dependency on external inputs (Bowles et al., 2018; Jilling et al., 2018, 2020).

At the most basic level, change in SOM is simply the difference between the organic carbon added to soil and the organic carbon lost via biological oxidation of SOM to CO₂. 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 losses 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; Kallenbach et al., 2015). Relationships between residue inputs and SOM are complicated by potential changes in microbial physiology, enzyme dynamics, and decomposition processes following nitrogen fertilization and other agricultural practices (Fontaine et al., 2003; Waldrop et al., 2004). Further, high rates of aboveground productivity and residue inputs in many annual cropping systems can mask a lack of critical belowground root inputs that contribute disproportionately to SOM.

Nevertheless, significant residue inputs are a prerequisite for building SOM. Removing all aboveground residues – as is the case for corn silage, wheat straw production, or cellulosic bioenergy crops, for example – removes a major source of biomass otherwise available for SOM accumulation. In fact, with other factors held equal, field experiments have generally found a close linear relationship between the rates of residue return and the levels of SOM in temperate-region agricultural soils (e.g., Rasmussen et al., 1980). Since root inputs are particularly important for building SOM, short-duration seasonal cover crops can help maintain SOM via substantial root inputs even when aboveground production is minimal. Organic amendments such as compost also provide a direct and effective means for building SOM. For example, in a long-term continuous wheat-cropping experiment at Rothamsted, England, plots that annually received farmyard manure (35 t ha⁻¹) over a 100-year period effectively doubled their SOM levels (Jenkinson, 1982).

Decomposition rates of both 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 of organic matter is also affected by litter quality. Plant tissues lower in nitrogen and higher in structural compounds such as cellulose, suberin, and lignin will decompose more slowly than tissues that are higher in sugars, protein, and nitrogen. For example, soybean leaves decompose much faster than will 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 then that SOM is likely to accumulate faster with the addition of more structurally complex organic materials, although these relationships may be complicated by interactions among decomposition products, soil physical processes, and the impacts of residue chemistry on the decomposer community. For example, the rapid production of polysaccharides associated with the decomposition of legumes can facilitate aggregate formation and increased physical protection of SOM. Legumes and other readily

decomposable residues can also promote a higher microbial growth efficiency, resulting in a higher proportion of residue inputs entering SOM pools rather than leaving the soil as CO₂. Yet, it is the production of chemically diverse residue inputs that include legumes and more chemically complex plant residues that optimizes the mineral-microbe-SOM interactions that promote SOM formation. More research is needed, however, to determine how plant and microbial communities interact to control rates of decomposition and, in particular, the formation of particular biochemicals that stabilize SOM in agricultural soils.

No-till soil management and other forms of conservation tillage 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 there is no primary crop present – late fall, winter, and early spring, for example – can also reduce the potential for soil erosion and add additional biomass 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 practices, and cover cropping. While any organic matter inputs will help to build SOM, the most effective will be those from roots and those that promote both soil structure formation and a large and efficient microbial community. The rotational complexity of cropping systems will help to restore SOM by promoting an active microbial community and the mineral-SOM-microbe interactions that build up SOM.

5.3.2 IMPROVING NUTRIENT-USE EFFICIENCY

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

Likewise, facilitating decomposition of the prior crop's residue early in the next crop's growing season is 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 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

main crop most needs it. Cover crops can additionally help to capture nutrients released into 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 (e.g., Fontaine et al., 2003). This is referred to as the priming effect: a strong change in the rate of turnover of SOM in response to a soil amendment (Kuzyakov et al., 2000). Priming effects may play a critical role in controlling soil carbon balance and nitrogen turnover in ecosystems.

However, our ability to exploit the underlying microbial processes to manage soil fertility is still 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, priming should remain an area of active research because the potential benefits are great from being able to manipulate SOM turnover and nutrient mineralization in order to have these when and where they are most needed by making relatively modest additions of nitrogen or carbon to the soil at opportune times.

Spatial synchrony or coincidence can be achieved at two levels. At the row versus between-row level, inputs such as fertilizer 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, which is used by many low-input farmers in the Midwestern United States (NRC, 1989), minimizes spatial asymmetry by periodically mounding the between-row surface horizon of soil into semipermanent ridges onto which the crop is planted. This concentrates the labile organic matter and soil biotic activity within rather than between rows, achieving the same effect as fertilizer banding. Modern geospatial guidance systems can maintain the same ridge positions from crop to crop.

At the larger field scale, variability can be addressed by using site-specific application technologies. Almost all harvest combines today are sold with global positioning system (GPS) equipment that permits highly resolved yield mapping. With proper application equipment, these yield 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 nitrogen, for example, the highest rates can be applied only where predicted productivity, and therefore plant nutrient uptake, will be high, reducing nutrient losses from low-productivity areas (Basso et al., 2019). In effect, this method uses the plants in the field as bioassays for the

nitrogen being made available by soil microbes. It guides the application of nitrogen fertilizer to be adjusted to the capacity of plants 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. From the producer's standpoint, adding a limiting nutrient such as nitrogen at high rates is inexpensive insurance against the perceived opportunity cost of not having provided enough – despite nitrogen's high environmental cost. Thus, socioeconomic factors influence farmer decisions about practices that increase 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).

5.4 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 versus tropical regions, although often less than is implied by the terminology. Important differences are that temperate-region soil systems are usually exposed to seasonal cold or frozen periods. Further, temperate-region soils are in general geologically younger soils dominated by permanent-charge mineralogy. The biological environment includes enormously complex food webs and a truly amazing diversity of microbes and invertebrates. We still know little about how to manage the extraordinary biological diversity in soils, 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 can be addressed in practice with current knowledge and technology, but 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 conceptual than practical in production-oriented systems. 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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