9 Strategies for Managing Soil Organic Matter to Supply Plant Nutrients

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INTRODUCTION

Environmental and economic concerns have prompted agricultural producers and researchers to look for improved nutrient management strategies. Environmental and human health concerns about nutrient management are focused on nitrogen and phosphorus that are in excess of crop requirements and might escape from agroecosystems into ground and surface waters (Daniel et al., 1994). Economic considerations in nutrient management include efforts to reduce cost and increase the efficiency of agricultural inputs. Agricultural nutrient management thus aims to balance nutrient inputs with crop demand and to increase the degree of internal nutrient cycling. Management of soil organic matter (SOM) has emerged as a major strategy to help achieve these goals because of the central role SOM plays in storing and cycling nutrients.

The two main objectives of organic matter management in agricultural systems are to (1) restore or maintain SOM to benefit soil quality and (2) supply crops with nutrients contained within or associated with SOM (Bruce et al., 1990). These two objectives are not always

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compatible (Bouldin, 1987) because mineralization that releases nutrients also destroys SOM. Conditions that favor SOM accumulation can also favor nutrient immobilization, which reduces the nutrients available for crop growth. Hendrix et al. (1992) noted that the two objectives of organic matter management are not necessarily mutually exclusive but might require different management approaches than those commonly used. Special considerations need to be given to the timing and intensity of management practices when trying to meet nutrient and organic matter management goals. The ultimate goal is to provide a continuous supply of nutrients while preventing loss of SOM. The chapter provides an overview of the general role of SOM in nutrient storage and nutrient availability and then discusses how various SOM management practices can contribute to sustainable nutrient management.

NUTRIENTS IN SOIL ORGANIC MATTER

COMPONENTS OF SOIL ORGANIC MATTER CONTROLLING NUTRIENT STORAGE

SOM provides a vast reservoir of nutrients for plants (Power, 1994; Brady and Weil, 1999). The mineralization of SOM is the primary source of available nitrogen, phosphorous, and sulfur in natural ecosystems. To a depth of 1 m a rich virgin soil can contain 17 t ha^{-1} of N, not counting N in roots and surface litter (Jenny, 1985). Much of that N is contained in the SOM as a variety of compounds, ranging from amino acids to aromatic structures. Schulten and Leinweber (2000) developed molecular models of SOM. They calculated an elemental analysis of 54% C, 5.2% H, 4.7% N, 35.7% O, and 0.4% S for a total humic substance. However, the heterogeneity and dynamic nature of SOM result in a highly variable nutrient content. For example, the N content of SOM can range from less than 0.5% to more than 6%, depending on biotic and abiotic ecosystem properties such as climate, soil depth, annual input of organic materials, and soil mineralogy (Hassink, 1997). Nutrient content also varies widely between the different fractions of the SOM. For example, Paul and Clark (1996) found that fulvic acids contained 0.8% N and 0.3% S whereas humic acids contained 4.1% N and 1.1% S.

SOM is responsible for a large portion of the cation exchange capacity (CEC) in soil. Stevenson (1986) estimated that 20 to 70% of the whole soil CEC is because of humic substances, and the remainder can be attributed to silicate and nonsilicate mineral colloids. The relative contribution of SOM to total soil CEC in coarse-textured soils is usually greater than in fine-textured soils. Organic matter stabilization through association with clays means that SOM and the amount of CEC because of SOM increase as clay content increases. However, because of the increasing contribution of clay minerals to total soil CEC as clay content increases, the relative contribution of SOM to total CEC in fine-textured soils tends to be lower than in coarse-textured soils (see discussion in Chapter 1). The association of SOM with clay minerals provides physical protection from the mineralization activities of the soil organisms. The organomineral association, depending on its size, accounts for much of the potentially plant-available nutrients. Borogowski et al. (1976) showed that, depending on soil type, the organic–mineral complexes (<20 μm) can contain more than 90% of the exchangeable Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}. The availability of these nutrients is controlled by both equilibrium exchange into soil solution (which is analogous to mineral-associated CEC) and mineralization of SOM whereby nutrients are released from SOM as it degrades.

Conceptually, SOM is often divided into an active and a passive pool to describe the availability of nutrients from its complex assemblage of organic compounds and mineral interactions. The active pool provides many of the readily mineralizable nutrients and is composed of relatively recent plant residues, root exudates, and the microbial biomass (Tisdale and Oades, 1982). The passive pool is responsible for most of the CEC of the SOM and, in addition to exchangeable cations, contains nutrients that are tightly locked into complex organic–mineral assemblages (Stevenson, 1986). Intermediate pools of SOM are also involved in nutrient cycling along the continuum from active to passive SOM fractions. Jenkinson (1977) developed a model that described three SOM pools with different turnover times to describe C and N dynamics. Paustian et al. (1992) distinguished two litter and three SOM pools to describe SOM dynamics and nutrient cycling. The chemical extraction of SOM of classic humic fractions can also describe the fate of recently added N to soil. Bird et al. (2002) showed the importance of soil humic fractions, ranging from labile light fraction to resistant humin, in controlling the availability of recently added N fertilizer. The physical size separation of SOM-associated soil fractions has also shown promise in predicting available soil nutrients. Other approaches to determine the contribution of SOM to nutrient cycling include measuring the amounts of soil mineralizable C and N, microbial biomass, and enzymes (Gregorich et al., 1994). Despite extensive research by chemical, physical, biological and conceptual techniques, the accurate quantification of potentially available nutrients in SOM remains a challenge (Magid et al., 1996).

PROCESSES AFFECTING NUTRIENT AVAILABILITY IN SOM

The availability of essentially all major nutrients is influenced by the presence of SOM (Magdoff and van Es, 2000). SOM supplies the available nutrient pool via mineralization and desorption and binds nutrients via immobilization and adsorption reactions (Figure 9.1). The fate of nutrients in the SOM is dependent on processes affecting organic matter decomposition and formation. The decomposition process is controlled predominantly by bacteria and fungi (Scow, 1997). Fauna that graze on microbes such as protozoa, nematodes, and earthworms also play a major role in nutrient cycling and are involved in the mineralization of nutrients previously thought to be attributed entirely to the microbial biomass (Clarholm, 1985; Coleman et al., 1984; Ruz-Jerez et al., 1992; Coleman and Crossley, 1997). Management strategies that target SOM accumulation for sustained nutrient availability must therefore provide a favorable environment to soil fauna and microflora because of their dominating role in mineralization–immobilization processes.

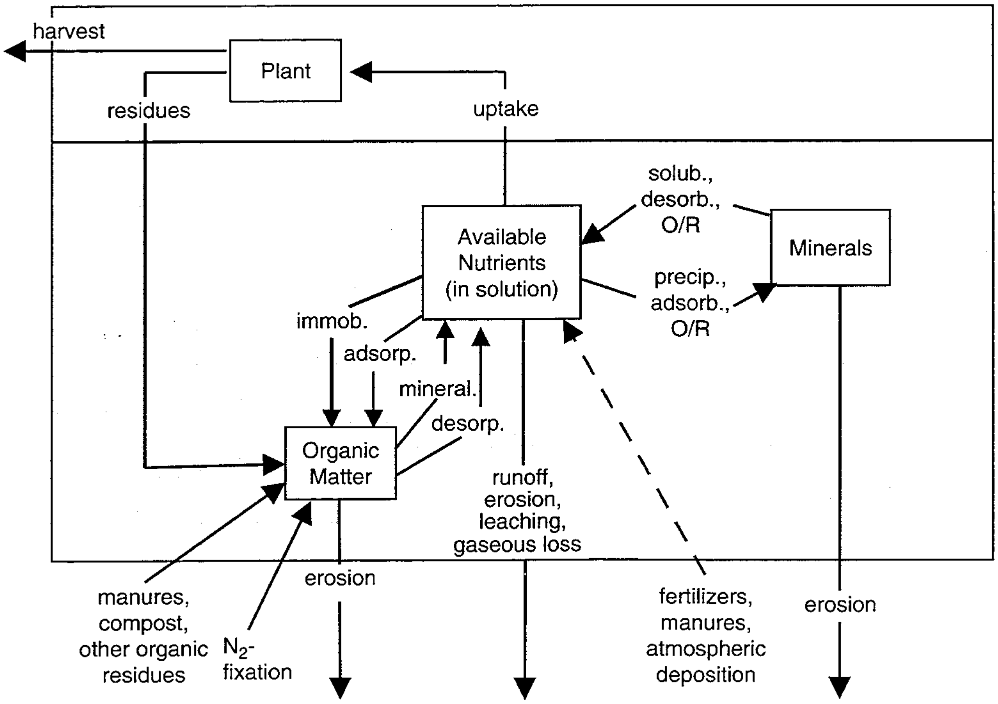


FIGURE 9.1 Simplified nutrient flows and transformations in the soil-plant system. (Adapted from Magdoff, F. et al. 1997. *Adv. Agron.* 60:2–68. With permission.)

An often-cited goal of sustainable agroecosystem management is to accumulate and maintain SOM (Magdoff and van Es, 2000). The challenges in determining nutrient availability in cropping systems that are managed to accumulate SOM include assessing (1) the interaction of added nutrients (via organic residues and synthetic fertilizers) with soil organic nutrient pools and (2) the changes in SOM turnover dynamics due to management practices that slow the depletion of SOM (such as reduced tillage). Initially, in a low SOM situation the supply of plant-available nutrients is restricted because of inadequate active organic matter, specifically the particulate organic matter (POM) fraction and microbial biomass. As plant residues are added and SOM formation proceeds, soil microbial and fauna pools as well as POM increase (Hassink et al., 1994; Paul and Clark, 1996). These components of the active SOM are key to promoting nutrient mineralization in agroecosystems. Microbial and faunal biomass mediate the N mineralization, whereas POM contains much of the partially decomposed plant material that fuels mineralization (Hassink, 1995; Wilson et al., 2001).

In general, it is assumed that 1.5 to 3.5% of the SOM-N is mineralized annually in temperate climate agroecosystems (Brady and Weil, 1999). The actual rate at which nutrients are made available is highly variable and depends on a complex set of interacting factors, including vegetation type, SOM level, pH, soil texture, soil moisture, soil aeration, soil temperature, and management practices such as tillage and fertility amendments. Vegetation type and associated quality of residue inputs directly affect the availability of nutrients by influencing microbial C and nutrient use efficiency. Lower-quality plant residue having high C:N ratios, lignin, and polyphenol content can lead to immobilization or slow release of nutrients (Horwath et al., 2002). By contrast, very high-quality residues containing a low C:N ratio (and low lignin and polyphenols) can cause mineralization of nutrients far more than crop needs.

The quantity of N mineralized is not directly proportional to SOM. Magdoff (1991) showed that SOM level and soil texture interact to influence availability of N. At low soil N levels (and low SOM) in coarse-textured soils, mineralization rates are high but the low amounts of organic N mean that little N is made available. In fine-textured soils with high soil N (and high SOM), mineralization rates are low (probably because of stabilization of SOM in organomineral complexes), which also results in a relatively low N availability. SOM quantity and quality also affect the availability of nutrients other than N. Olk and Cassman (1995) found that SOM fractions rich in labile N could decrease K fixation by clay minerals in soils with high K-fixation potential. SOM can also increase P availability through mineralization of organic P sources as well as by reducing the adsorption onto Al and Fe oxides in tropical soils (Lopez-Hernandez, 1986).

Management practices that accumulate or maintain SOM usually also tend to have a high capacity to supply nutrients. Wilson et al. (2001) found that N mineralization potential (defined as the intrinsic ability of the soil to supply inorganic N through mineralization over time) (1) was higher in untilled perennial systems than in tilled annual systems, (2) increased with the addition of compost, and (3) was higher in rotation systems, including wheat and legume cover crops, than in corn–soybean rotations without cover crops. Management practices also affect how nutrient availability is synchronized with plant nutrient demand, which is important to reduce losses of soluble nutrients and increase nutrient use efficiency. Cover crops, for example, can buffer asynchrony by gradually releasing previously immobilized nutrients during time of peak demand. However, SOM and crop-residue mineralization might not supply sufficient nutrients during the peak demand times. Other management strategies can facilitate synchronization of nutrients from SOM. Hendrix et al. (1992) suggested cultivation to stimulate mineralization during plant growth, residue return to immobilize excess or residual inorganic nutrients, and continued organic inputs to replace nutrients removed from harvest.

Managing for SOM accumulation often produces improvements in soil quality, which can influence nutrient availability indirectly. Higher SOM levels generally increase porosity, which in turn promotes better root growth and distribution. This can lead to increased interception of nutrients and facilitate water-mediated nutrient movement to the roots. Nutrient availability is also influenced by the presence of chelating substances in the SOM. Chelators are substances of low molecular weight produced by soil microorganisms and present in SOM and organic amendments such as compost (Chen et al., 1998). Humic materials can also be important metal chelators in soils (Chapter 4). Chelating substances react with trace elements such as iron, zinc, copper, and manganese, forming bonds that protect these ions from precipitation reactions. In the absence of chelation, these nutrients would become insoluble and unavailable to plants at pH values commonly found in agricultural soils (Hodges, 1991).

The presence of growth-stimulating substances in the SOM can also contribute to enhanced nutrient capture and accumulation (Wiersum, 1974). These substances are biologically active metabolites of microbes produced during decomposition and formation of SOM, which stimulate plant root growth (Frankenberger and Arshad, 1995). Applications of humic material, such as humin, humate, and fulvic acids, have increased root growth and water uptake in agricultural crops (Russo and Berlyn, 1990) as well as sap flow in tree seedlings (Kelting et al., 1998a). Additions of these materials appear most effective in soils with low levels of humic substances (Mylonas and McCants, 1980), indicating that crops probably benefit from the higher levels of these substances present in soils well supplied with SOM (Kelting et al., 1998b). However, much of the effect of humic substances on plants can be their role as metal-chelating agents (Chapter 4).

CROP MANAGEMENT STRATEGIES

Cover Crops

Cover crops are an important tool for integrated nutrient and SOM management. Cover crops can sustain nutrient cycling by adding N through fixation, retaining nutrients through SOM formation and nutrient uptake, and preventing nutrient leaching and runoff and erosion losses. One of the most important aspects of cover crops is the uptake of residual soil nutrients, which can significantly reduce nutrient movement off-site. Winter cover crops can significantly reduce soil nitrate in the soil profile (Figure 9.2). Cover crop management for nutrient retention and SOM accrual can be effective in a wide range of agricultural systems ranging from conventional to organic.

Vigorously growing legume cover crops can fix up to 300 kg ha^{-1} of N, but 60 to 150 kg ha^{-1} is the common range in temperate climate cropping systems, depending on cover crop species, plant density, and crop growth (Sarrantonio, 1994). Cover crops also contain significant amounts of phosphorous, potassium, and other nutrients. The need for externally supplied nutrient inputs can be reduced because nutrients in cover crop tissues become mineralized during decomposition and are potentially available to subsequent crops. Only a portion of the residue nutrients will be mineralized during the cropping season after killing of the cover crop. First-year legume N recovery rates range from 10 to more than 50% (Ladd et al., 1983; Hesterman et al., 1987; Bremer and van Kessel, 1992; Chung et al., 2000). Nutrient recovery from cover crop decomposition varies with differences in environmental factors (e.g., climate, soil conditions), type of management (e.g., shredding, mixing, soil incorporation), and tissue quality characteristics (e.g., content of C, N, cellulose, lignin, polyphenols).

For most cover crop species, the tissue C:N ratio increases with maturity. Therefore, the later a cover crop is killed, the less readily its N is mineralized. Herbaceous or vegetative-stage cover crops can rapidly decompose, providing N without increasing SOM (Kuo and Sainju, 1998). Under certain conditions, incorporating high-N cover crops can even result in a priming effect whereby the input of easily decomposable organic N can increase soil microbial activity, causing increased levels of SOM decomposition and associated nutrient release (Lovell and Hatch, 1998). In contrast, cover crops resistant to decomposition, such as mature small grains with high C:N ratios in the vegetative tissue, can increase SOM but provide only a small amount of readily available nutrients. Early studies reported that cover crops increased soil C in proportion to the quantity of C added (Pinck et al., 1948). However, the effects of cover cropping

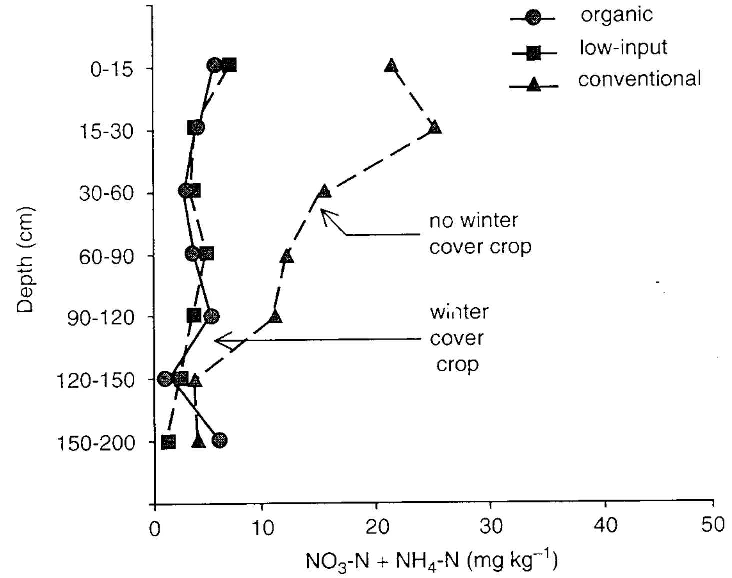


FIGURE 9.2 Soil mineral N in the spring following tomato in the previous year at the Sustainable Agricultural Farming System Project at the University of California, Davis. A mixture of leguminous and grass cover crops was used in the organic and low-input agricultural systems. The conventional system was fallow during the winter. All systems received similar amounts of fertilizer as organic or inorganic sources. (From Poudel, D. D. et al. 2001. *Agric. Syst.* 68:253–268. With permission.)

on SOM levels vary widely. Ndiaye et al. (2000) found no consistent effect on total soil C when comparing a range of winter cover crops to winter fallow in rotation with summer vegetables for up to 7 years. When used at the same input rate of dry matter, cover crops usually increase SOM levels to a lesser degree than do animal manures or other more recalcitrant organic amendments such as peat (Gerzabek et al., 2001).

Various cover crop strategies have been developed to make nutrients readily available and at the same time build SOM. Drinkwater et al. (1998) showed that using high-N cover crops in combination with a diverse crop rotation can significantly increase soil C while meeting crop N needs. Another cover crop strategy involves growing mixtures of small grains and legumes, providing for a range of potential residue qualities in a single input (Kuo and Sainju, 1998). After incorporating the plant mixture, legume residues decompose quickly and provide nutrients whereas small grain residues (depending on the stage of development) decompose more slowly and contribute more to organic matter build-up. Incorporating cover crop residues with a range of residue C:N ratios can lead to the timely mineralization of available soil N for crop uptake. Collaa et al. (2000) showed that winter legume/grass cover crop mixtures maintained cash crop yields equivalent to those by using synthetic fertilizer (Table 9.1).

The concept of mixing residues with varying C:N ratios can be applied to a variety of organic amendments and cropping systems. For example, a mixture of slow and fast decomposing materials is used in alley cropping. In this system, crops are grown between rows of woody shrubs, which are cut periodically. Shredded prunings from the shrubs are then incorporated into the soil to serve as a green manure for the crops grown in the alleys (Kang et al., 1990). Decomposing leaves and small twigs provide readily available nutrients and decomposing pieces from woody branches provide slow-release nutrients and the raw material for organic matter build-up. Alternatively, use of cover crops in combination with manure applications can have similar effects (Poudel et al., 2001).

TABLE 9.1
Two-Year Average Yield of Tomato in Conventional (Inorganic Fertilizer Only), Low-Input (One Half Conventional Fertilizer Rate Plus Winter Leguminous/Grass Cover Crop), and Organic (Manure and Winter Leguminous/Grass Cover Crop) Cropping Systems after 9 Years of Management

Nutrient Input	Marketable Yield (t ha^{-1})	Unmarketable Yield (t ha^{-1})	Total Yield (t ha^{-1})
Full-rate inorganic fertilizer	72.2	19.7	91.9
Half-rate inorganic fertilizer + winter leguminous/grass cover crop	72.6	25.4	98.0
Manure + winter leguminous/grass cover crop	69.0	26.9	95.9
	N.S.[a]	N.S.[a]	N.S.[a]

Note: All systems received similar amounts of N.

[a] Not significantly different. Determined by Duncan's multiple range test at the 0.05 probability level.

Source: Adapted from Collaa, G. et al. 2000. *Agron. J.* 92:924–932. With permission.

CROP ROTATIONS

Carefully planned rotations can maintain or enlarge the active SOM pool to provide a steady supply of available nutrients for each crop in the sequence. Integration of perennial and high-residue crops into a crop rotation is a particularly important rotation strategy. Integrating crops with a diversity of life strategies (e.g., perennials vs. annuals), growth habit, and nutrient strategies ensures that over time residue materials of varying decomposition rates enter the soil to supply nutrients while maintaining SOM.

Including Perennial Crops

Including perennial forage grasses or perennial legumes in a crop rotation that is otherwise composed of annual crops is an invaluable tool to increase SOM and nutrient supply for subsequent crops. During a long-term experiment in Germany, soil C content rose by 10% in plots with continuous grassland whereas soil C under continuous potato monocrop (fertilized with synthetic fertilizer) decreased by 50% over the course of 32 years (Haider et al., 1991). Tillage intensity and frequency are often found to be primary factors in determining C loss or accumulation (Wood et al., 1990). Weil et al. (1993) compared cropping systems of various management intensities and found SOM levels significantly higher in a grass system that was only mowed than in various annual cropping systems that included tillage (Table 9.2).

Active SOM fractions that provide potentially plant-available nutrients are markedly increased under perennial forages (Drury et al., 1991; Angers et al., 1993). The continuous contribution by the roots (rhizodeposition) is a major factor that promotes higher levels of these active SOM sources. Rhizodeposition in the form of fine root turnover and root excretion of organic compounds can account for more than 30% of the net primary production of perennial forages (Johansson, 1992; Beauchamp and Voroney, 1994). In cropping systems containing perennial legumes, decomposing nodules and excretion of organic compounds provide N-rich substrates for the soil microflora (Burity et al., 1989; Dubach and Russelle, 1994) and contribute significant quantities of available nutrients to succeeding crops. Weil et al. (1993) observed approximately twice as much metabolic activity in soil under grass compared with continuous tilled corn, indicating the value of including crops in rotation that contribute to the active SOM fractions.

TABLE 9.2
Total Organic C and Extractable C in the 0- to 15-cm Soil Layer of Five Cropping Systems Established in 1985 as Determined by Wet Digestion in 1991

Cropping System	Total Organic C (g kg^{-1})	Extractable C[a] (g kg^{-1})
Continuous grass	20.0	0.51
Rotation of annual crops: no-till + chemicals	11.0	0.32
Rotation of annual crops: minimum till + reduced chemicals	8.3	0.29
Rotation of annual crops: reduced till, organic	9.6	0.23
Continuous corn: conventional till	7.9	0.12
	4.8 ($LSD_{0.05}$)	0.15 ($LSD_{0.05}$)

[a] 0.5 *M* $NaHCO_3$ extract.

Source: Adapted from Weil, R. R. et al. 1993. *Am. J. Altern. Agric.* 8:5–14.

In addition to increasing active SOM pools, perennial crops can also reduce the loss of total SOM. The permanent cover provided by perennial crops can protect the soil from water and wind erosion, which can carry away SOM-rich soil fractions (Tisdale and Oades, 1982). Furthermore, nutrient uptake and subsequent conversion into plant biomass in perennial crops occur over a longer time period in the cropping season compared with annual crops. The prolonged growth habit of perennials ensures scavenging of residual soil nutrients. Integrating perennials into a crop rotation thereby conserves nutrients in the soil ecosystem and is a positive step toward creating sustainable nutrient cycling from active SOM fractions.

Including High-Residue Crops

In many agricultural systems worldwide, the decline in long-term soil fertility is often a direct consequence of partial or complete removal of aboveground biomass as food, feed, bedding, fuel, or building materials. Loss of near-surface nutrient-rich soil and active SOM fractions exacerbates this problem. Growing crops that return a large amount of residue to the soil is an important strategy to replace nutrient outputs, replenish SOM pools, and reduce the need for other inputs such as fertilizers, cover crops, or organic amendments. When corn (*Zea mays*) is harvested for silage, with the exception of short stubble, virtually all aboveground biomass is removed. At a yield of 45 Mg ha^{-1} of 30% dry matter silage, the average nutrient removal amounts to 202 kg of N, 49 kg of P, and 205 kg of K (Jokela et al., 2000). Supplemental nutrients are needed to replenish the nutrient pool. Reliance on mineralization, desorption, and mineral dissolution for the supply of nutrients to succeeding crops when no organic amendments or cover crops are used leads to a long-term decline in nutrient reserves (Magdoff, 1991).

One of the most important factors determining the level of SOM is the size of the C inputs to the soil (Rasmussen and Collins, 1991; Park, 2001). Residue removal or prolonged fallow periods without considerable substrate additions via weeds or soil amendments can have a dramatic negative effect. Gerzabek et al. (2001) measured a 30% loss of the organic C from the topsoil layer over the course of 44 years in fallow plots of a long-term experiment in Sweden. Available nutrients are quickly depleted without continuous biomass input, because active SOM components are mineralized early in the decomposition process (Elliott and Papendick, 1986). Microbial activity decreases once labile components are depleted, which further limits the SOM to supply nutrients for plant growth. Conversely, nutrient turnover can quickly be restored when residues are added to soil.

Alvarez and Alvarez (2000) observed that the active microbial biomass highly correlated to the amount of plant residue during the first year after the introduction of different cropping systems. These studies indicate that a lack of C inputs reduces the active SOM fraction. At the same time, active SOM responds readily to C additions and the degree to which nutrient availability is restored depends also on the quality of the organic matter addition.

Hendrix et al. (1990) described hypothetical patterns of litter decomposition, nutrient availability, and plant nutrient uptake for four litter input scenarios to illustrate how residue quality influences the degree to which nutrient availability is synchronized with crop demand (Figure 9.3). High-quality residue (high N, low lignin, low polyphenol concentrations) can decompose quickly but not increase SOM even at a high dry matter input (Bruce et al., 1990). Conversely, returning large amounts of low-quality biomass can increase SOM and immobilize nutrients. For example, Powel and Hons (1991) investigated the effects of stover removal on SOM and extractable nutrients in a continuous sorghum cropping system. They found that when low-quality stover was returned to the soil over a 4-year period, sorghum yield and P uptake were lower, whereas complete stover removal resulted in decreased SOM levels but a net release of nutrients.

Residue return and tillage systems are interrelated in their effect on SOM. In cropping systems with a low residue return, such as silage corn, the type of tillage practice or its intensity might not affect total soil C significantly (Angers et al., 1993). On the other hand, intensive tillage can reduce or even negate the generally positive effect of high biomass additions on SOM levels by increasing SOM mineralization (Reicosky et al., 2002).

Including a Diversity of Crops

At least since the 18th century, crops were classified as either soil enriching or soil depleting (Deane, 1790). This knowledge has led to the practice of alternating crops that differ in their effects on soil fertility. Although some of the specific beliefs from that era had to be adjusted (e.g., the belief that all root crops are soil enriching), the basic rotation principle is still valid and used at present. Several recent studies have found that diverse crop rotation can achieve both an increase in SOM and provide sufficient amounts of available nutrients. Topsoil organic C increased by 6.6 Mg ha^{-1} over a 15-year period when legume cover crops were the sole supply of N for grain crops in a long-term study at the Rodale Institute in Pennsylvania (Drinkwater et al., 1998). Soil N levels paralleled the SOM increase. The authors attributed these results to the diversity of the cropping sequence and the associated qualitative differences in organic residues returned to the soil. Differences in tillage intensity might also have played a role in changes in SOM. Franco-Viscaino (1996) compared a wide range of high- and low-diversity cropping systems and showed that increased diversity of residues was associated with improved soil tilth, nutritional status (higher total N but not extractable N), and biological activity. Improvements were associated not with a single management practice but rather with diversity and frequency of residue sources coming from crop rotation, cover crops, or manure applications. The exact mechanism of how the diversity of residue inputs enhances SOM and nutrient levels is not well understood but probably relates to components of the active SOM and microbial processes. Diversity of inputs most likely leads to a complex microbial community structure (Neher, 1999; Chapter 7), which leads to a broad functional diversity, resulting in a greater substrate utilization efficiency and stress resistance (Kennedy, 1995).

A study by Sanchez et al. (2001) supports the link between substrate diversity and potentially available nutrients. Net N mineralization measured *in situ* at 70 d in a diverse cropping system was 70% higher compared to a corn monocrop system. Net N mineralization in the diverse system was enhanced by the incorporation of residues from legumes, grasses, and composted manure. However, they pointed out that the two systems did not differ in their ability to mineralize added substrate. There was no significant difference between both systems in the percentage of N mineralized from added legume residues or compost. Jenkinson (1977) also observed that the rate of mineralization of plant residues was independent of the rate of addition. These studies suggest that input history

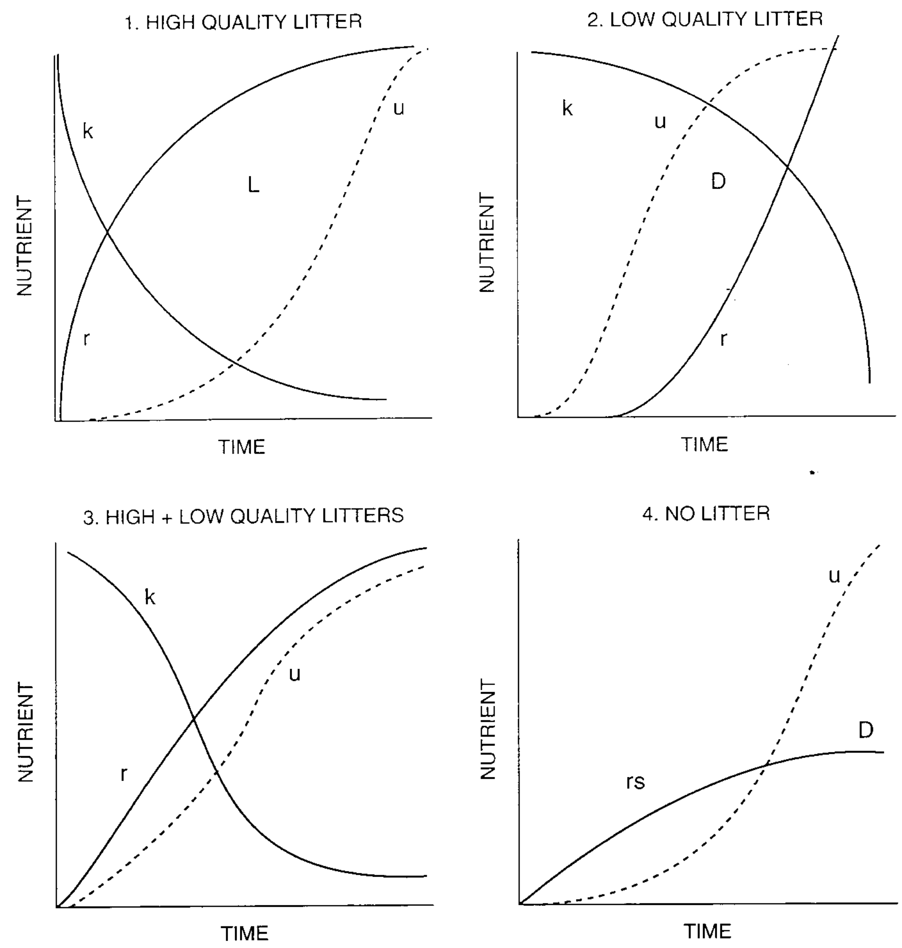


FIGURE 9.3 Hypothesized pattern of decomposition (k), soil nutrient availability (r), and plant uptake of nutrients (u) in systems subject to inputs of various qualities; (rs) is release of nutrients from soil. Area L represents potential of nutrient loss by leaching; area D represents potential nutrient deficit (Swift, 1987). High-quality litter (Panel 1) decomposes quickly, releasing nutrients out of phase with plant uptake, resulting in high potential for loss. Low-quality residue (Panel 2) decomposes too slowly to provide nutrients for plant uptake and might stimulate microbial immobilization, resulting in a deficit for plants. Panel 3 represents ideal situation in which nutrient release is synchronized with plant demand. Nutrient release from soil organic and mineral pools (Panel 4) might also be synchronized with initial stages of plant growth but might not meet plant demand in many soils. (From Hendrix, P. F. et al. 1990. In Edwards, C. A., Lal, R., Madden, P., Miller, R. H., and House, G. (Eds.), *Sustainable Agricultural Systems*. Soil and Water Conservation Society, Ankeny, IA, 637–654. With permission.)

is of little importance in a cropping system's ability to mineralize nutrients and is more likely a result of the microbial biomass reacting to the input of easily decomposable compounds through the increase of its size and activity (Paul and Clark, 1996).

Alternating crop types with different growth habits also promotes the protection of SOM and nutrient availability. Rotating between deep- and shallow-rooted crops provides the obvious benefit of nutrient extraction from different soil layers. Including deep-rooted crops in the rotation also introduces new organic material into deeper soil layers by rhizodeposition. Park (2001) notes that continually growing shallow-rooting crops can lead to a gradual loss of organic material in deeper soil layers, the consequence of which could be a sharp decline in soil quality in that layer.

TILLAGE

Tillage plays an important role in the management of soil nutrients through its influence on SOM dynamics. Tillage incorporates plant residues or living plants into the soil. The mixing action enhances aeration and the contact between soil and plant debris, resulting in favorable conditions for rapid mineralization of C and other organically bound nutrients (Parr and Papendick, 1978). In addition, the breaking apart of macroaggregates by tillage increases the availability of occluded SOM to soil organisms. Type, frequency, and intensity of tillage determine the degree to which mineralization processes occur. Higher intensity and frequency of tillage generally result in lower SOM (Blaesdent et al., 1990; Carter, 1992), nutrient retention, and nutrient cycling capacity (House et al., 1984). Gallaher and Ferrer (1987) showed that untilled soil contained 20 and 43% more Kjeldahl N than conventionally tilled soil in the 0- to 5-cm soil depth after 3 and 6 years, respectively. Staley et al. (1988) observed higher organic P levels in the top 0- to 15-cm soil depth at lower tillage intensity. Absence of tillage tends to increase N mineralization capacity (Weil et al., 1993). For example, Doran (1987) found potentially mineralizable N to be 37% higher in the surface layer of no-till soil compared with tilled soil.

Most changes in SOM fractions due to reduced tillage occur in the upper few centimeters of the soil (Chapter 8). Reduced-tillage systems tend to accumulate plant residues, fine roots, and microbial and microfaunal debris (Gregorich et al., 1994; Alvarez et al., 1998), thereby increasing the rapidly mineralized pool of organic matter. Intensive tillage, on the other hand, reduces labile SOM. Angers et al. (1993) found similar total soil C in reduced tillage and moldboard plowing treatments, but microbial biomass and labile sand-sized OM fractions (accounting for 1 to 20% of total soil C) were significantly larger under reduced tillage. Microbial biomass in their study accounted for 1.2–1.4% of the organic C in the moldboard plow treatment and 3.5–5.1% in the minimum-tillage treatment. Higher microbial biomass can result in higher immobilization of added fertilizer N in the 0- to 5-cm soil depth of no-till compared to conventional-till systems (Carter and Rennie, 1984).

The labile POM fraction is affected disproportionately by tillage and often adversely impacts C and N mineralization (Hassink, 1995; Hussain et al., 1999). POM is lost as tillage disrupts macroaggregates that provide physical protection from decomposing organisms (Elliott and Papendick, 1986). Conversely, no-till practices often increase the amount of organic C and N in POM (Wander and Bidart, 2000). Fine SOM fractions are less vulnerable to tillage disruption due to closer binding to soil minerals in the form of mineral–organic complexes. Over time, intensive tillage increases the percentage of the SOM associated with minerals as more free organic plant debris is lost (Tiessen et al., 1994). The reduced quantity of POM and fresh plant residues decreases the ability of the soil to supply available nutrients to agricultural crops because these SOM fractions are the main sources of mineralizable N in many soils (Wilson et al., 2001).

Contributing to the reduced mineralization potential in intensively tilled systems is the negative effect of tillage on the number of macro- and mesofauna, such as earthworms and arthropod species (Hendrix et al., 1986; Parmelee et al., 1990). Soil fauna contribute to soil C and N mineralization directly through their own C and N mineralization and indirectly through grazing on microbes and passing plant residues and soil through their digestive tracts. (Hassink et al., 1994; Coleman and Crossley, 1997). Without the grazing activities less N in the microbial biomass is mineralized and unavailable for plant uptake. Beare et al. (1992), for example, found a 25% higher N retention in plots in which fungivorous microarthropods were excluded from no-till surface litter compared with plots with microarthropods. The effects of soil fauna on nutrient availability are generally positive; however, there have been limited studies to assess their impact across a range of soil management practices.

The type of tillage system and the implements used determine how plant debris is distributed in the soil. Associated with the distribution of plant debris are SOM and nutrient levels. Plowing followed by harrowing, for example, distributes nutrients throughout the tillage depth (Hussain et al., 1999), whereas reduced-tillage systems tend to accumulate nutrients and decomposable organic matter in the soil surface (House et al., 1984; Karlen et al., 1994). Microbial activity levels mirror the organic matter distribution (Kandeler et al., 1999). Compared with plowed soil, higher microbial activity is consistently found in the surface layer of reduced-tillage soil, whereas less microbial activity is observed in deeper layers (Granastein et al., 1987; Angers et al., 1993; Friedel et al., 1996). Higher microbial biomass in no-till systems is observed usually only in the 0- to 7.5-cm layer, whereas biomass in the 7.5- to 15-cm layer is often more in the conventionally tilled soil (Staley et al., 1988). The stratification of fresh plant residue and decomposed organic matter under different tillage systems also affects the microbial community structure, leading to changes in soil C and N dynamics (Bossio et al., 1998; Chapter 10). Reduction in tillage intensity and retention of residues on the soil surface tend to favor fungi over bacteria. The higher C assimilation efficiency and slower turnover of fungi tend to promote slower nutrient cycling (Holland and Coleman, 1987; Hendrix et al., 1990; Beare et al., 1992).

Tillage-induced changes in SOM levels can directly affect nutrient storage and availability. For example, when intensive tillage lowers SOM levels, the CEC is also reduced. Various studies that compared different tillage systems have tracked CEC. Long-term plowing and harrowing on a clay soil caused a decline in SOM from 5.2 to 4.3% and a concurrent decline of CEC from 17.8 to 15.8 cmol kg^{-1} (Magdoff and Amadon, 1980). Mahboubi et al. (1993) also found that after 28 years there was lower CEC with higher tillage intensity. Karlen et al. (1994), on the other hand, found no effect over 12 years. The mixed findings are likely a result of interacting environmental and management factors and the extended period of time, often 10 to 20 years, required to observe measurable changes in SOM. Hussain et al. (1999) noted that individual nutrients could be affected differently by various tillage systems because of tillage-induced changes in the soil matrix. In their study Ca, Mg, and Bray P-1 increased in surface soil of no-till plots compared with plowed soil, whereas increased leaching under no-till lowered exchangeable K levels.

NUTRIENT APPLICATIONS

INORGANIC FERTILIZER

Inorganic fertilizer applications affect SOM and nutrient management in many ways. First, as a nutrient source, inorganic fertilizers promote the production of plant biomass and therefore affect the potential amounts of crop residue that can be returned to the soil (Allison, 1973). Second, inorganic fertilizer nutrients such as P and N can become integrated into the soil matrix either directly into organic compounds of labile SOM fractions or as part of mineral–organic complexes (Polglase et al., 1992). Integration into the organic matter pools can be rapid. Balabane and Balesdent (1992), for example, recovered 26% of the ^{15}N-labeled ammonium nitrate fertilizer in SOM 6 months after application. The microbial biomass is often a large part of the initial build-up of added N, which is then followed by their turnover into more stable fractions such as organomineral phases (Paul and Clark, 1996).

Inorganic fertilizer applications also affect decomposition rate of fresh residues and the integration of residues into the SOM (Parr and Papendick, 1978). Inorganic N in particular can drastically affect the microbially mediated breakdown of fresh plant residues because microbial activity is often limited by N (Jenkinson et al., 1985). To reduce the immobilization of N already present in the soil or to speed up the microbial decay process, farmers often use inorganic N applications when large quantities of organic materials with a high C:N ratio are incorporated into the soil. The amount and timing of the N application to achieve these goals depend on the organic material being decomposed and climate conditions that would promote decomposition.

Different views exist on the effect of inorganic N applications on the SOM levels. N fertilizer applications generally result in a decline of organic matter because the readily available N leads to rapid microbial decay of SOM in some soils. Green et al. (1995), for example, observed decreased

SOM in studies in which excessive amounts of nitrate fertilizer were added annually for multiple years. Based on laboratory incubation studies, another view on the effect of N fertilizer holds that there is only a short-term stimulation of the organic matter decay process but long-term SOM levels are not affected (Allison, 1973). Glendining and Powlson (1991) compared multiple long-term field studies and found that continuous inorganic N fertilization increases both the amounts of total soil N and readily mineralizable N. Increase in the proportion of mineralizable N over time indicated that the additional organic N returned to the soil as a result of using fertilizer N (i.e., via higher plant biomass or incorporation by the microbial biomass) is in a fraction that turns over more rapidly than the N in older organic matter.

Inorganic fertilizers generally enhance C inputs through increased biomass production, but excessive inorganic fertilizer applications can have negative effects on active SOM and soil N pools, such as microbial biomass (McCarty and Meisinger, 1997). Microbial biomass is usually lower in soils with long-term inorganic N applications than soils that have received organic amendments (Collins et al., 1992). Fauci and Dick (1994a) analyzed soils from a long-term study and found that of the crops that received additional N, microbial C and microbial N were lowest in plots with a 59-year history of inorganic N fertilizer, intermediate in plots fertilized with pea vine residues, and highest in manure plots. The differences were closely related to the quantity and quality (C:N ratios) of C substrate added.

ANIMAL MANURE

The application of animal manure is an important tool for an integrated nutrient management strategy because applications can simultaneously increase SOM levels and supply nutrients for crop growth. The mix of feces, urine, and bedding material present in many types of animal manure generally provides a combination of recalcitrant and labile organic materials. For example, annual application of 34 Mg ha^{-1} of fresh dairy manure provided all necessary nutrients to crops and tripled SOM levels over the course of 120 years at the Rothamstead experiments (Jenkinson, 1991). The rate of SOM accumulation is usually highest in the first 10 years of manure application and slows thereafter (Sommerfeldt et al., 1988). Increases are generally lower when initial SOM levels are already high. Magdoff and Amadon (1980) showed that yearly applications of 66 Mg ha^{-1} of fresh dairy manure were needed to increase SOM from 5.2 to 5.5% over the course of 11 years on a land on which continuous silage corn was produced by using conventional tillage (Table 9.3). Yearly applications of 44 Mg ha^{-1} were needed to maintain SOM at the original level.

TABLE 9.3
Effect of 11 Years of Solid Dairy Manure Additions on Properties of a Panton Clay Soil (Typic Ochraqualf) in Vermont

		Yearly Application Rate (Mg ha^{-1} Wet Weight)			
	Original	**None**	**22**	**44**	**66**
Organic matter (%)	5.2	4.3	4.8	5.2	5.5
CEC (me 100g^{-1})	17.8	15.8	17.0	17.8	18.9
pH	6.4	6.0	6.2	6.3	6.4
P[a] (mg kg^{-1})	4	6.0	7.0	14.0	17.0
K[a] (mg kg^{-1})	129	121.0	159.0	191.0	232.0
Total pore space (%)	N.A.[b]	44.0	45.0	47.0	50.0

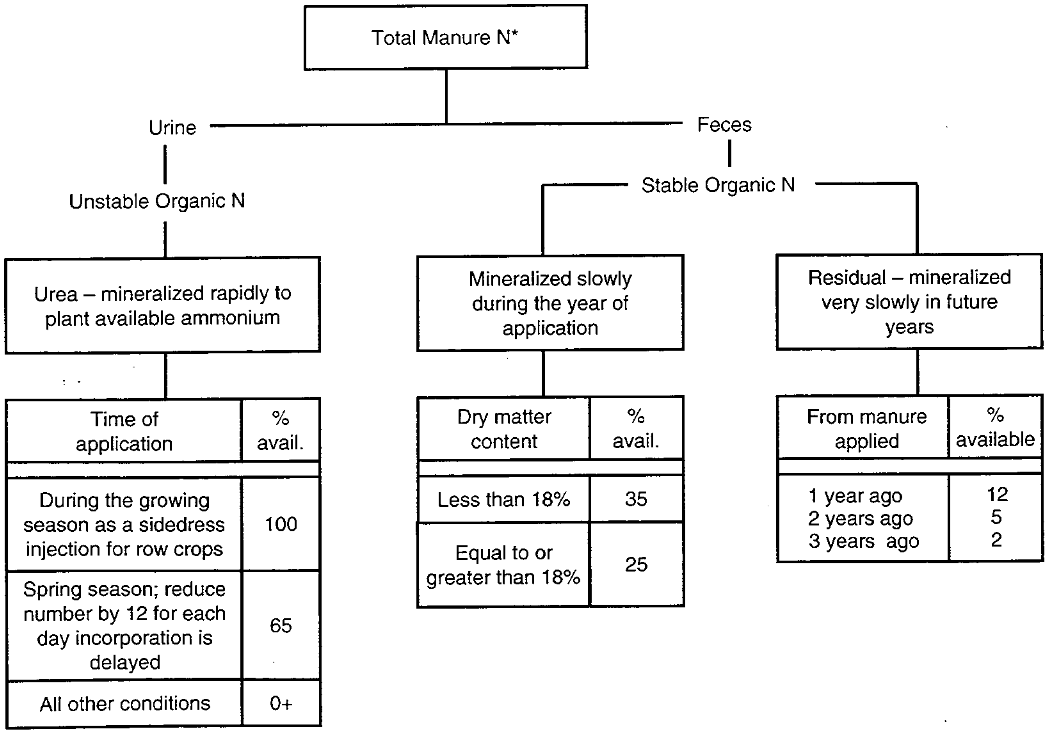
[a] Determined by modified Morgan extraction.

[b] Not available.

Source: From Magdoff, F., and van Es, H. 2000. *Building Soils for Better Crops*. USDA Sustainable Agriculture Network (www.sare.org), Beltsville, MD. With permission.

After manure is applied to the soil, organic nutrients become either part of the vegetation or the SOM, or they are lost from the field. For N, losses occur via runoff, erosion, volatilization, and denitrification. Of the N that becomes part of the SOM, some fractions are mineralized rapidly and available for plant uptake in a short time whereas other fractions are mineralized more slowly. The rate of manure N mineralization has been reported to range from 13 to 86% (Chae and Tabatabai, 1986). This rate is affected by a multitude of factors, including manure composition (manure N concentration, C:N ratio, stability of C and N), animal type, environmental factors (soil temperature, soil moisture, aeration), soil texture, and various factors that affect microbial activity (pH, soluble salt content, toxic chemicals, heavy metals).

Animal and manure management have a strong influence on whether manure nutrients are integrated into the stable SOM or the labile SOM pools. For example, the type and quantity of bedding can significantly alter the C:N ratio and thus the balance between immobilization and mineralization. Magdoff and van Es (2000) noted that dairy and beef manures that contain a high amount of lignified substances, such as bedding or undigested parts of forage, contribute to SOM maintenance much more than layer chicken manure, which commonly does not contain bedding material. The manure storage system in part determines manure dry matter content, which also plays a significant role in organic nutrient fluxes. In a 4-year study in California, Pratt et al. (1976) found that dry manure gave higher increases in SOM compared with liquid manure (19% vs. 4%), whereas liquid manure had larger gaseous losses (24% vs. 2%) by ammonia volatilization and denitrification. As an approximate guide for nutrient management planners, Klausner (1997) estimated availability of different forms of N in dairy manure for northeastern U.S., based on time of application, dry matter content, and residual organic manure N (Figure 9.4).



Time of application	% avail.
During the growing season as a sidedress injection for row crops	100
Spring season; reduce number by 12 for each day incorporation is delayed	65
All other conditions	0+

Dry matter content	% avail.
Less than 18%	35
Equal to or greater than 18%	25

From manure applied	% available
1 year ago	12
2 years ago	5
3 years ago	2

* *In solid dairy manure approximately 50% of total manure N is in the urine and 50% in the feces.

FIGURE 9.4 Estimated availability of different forms of N in dairy manure in northeastern U.S. (Adapted from NRAES, 1997. *Nutrient Management: Crop Production and Water Quality.* Publication 101, Northeast Regional Agricultural Engineering Service (NRAES), Ithaca, NY. With permission.)

Organic manure N not mineralized becomes integrated into the SOM and is an important residual nutrient source for future crops. Pratt et al. (1973) developed the concept of a decay series that described the amount of inorganic N that becomes available with time. Klausner et al. (1994) developed a decay series for dairy manure. They suggested that under the climate conditions of northeastern U.S., ca. 21% of the initial total N mineralizes in the first year, 9% of the N remaining after the first year mineralizes in the second year, and 3% of N remaining after the second year mineralizes in the third year. Residual organic N can supply the entire N need for crops in combination with the rapidly available N fraction from a current manure application. Klausner (1997) reported that without residual N or supplemental inorganic fertilizer, an application of 168 Mg fresh weight of solid dairy manure per hectare was required to provide sufficient available nutrients to achieve optimal corn silage yield in trials in northeastern U.S. In a separate trial, only 52 Mg fresh weight of solid dairy manure per hectare was required to achieve optimal corn grain yield when applied continuously to create large residual nutrient pools.

The gradual release of inorganic N from soil that is continuously supplied with manure is often well synchronized with the nutrient demand of long-season agronomic crops such as corn. Ma et al. (1999) compared N mineralization, N uptake, and yield in corn to which solid dairy manure was applied in the fall with corn that received NH_4NO_3 fertilizer in the spring. They found that available N in the manured system was better synchronized with plant demand than in the inorganic fertilizer system. Yield and plant N uptake were higher in the manured crops, whereas mineral N losses from the rooting zone were higher in the system that received inorganic fertilizer. In contrast, Kirchmann and Bergström (2001) noted that the nitrate-leaching potential from manures is high when organic N is mineralized in the soil and no N uptake by the crop occurs. In temperate-climate agricultural systems, this usually occurs in the spring when the cash crops have not been planted or are still very small and also occurs in the fall when the cash crop is already harvested and no cover crops were planted.

COMPOST

Compost applications can form the foundation of a successful whole-farm nutrient management strategy. Composts are a major source of nutrients in organic farming systems (Lampkin, 1990). Biodynamic and biointensive farming also rely heavily on compost applications for crop nutrient supply (Pia, 1998; Carpenter-Boggs et al., 2000). Nutrient release rates vary widely with type of raw materials, method of composting, and maturity (Sims, 1995). Nutrients in composts are usually less available than in fresh manure (Hadas et al., 1996) because of stabilization by microbial assimilation and humification during the composting process (Castellanos and Pratt, 1981). Within one growing season, Eghball (2000) measured 11 and 21% organic N mineralization from a field applied composted and noncomposted beef cattle feedlot manure, respectively. Haddas et al. (1996) found high N mineralization rates of composted cattle manure under favorable conditions. In their study up to 26% of the total N was mineralized in only 33 weeks. A flush of net N mineralization in the first week was followed by net N immobilization between 2 and 4 weeks after application. They noted that percent recovery of compost N as inorganic N was independent of soil history or rate of application, but largely reflected the properties of the compost.

Depending on the total amount of compost applied and the residual from previous applications, the supply of mineralized nutrients from a compost application, particularly N, might not be adequate to achieve optimum yield (Eriksen et al., 1999; Chung et al., 2000). Inorganic fertilizers are sometimes applied along with compost if there is concern about low N availability. This practice might result in a priming effect in which N mineralization from compost is increased. Application of organic sources of labile N, such as clover residues, in combination with compost has the same effect (Sanchez et al., 2001). It appears that the addition of labile N sources mainly stimulates mineralization of compost and less of SOM (Sikora and Yakavchenko, 1996). However, the practice can result in high nitrate leaching rates if plant nutrient uptake is not synchronized with mineralization of the added compost (Gerke et al., 1999). C and nutrient losses during the composting process are significant and need to be considered when assessing the value of compost applications to long-term soil fertility.

Depending on raw materials and composting method, 20 to 90% of the C present in the raw materials can be lost (Eghball et al., 1997; Shellinger and Breitenbeck, 1998). In a comparison of windrow composting of nine different raw materials, Shellinger and Breitenbeck (1998) observed N, P, and K losses of 0–62%, 9–70%, and 1–79%, respectively. They noted that greatest losses of these nutrients occurred in silage, bark, and cotton gin trash, all raw materials that contain large amounts of readily degraded organic substrate and low amounts of mineral matter, such as clay or other soil contaminants. Eghball et al. (1997) measured 40% loss of total N where ammonia volatilization accounted for 92% of the N loss. Compost storage can play a significant role in the extent of nutrient losses. Sommer (2001) found that compacting and covering with a porous tarpaulin reduced N leaching losses from 28% to 12–18%. The same treatments also reduced K leaching.

Nutrient and C losses during composting challenge the notion that composts are an efficient way to increase the capacity of the soil to meet long-term nutrient needs. Nevertheless, high compost applications can effectively increase SOM and nutrients. In addition, compost is less likely to act as a priming agent (Smith, 1979), whereas applying less stable materials such as fresh animal manures can lead to mineralization of SOM (Glendining et al., 1996; Ma et al., 1999). In the long term, however, the amount of organic matter applied can be more important to SOM accumulation than the type of organic amendments used (Delschen, 1999).

The increase of SOM in soil continually supplied with composts can result in improvement of soil quality indicators that facilitate nutrient availability and uptake (Roe, 1998). For example, Pinamonti (1998) showed that improved porosity and water retention as well as reduced temperature fluctuations in a vineyard supplied with compost were more important in improving nutrient uptake than increased availability of soil nutrients. Biological soil quality indicators, such as biomass C and basal respiration, also improve with compost applications (Pascual et al., 1997). Application of composts that contain high levels of heavy metals, however, can inhibit biological soil quality indicators, such as enzyme activity (Moreno et al., 1998) and microbial biomass (Moreno et al., 1999) and might impede nutrient mineralization processes.

EXCESS NUTRIENT LOADING ASSOCIATED WITH ORGANIC AMENDMENTS

The need to reduce input cost and the heightened awareness of the potential soil quality benefits have contributed to the increased popularity of manure, compost, and other organic amendments in agricultural production. At the same time, improper storage and excessive land application rates of organic amendments (especially animal manures) have contributed to some of the most serious environmental issues facing agriculture at present. These issues have led to an intense debate on the appropriate management of animal-derived nutrients, particularly in regions that have a high concentration of farm animals and limited land area to apply manure.

Throughout this chapter we have argued that adding plant and animal residues to the soil has positive effects on soil and environmental quality. There is a widely held belief that compost applications in particular are environmentally benign because nutrients are released relatively slowly. However, there is increasing evidence that animal manure and compost applications applied at rates used by some farmers can result in dramatic overloading of available nutrients in soil. Soil and tissue testing show that excessive soil nitrate concentrations during and beyond the growing season are commonplace in agricultural systems that use animal manures and compost (Maynard, 1994; Leclerc et al., 1995). Excessive P levels are frequently created by basing manure and compost application rates on the N need of the crop. The combination of low N:P ratios in many organic amendments and low crop P removal rates leave much of the applied P unused in the soil. In addition, several studies have found that manure P is more mobile than synthetic fertilizer P (Eghball et al., 1996; Parham et al., 2002), enhancing its potential for off-site movement.

Potential consequences of overloading the soil with nutrients and off-site movement include leaching of nitrate into groundwater (Sommerfeldt et al., 1988) and the accumulation of P in the soil (Gartley and Sims, 1994). This accumulation increases the chance of harmful P concentrations leaving the field through surface runoff and subsurface flow (Daniel et al., 1994). An example of the potential problems associated with organic amendments is a recent study at the Rodale Research Institute in Pennsylvania, which compared nutrient budgets and soil C levels following four composts, raw dairy manure, and mineral fertilizer applications (Reider et al., 2000). Application rates were chosen to provide similar amounts of available N to all treatments, but total nutrient inputs differed widely (Table 9.4). After 3 years, three (dairy manure leaf compost, yard clipping compost, and controlled microbial compost) of the four compost treatments created a significant increase in SOM, whereas mineral fertilizer and raw manure did not. The compost treatments created a significant nutrient surplus and at the same time elevated levels of extractable soil potassium. Extractable P and total N were less affected, suggesting that the vast surplus of these nutrients were fixed in the soil matrix or were lost from the topsoil layer through runoff, erosion, leaching, or volatilization. The researchers recommended that compost applications should be reduced and substituted with alternative nutrient sources.

The striking difference in residual nutrient content between organic additions and nonorganic fertilizers requires distinctly different management strategies. Inorganic fertilizers are usually managed on a seasonal basis, with emphasis on meeting crop demand during the growth period. On the other hand, the use of organic amendments probably means higher total nutrient application rates during the initial transition from inorganic-fertilizer-based systems. Mineralization of organic residues from the previous year's application, as well as earlier applications, add to the pool of available nutrients. Thus, if the annual application rate of an organic amendment is constant, over time the ratio of the quantity of nutrients made available by mineralization relative to total nutrient input from organic amendments will increase. For example, Suzuki et al (1990) found that when applying compost annually at a rate chosen to supply the entire N needed in the first year, the amount of N mineralized each year increased from about the equivalent of 70% of the total N applied annually after 20 years to ca. 90% after 50 years. Because of the increased availability of nutrients from residual sources, a gradual reduction of the annual input is needed to reduce nutrient overloading (Figure 9.5 and Figure 2.2). Quantification of the appropriate reduced rates over time under various soil and climate conditions has so far not received adequate attention in long-term research studies.

Integrating legume cover crops to supply N as part of the fertility management regime will also reduce the potential of nutrient overloading and reduce possible problems with excess salt build-up. Another strategy involves a combination of organic wastes and inorganic fertilizers to take full advantage of all the potential nutrient sources and reduce losses to the environment. Fauci and Dick (1994b) found that, under greenhouse conditions, a decreasing rate of synthetic fertilizer over the course of several cropping cycles in combination with poultry manure or pea vine residues was an effective means of maintaining crop productivity during the transition from inorganic to organic fertility sources. Gerke et al. (1999) used a combination of kitchen and garden waste compost at a rate of 10 Mg ha^{-1} year^{-1} and synthetic N additions of ca. 20 kg ha^{-1} year^{-1} in a crop rotation dominated by winter grain to achieve relatively high yields and acceptably low nitrate concentrations. They further suggested that similar results can be achieved with a combination of matured and nonmatured compost.

CONCLUSIONS

Nutrient management goals at the field level require such strategies as greater return of organic materials, use of perennial and cover crops, and reduced tillage. These strategies contribute to the accumulation of the active fraction of the organic matter, which is crucial for a sustainable management of nutrient cycles in agroecosystems. Management practices that promote SOM

TABLE 9.4
Average Dry Matter Application Rate and Cumulative N, P, K Budget of Organic Amendments in a Three-Year Study in Pennsylvania

	DM Input[a]	Nutrient Surplus[b]			Changes in Soil Properties[c]						
	(Mg ha^{-1})				Total N[d]		Extractable P[e]		Extractable K[e]		Total C[d]
Organic Amendment		N	P	K							
Inorganic fertilizer		96	11	141	−356	****	−4	ns	+32	ns	−1808
Raw dairy manure	7.5	505	146	337	−170	ns	+21	ns	+49	*	−19
Dairy manure and leaf compost	27	865	299	384	+425	*	+55	ns	+56	**	+7963
Broiler litter and leaf compost	14	614	351	326	+41	ns	+79	ns	+79	***	+2174
Controlled microbial compost[f]	47.5	795	445	972	+231	ns	+46	ns	+223	****	+5421
Yard clipping compost	14.5	485	60	127	+4	ns	0	ns	+23	ns	+3504

Note: ANOVAs were done by replication and treatment with year and replication as main effect. Significant change from 1992 to 1995 noted as follows: ns, not significant; * $p < 0.5$; ** $p < 0.01$; *** $p < 0.001$, **** $p < 0.0001$.

[a] Average yearly application rate applied for 3 years.

[b] Surplus equals the total inputs minus harvested outputs.

[c] Temporal changes in N, P, K from October 1992 to November 1995.

[d] Calculated using bulk density measurements of the plow layer (0- to 20-cm depth) and discounting weight of rock fragments >2 mm.

[e] Calculated based on the assumption that the plow layer contains 2,240,000 kg ha^{-1}.

[f] Mix of farm animal manure and bedding, clay loam, rock powder, microbial inoculant, and finished compost from a previous batch.

Source: Adapted from Reider, C. et al. 2000. *Compost Sci. Util.* 8:328–339.

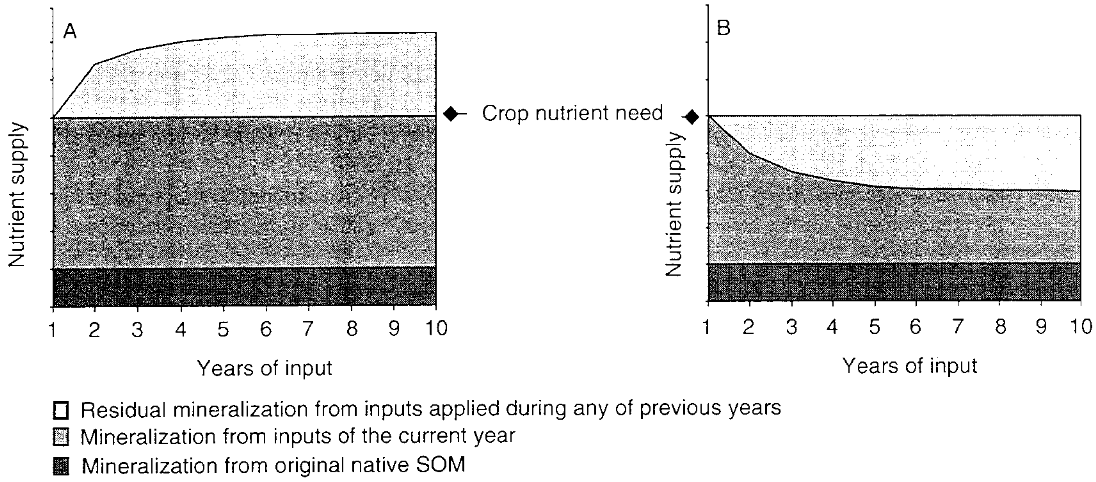


FIGURE 9.5 Two hypothetical scenarios of nutrient availability from long-term annual organic amendment inputs: (A) constant annual input rates leading to excess nutrient loading and (B) decreasing annual input rates leading to a constant nutrient supply.

accumulation also address farm- and regional-level nutrient management goals. Increased SOM, for example, might diminish the need for transport of nutrients on farm and between farms, thereby saving economic resources and reducing the risk of environmental impact. Higher SOM levels might similarly benefit regional agroecosystems in which the dependence of large quantities of imported nutrients has negatively impacted water resources and increased economic vulnerability (Burkart et al., 1995).

The shift toward environmentally sound agricultural systems incorporates the objective to increase SOM for sustained nutrient availability. To what level SOM should be increased can depend on the management objective. For the purpose of soil fertility, Domsch (1985) argues that the highest possible humus level for a specific location is desirable because it represents a steadily flowing nutrient and energy source for the plant and soil organism communities. However, as the preceding discussion showed, managing for an increase in SOM is generally beneficial, but doing so without attention to potential problems can lead to a reduction of nutrient use efficiency or excess loading of soil nutrients. The variability in soil, climate, and crops produces unique management scenarios for regional and local agroecosystems, which must be understood when managing for SOM and its associated benefits.

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