

SOIL PROCESSES AND THE CARBON CYCLE

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Relationships between Soil Organic Carbon and Soil Quality in Cropped and Rangeland Soils: the Importance of Distribution, Composition, and Soil Biological Activity

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I. Introduction

The often-cited positive relationship between soil organic carbon (SOC) content and soil quality (Arshad and Coen, 1992; National Research Council, 1993; Doran and Parkin, 1994; Manley et al., 1995; Pikul and Aase, 1995; Karlen and Cambardella, 1996) is consistent with the results of over one hundred years of modern agricultural research (Bauer and Black, 1994) and with thousands of years of on-farm observation and experimentation (Magdoff, 1992). This relationship is based on contributions which SOC makes as a constituent of soil organic matter (SOM) to critical soil properties, processes and functions. The term "SOM" will be used in the remainder of this chapter except where carbon per se is of interest. "SOM" is preferred here because it reflects the reality that impacts of SOC on soil quality are determined by its chemical, physical, and biological configuration within SOM.

The positive correlation between SOM and soil quality holds, in general, for all of the definitions of soil quality listed by Doran and Parkin (1994), as well as for the concepts of soil quality discussed by Warkentin (1995). Soil organic matter content was listed by a group of 28 Wisconsin farmers as the single most important property for characterizing soil health or soil quality based on their personal definitions (Romig et al., 1995). SOM was also cited as "perhaps the single most important indicator of soil quality" in a NRC (National Research Council) report on soil and water quality. The report defined soil quality as "the capacity of the soil to promote the growth of plants; protect watersheds by regulating the infiltration and partitioning of precipitation; and prevent water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals" (National Research Council, 1993).

For the purposes of this chapter, soil quality is defined as the capacity of a soil to perform functions which sustain biological productivity and maintain environmental quality. Soil quality depends on current soil functional integrity and on soil's resistance to, and resilience following, perturbation. Resistance is inversely proportional to loss of soil functional integrity following perturbation, while resilience is proportional to the recovery of functional integrity (Figure 1; Pimm, 1984). It is clear that a general relationship exists between SOM content, soil functions, and the capacity of the soil to maintain and/or recover those functions over time. However, a closer examination of the literature

$$\text{Resistance (sensitivity)} = C/A$$

$$\text{Resilience (recovery)} = (B - C)/(A - C)$$

$$\text{Resilience (recovery rate)} = d[(B-C)/(A-C)]/dt$$

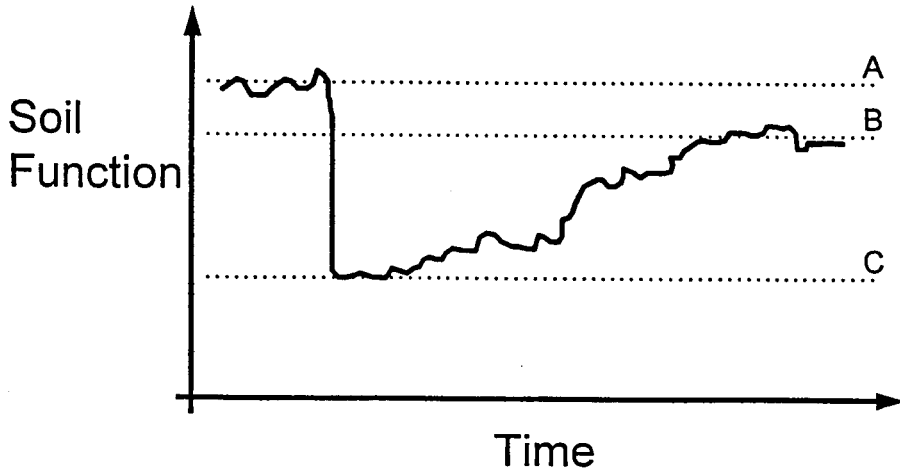


Figure 1. Relationship between soil functional integrity, disturbance, resistance, and resilience. The Y axis represents a generalized soil function, such as infiltration capacity.

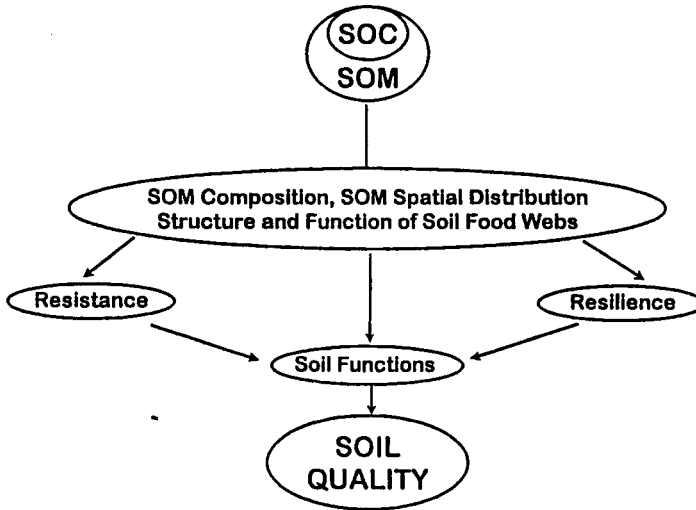


Figure 2. Conceptual model of relationship between soil organic carbon and soil quality.

suggests that the net effect of SOM often depends less on its quantity than on a combination of other factors including (1) its spatial distribution (horizontal, vertical, and location relative to soil aggregates) and (2) its composition, understood in both biochemical and functional terms. These two factors are mediated by a third: the structure and integrity of soil food webs (Figure 2). Organisms

have direct and indirect effects on soil physical integrity, fertility, and a variety of soil properties, processes, and functions which are related to environmental quality. Soil food webs are discussed in a number of reviews of the role of soil biodiversity in ecosystem processes (Oades, 1993; Kennedy and Smith, 1995; Whitford, 1996).

The objective of this chapter is to explore the relationships between SOM and soil quality by: (1) defining the basic contributions of SOM to soil functions as related to soil quality (section II), (2) highlighting the role of SOM composition and spatial distribution in determining the effect of SOM on soil quality (section III), and (3) illustrating the dynamic nature of SOM-soil quality relationships through a discussion of resistance and resilience (section IV).

II. Contributions to Soil Function

SOM contributes to soil quality through its effects on specific soil functions. These functions include serving as a medium for the growth of plant roots and root-symbionts, regulating the flow of water, air, and nutrients, partitioning precipitation into plant-available-, ground-, and surface-water, serving as a repository for atmospheric carbon, and mitigating the impacts of pollutants on human and ecosystem health (National Research Council, 1993; Doran and Parkin, 1994; Elliott et al., 1994). SOM affects these functions by causing or mediating changes in soil properties and processes which are related to (1) soil physical integrity, (2) soil fertility and productivity, and (3) environmental quality.

A. Physical Integrity

There is a strong association between soil structure and SOM in the agronomic literature. A change in SOM content has often been cited as the single most important factor contributing to changes in functions related to soil physical integrity. For example, Zwerman (1947) attributed a twelve-fold increase in soil water infiltration rates in kudzu-planted fields to increased organic matter content in those fields relative to fallow soils under broom sedge and weeds. Bruce et al. (1995) identified carbon content as the single soil property which could be managed in degraded Appalachian piedmont soils to limit erosion and improve plant water availability. Hudson (1994) and Emerson (1995) found highly significant positive correlations between SOM content and available water capacity based on both experiments and a reexamination of the literature. Regression-based empirical pedotransfer functions for many soil physical properties include soil organic matter as a key component (Dutartre et al., 1993; Rasiyah and Kay, 1994; Bell and van Keulen, 1995). Farmers also frequently associate high levels of SOM with good soil structure as soils with higher SOM tend to be easier to till over a wider range of moisture contents.

These general associations between soil structure and SOM are supported by more specific studies. Micromorphological and process-based studies have demonstrated the mechanistic role of organic matter in the formation and stabilization of soil aggregates (Tisdall and Oades, 1982; Elliott, 1986). Soil aggregate structure and stability, in turn, are related to soil erodibility (Lal and Elliot, 1994), infiltration characteristics (Eldridge, 1993), and soil compactibility (Soane, 1990).

B. Fertility and Productivity

The high correlation between soil organic matter content and soil fertility, the capacity of a soil to supply essential plant nutrients, has long been known (Russel, 1988). SOM contributes to soil fertility by serving as a source of plant nutrients (Broadbent, 1986), by providing exchange surfaces for

nutrients from other sources (Mengel and Kirkby, 1987), and through its capacity to act as a pH buffer (Cantrell et al., 1990). In non- or little-fertilized systems, plant N, P, S, and microelement nutrition can depend heavily on mineralization of SOM and residues of plants and animals (Chen and Stevenson, 1986; Broadbent, 1986). Base cations, which are present only in trace amounts in humic substances, are supplied by decay of fresh organic residues. Their availability is influenced by SOM chiefly through its impact on ion exchange (Barber, 1984; Mengel and Kirkby, 1987).

SOM contributes to, and is affected by, biological productivity in natural and managed ecosystems. Zak et al. (1994) demonstrated this using a gradient spanning North America. They showed that net primary productivity of late succession ecosystems was positively correlated with microbial biomass and labile organic matter pools. In managed systems, maintenance of SOM levels benefits crop yields even when mineral nutrition is optimized by fertilizer application (Avinemelch, 1986; Cassman and Pingali, 1995). Laboratory studies have demonstrated that organic substances themselves have direct effects on plant growth. Organic matter can influence plant nutrient uptake through its impact on root physiology, root morphology, and even genome expression (Durante et al., 1994). SOM can also improve productivity by decreasing or preventing disease (Cook and Baker, 1983). The mechanisms involved in disease suppression and resistance can be direct or indirect, resulting from biochemical or microbial interactions. In controlled experiments, Chen and Aviad (1990) found that humic substances stimulate plant growth directly. Benefits can arise from hormone-like interactions or can result from increased rooting volumes. SOM can also improve productivity by decreasing or preventing plant disease (Cook and Baker, 1983; Hoytink et al., 1986; Weltzien, 1992).

C. Environmental Quality

Soil quality and environmental quality are conceptually and functionally related. Soils are often viewed as contributing to environmental quality because they influence more traditional indicators such as atmospheric dust and water pollutant concentrations. However, soil quality has not historically been included in environmental quality assessments. Attempts are being made to quantify soil quality as an indicator of environmental quality for terrestrial ecosystems. This trend is illustrated by the Environmental Protection Agency's foray into the arena through its Environmental Monitoring and Assessment Program (EMAP) (Hunsaker and Carpenter, 1990), as well as by the establishment of soil quality standards by the International Standards Organization (ISO) (Hortensius and Welling, 1996).

SOM contributes to environmental quality both through its impact on overall soil quality and through effects on off-site environmental problems that are regulated by soil processes. Two of the most intensively studied SOM-related environmental problems which SOM directly affects are global climate change and water quality (National Research Council, 1993; Murphy and Zachara, 1995). The potential for soils to store additional carbon and thereby reduce the impacts of fossil fuel combustion on global climate change is widely recognized (Post et al., 1990; Schlesinger, 1991; Anderson, 1992), and there is a large body of knowledge on management-induced changes in soil carbon storage (Bolin, 1977; Barnwell et al., 1992; Wallace, 1994). Effects of tillage, drainage, residue management, and range management on SOC have been widely documented (Burke et al., 1989; Schlesinger, 1990; Sims et al., 1994; Manley et al., 1995; Ash et al., 1996). However, the relative magnitudes of the impact of tillage on soil carbon reductions (Burke et al., 1989) and of SOC storage on atmospheric carbon levels (Schlesinger, 1990; Kern and Johnson, 1993; Trumbore et al., 1996) continue to be debated.

SOM affects the quality of both ground and surface water supplies. Soil protects ground water by acting as an active filter in which contaminants are trapped and degraded or transformed into substances which are less toxic (Murphy and Zachara, 1995). SOM provides adsorbing surfaces and supports an active community of microorganisms capable of modifying and degrading contaminants. SOM impacts on adsorption and degradation similarly reduce groundwater pollution. Its effects on soil

structure reduce runoff and erosion, thereby reducing transport of contaminants to surface water. Unfortunately, coarse-textured soils, which are among the most susceptible to groundwater pollution, tend to have low SOM contents.

The environmental fate of metals and organic contaminants in soils depends upon chemical lability and soil biology as well as compound adsorption and partitioning characteristics. In general, metal concentrations are positively correlated with clay contents (Holmgren et al., 1993) and, therefore, with SOM contents. The fate of metals is influenced by organic matter complexation, exchange, adsorption, precipitation, dissolution, and acid-base equilibria (Chen and Stevenson, 1986). Similarly, the fate of organic chemicals is also controlled by interacting mechanisms (Rao et al., 1993). For example, Reddy et al. (1995) showed that chlorimuron degradation in conventionally tilled and nontilled soils was regulated by native microbial populations' adaptability to the substrate and not by sorption, desorption, total SOM, or biomass. SOM influences adaptability directly by supporting individual heterotrophic organisms, and indirectly by influencing the physical space within which organisms and substrates interact.

III. Critical Factors

While higher levels of SOM are generally associated with improved physical integrity, higher soil productivity, and enhanced environmental quality, correlations are highly variable. Relationships between SOM and soil quality can be refined by considering two critical factors in the context of soil biological processes: (1) SOM composition, and (2) SOM spatial distribution.

A. Composition (Biochemical and Functional Aspects)

Soil organic matter includes all carbon in soil which is bound in organic forms. Accordingly, SOM refers to a heterogeneous range of living and dead C-based materials, the quantity and composition of which are known to vary significantly within major ecosystem types (Post et al., 1982; Anderson, 1991). The diversity of SOM is reflected by numerous characterization schemes (Hayes et al., 1989; Wilson, 1991). While there is some correlation between SOM characteristics and performance criteria, the extensive information available about the chemical composition of various SOM fractions has not been systematically tied to soil functions. However, existing research does indicate that specific SOM fractions may be superior to total SOM as indices of soil functions and, therefore, soil quality (Gregorich et al., 1994). By linking SOM composition to turnover characteristics, biochemical aspects of SOM can be tied to soil function (Table 1).

The living SOM component embodies only a small percentage of total carbon mass and includes below-ground roots, bacteria, fungi, and soil micro-, meso-, and macro-arthropods. This is the most dynamic portion of all SOM (Coleman and Crossley, 1996). Living SOM carbon is thought to play a regulatory role in soils, acting as a feedback mechanism controlling soil material and energy cycling characteristics (Elliott and Coleman, 1988).

Nonliving organic matter includes a range of materials that vary greatly in age, dynamic characteristics, and functional significance. These materials have been divided into pools or fractions which have different turnover characteristics (Jenkinson and Rayner 1977; Jenkinson and Parry, 1989; Parton et al., 1987; Paustian et al., 1992). The fractions are identified through isotopic tracer studies. The differentiation of organic matter among such dynamically distinct pools is caused not only by the chemical structure of constituent molecules, but also by their physical location in soils and the precise nature of their association with soil minerals (Greenland, 1965a,b; Tisdall and Oades, 1982; Waters and Oades, 1991). The biologically active, physically protected, and recalcitrant or stable fractions are three of the most commonly recognized pools.

Table 1. Management impacts on soil organic matter composition and turnover characteristics. Data are from the Rodale Research Center's Farming Systems Trial after ten years comparing organic-animal, organic-cover cropped, and conventionally-based corn and soybean rotations.

| | Total C | Humin | Humic substances | Light fraction |
|---------------|---------------------------|--------|------------------|----------------|
| | g C kg ⁻¹ soil | | | |
| Animal | 23.4ab | 11.7ab | 10.1ab | 1.7ab |
| Cover cropped | 24.5a | 12.4a | 10.2a | 2.0a |
| Conventional | 21.3b | 11.0b | 8.9b | 1.6b |

| | Available N† | Mineralizable N† | Respired C† | Biomass |
|---------------|----------------------------|------------------|---|-----------------------------------|
| | mg N kg ⁻¹ soil | | mmol CO ₂ kg soil d ⁻¹ | nmol PLFA g ⁻¹ soil |
| Animal | 17.3 | 34.1 | 14.2a | 29.17 |
| Cover cropped | 16.5 | 30.1 | 12.4b | 33.00 |
| Conventional | 14.8 | 26.8 | 9.4c | 26.60 |

†Values are seasonal averages based on samples collected on five dates in 1990. Available N is NH₄ and NO₃ extracted from fresh soil. Mineralizable N is additional N recovered. Respired C is CO₂ evolved during subsequent aerobic incubation. (Data from Wander et al., 1994, 1995; and Wander and Traina, 1996.)

The most dynamic or rapidly cycled SOM fraction is the biologically active fraction, which is tied to mineralization characteristics and, therefore, soil nutrient supply capacity (Greenland and Ford, 1964). No single method effectively isolates this important nutrient reservoir. The light fraction is a SOM pool defined by density. It is more sensitive to management impacts than total SOM and has been suggested as a measure of the biologically active fraction (Janzen et al., 1992; Wander et al., 1994; Barrios et al., 1996; Gregorich and Janzen, 1996) and, consequently, as an indicator of soil quality. Polysaccharides, which are also part of the active SOM pool, contribute to soil quality by increasing macroaggregation even in the absence of detectable changes in total SOM (Roberson et al., 1991; Breland, 1995; Roberson et al., 1995).

Physically protected SOM (material entrapped in mineral particles and theoretically sequestered away from organisms) is a second pool which is relevant to soil quality because of its importance to soil structure and, therefore, the soil's biological and ecological integrity (Elliott and Coleman, 1988). As with the biologically active fraction, measures of this pool are indirect and imperfect.

Chemically recalcitrant SOM dominates the third pool, which is usually the oldest and largest. This pool is relatively resistant to decay compared to the active and physically protected pools. Both chemical structure (particularly structural randomness), and organo-mineral associations contribute to the stability and longevity of this pool. Recalcitrant SOM affects multiple aspects of soil quality by influencing the fate of ionic and nonionic compounds, contributing to the long term stabilization of microaggregates, increasing soil cation exchange capacity, and influencing soil color.

The specific SOM fraction or fractions selected for study in any system will depend on the function or functions of interest. Hence, one might focus on residue characteristics for erosion, humic substances, and depth distribution for carbon storage potential, and biologically active SOM for nutrient supply. More research is needed to establish clear ties between procedurally defined SOM fractions and soil function as it occurs within individual ecosystems.

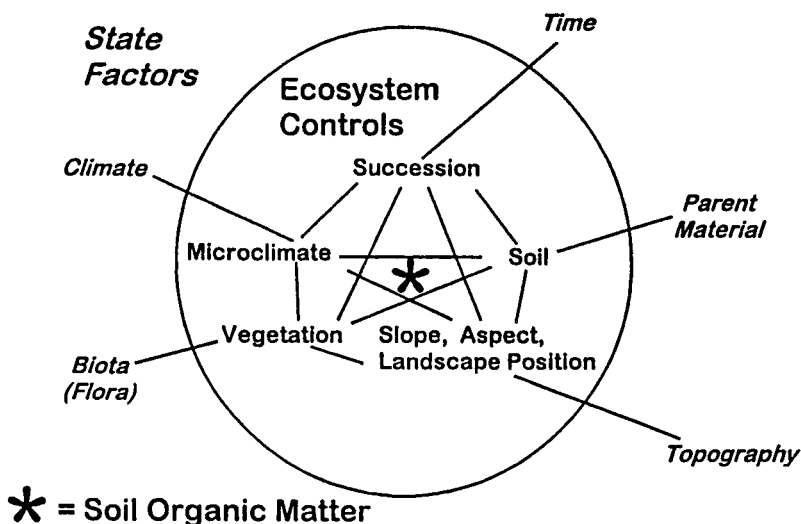


Figure 3. Soil organic matter content is determined by management in the context of local state factors and ecosystem controls. (Adapted from Van Cleve, 1991.)

B. Spatial Distribution

Soil organic matter exhibits strong spatial dependence in both agricultural and rangeland systems at scales ranging from the microaggregate (Kooistra and van Noordwijk, 1996; Tisdall, 1996) to the field (Cambardella et al., 1994) and the landscape (Burke et al., 1995). This spatial heterogeneity affects soil properties, processes, and functions at each of these scales (e.g., Gallardo and Schlesinger, 1992; Fromm et al., 1993; Lafrance and Banton, 1995) and, therefore, has an impact on soil quality. In fact, patterns of SOM distribution can be more important than total SOM content.

Patterns of SOM distribution and the relationship of these patterns to soil properties, processes and functions vary depending on the scale of interest. The scales discussed below (aggregate, root, plant and plant community, and landscape) are defined functionally with respect to the vegetative component of the system to emphasize the dynamic relationship between the plant as the primary source of organic matter and the soil as a medium which supports plant productivity (Figure 3). These scales, however, are by no means distinct. Patterns of variation in SOM content and composition vary continuously and some of the relationships described at the root scale could be equally applied at the plant level.

1. Aggregate Scale

Patterns at the aggregate scale range from submicron associations of clay domain and organic polymers to macroaggregate structures which encompass a cubic centimeter or more of soil volume (Tisdall and Oades, 1982). These macroaggregates may include microaggregates (< 250 μm) as well as plant fragments, fine roots, and fungal hyphae. One of the most important functions of the heterogeneous spatial organization of SOM at this scale is to provide structure and stability. Organic materials play a key role in both generating and maintaining soil structure. They function directly as binding agents. They also serve as an energy source for soil biota which create voids and rearrange and redistribute soil primary particles into new soil structures (Table 2). For a more detailed discussion

Table 2. Termite-dominated cattle dung decomposition impacts on soil bulk density in the surface 7 cm in a seasonally-dry Costa Rican pasture. Dung was deposited at the beginning of the 1993 dry season. Means \pm S.E. (n = 36 for 0 d and 9 for 12 - 270 d).

| Dung patch age | Dung removed | Bulk density |
|----------------|--------------|--------------------|
| days | % | g cm ⁻³ |
| 0 | -- | 1.16 (0.01) |
| 12 | 12.3 (2.8) | 1.14 (0.03) |
| 60 | 31.8 (2.2) | 1.09 (0.03) |
| 140 | 41.0 (1.8) | 1.02 (0.03) |
| 270 | 83.3 (3.9) | 1.05 (0.02) |

(Calculated from Herrick and Lal, 1995; 1996.)

of aggregate formation and structure, see related reviews in this volume and in earlier volumes in this series (e.g. Kooistra and van Noordwijk, 1996; Tisdall, 1996).

In addition to its role in aggregate structure and stabilization, the spatial and compositional heterogeneity of aggregate-associated SOM at the aggregate scale regulates the rate and pattern of many soil processes. The retention and release of water at intermediate tensions is regulated by the density and distribution of micropores within aggregates, as well as by characteristics of the organic matter itself. Soil carbon turnover rates are positively correlated with the diameter of the pore in which the carbon is located (Killham et al., 1993; Hassink et al., 1993; Nelson et al., 1994) and with aggregate size (Jastrow et al., 1996). Organic matter associated with macroaggregates is qualitatively more labile and more readily mineralized than SOM associated with microaggregates, and is the primary source of organic matter released when soils are cultivated (Oades et al., 1987; Balesdent et al., 1988; Waters and Oades, 1991). Parkin (1987) found denitrification, associated with microsites enriched in C, coincident with anaerobism. Barriuso and Koskinen (1996) demonstrated that atrazine biodegradation was associated primarily with particulate organic matter and Scow (1993) showed that pesticide decay rates are influenced by aggregate size and SOM content.

2. Root Scale

The root scale is defined as the soil volume explored by a single plant root or a segment of that root. Scale within a soil pedon is traditionally defined in a hierarchical framework of particles, aggregates, and clods. Many processes in soils are structured linearly. Roots generate many of these patterns, establishing zones rich in organic matter and biotic activity. Air- and water-conducting macropores are related linear structures that occur at the same scale. This scale also includes spatial variability associated with clods and organic fragments larger than a macroaggregate, such as corn stover and chunks of manure.

Critical soil properties related to SOM content at the root scale include nutrient availability and water holding capacity. The relationship between SOM content and nutrient availability is generally positive, although organic matter inputs with a high C-to-N ratio can result in a temporary reduction in plant-available nutrients due to microbial immobilization. Soil processes affected by local SOM concentrations include many biochemical transformations (Bonmati et al., 1991) and transport phenomena. While preferential flow through biogenic and physical macropores is frequently cited as a major factor in fate and transport studies, the distribution of SOM in the soil matrix relative to the macropores is also important (Felsot and Shelton, 1993). This illustrates the value of assessing soil quality in three dimensions, even at the intra- and inter-aggregate scales.

Table 3. Shrub-associated patterns of soil organic carbon distribution in the top 5 cm in the semiarid Great Basin and in the Sonoran Desert. The Great Basin data represent an average of eight sampling dates and include a range of interspace cover types from vesicular crust (lowest carbon) to moss-grass (highest carbon). The Sonoran Desert interspace were removed from a distance of one-third times the radius of the shrub from the edge of the shrub canopy.

| Dung patch age | Shrub | Interspace |
|----------------------------|-------|-------------|
| —————% Organic carbon————— | | |
| Great Basin | | |
| Sagebrush | 2.46 | 0.65 - 1.98 |
| Sonoran Desert | | |
| Velvet mesquite | 0.77 | 0.30 |
| Palo verde | 0.69 | 0.31 |
| Vine mesquite | 0.99 | 0.56 |

(Calculated from Blackburn et al., 1992; and Barth and Klemmedson, 1978.)

3. Plant and Plant Community Scale

The plant scale covers an extremely wide range of spatial patterns including higher SOM inputs associated with individual plants (Smith et al., 1994), individual cattle dung patches in a pasture (Herrick and Lal, 1995), and microtopographically-controlled patterns of litter distribution (Tongway and Ludwig, 1996). A common characteristic of these patterns is that they differentially affect resource availability to individual plants within a plant community. The relative importance of a change in SOM concentration or composition at the plant scale depends both on how different the particular concentration or composition is from that in the surrounding matrix, and on the size of the volume relative to the size of the organism or scale of the process affected by it. These relationships can evolve over time as, for example, with the growth of a seedling to a mature plant which exploits an increasingly large soil volume.

Soil properties, processes, and functions affected by spatial variability at the plant scale include all of those listed above for the root scale; however, the relative importance and persistence of the spatial patterns varies widely among ecosystems. Soil organic matter distribution in perennial rangelands is largely controlled by the spatial pattern of perennial plants. A number of studies have demonstrated "islands of fertility" in arid and semiarid rangelands associated with enhanced litter and SOM accumulation beneath shrubs (Table 3; Barth and Klemmedson, 1978; Santos et al., 1978; Blackburn et al., 1992; Smith et al., 1994; Schlesinger et al., 1996). In addition to adding organic matter directly to the soil through root exudates, root death, and litterfall, plants control the spatial redistribution of inputs through their effects on wind and water flow patterns. Spatial and temporal patterns of accumulation vary with shrub species (Barth and Klemmedson, 1982). Shrub-associated SOM islands are associated with enhanced soil quality, including higher nutrient availability and higher levels of soil biotic activity (Santos et al., 1978; Schlesinger et al., 1996). Soil surface hydrology is also affected. Blackburn et al. (1992) found that vegetation growth form was the most important factor contributing to soil surface properties which control infiltration and erosion in sagebrush dominated communities.

The ultimate impact of plant-scale concentrations of carbon resources on rangeland soil quality depends on local ecosystem dynamics. In water erosion-dominated areas of Australia, increased patchiness associated with banded vegetation systems is viewed positively. Linear patches intercept runoff and retain soil and water resources more effectively than more homogeneous systems in which threshold levels of resource availability required for vigorous vegetative growth are not reached

(Tongway and Ludwig, 1996). Conversely, shrub-associated patchiness on wind erosion-dominated soils in the arid U.S. southwest is cited as a sign of degraded rangeland as these systems are frequently associated with increased rates of soil erosion (Gibbens et al., 1983). Thus, while patch-level spatial distribution of SOM may serve as an excellent indicator of soil quality, the distribution pattern and scale must be carefully interpreted in the context of each ecosystem (Herrick and Whitford, 1995).

In annual cropping systems, the degree of SOM spatial heterogeneity and its impact on soil quality depends on the management system and the average SOM content. In general, reduced tillage systems are associated with a higher level of vertical SOM stratification in the rooting zone. A shift in the distribution of SOM associated with a shift to minimum- or no-tillage practices can dramatically impact other soil processes and ultimately alter soil biotic communities and trophic interactions, soil properties like macroporosity (Lee and Foster, 1991), and soil functions (Fromm et al., 1993; Pikul and Aase, 1995).

4. Landscape Scale

The landscape scale begins at the plant community or field scale. The upper limit depends on both the physiographic characteristics of the region and the properties, processes, and functions of interest. The upper limit can be defined in terms of a watershed. At this scale, soil quality, and the contribution of SOM to it, become more closely linked to social, political, and economic issues. SOM contributes to economic land values. It affects and is affected by the choice of management practice.

The redistribution of SOM by water can contribute to the development of isolated, deep, relatively fertile soils with enhanced physical integrity in regions which otherwise could not support arable agriculture (Forman and Godron, 1986). Where the source of the off-site organic matter inputs can be identified, SOM deposition can serve as a useful indicator of potential soil quality degradation at other landscape positions. In fact, the scale and pattern of variation at the landscape level may be one of the more useful and cost-effective regional indicators of soil quality (Herrick and Whitford, 1995), particularly if it is integrated with information on regional soil-climate-SOM relationships, such as those presented by Burke and others (1995).

5. Scale in Different Systems

At the aggregate and root scales, the impacts of SOM distribution are similar in agricultural and rangeland systems. In both cases, the three-dimensional spatial pattern of different carbon fractions affects soil structure and stability, nutrient availability, and the fate and transport of pollutants. At larger scales, the two systems diverge, with rangelands tending to exhibit more distinct and permanent spatial differences in SOM distribution and, consequently, in the properties, processes, and functions associated with these spatial patterns. In both systems, the spatial patterns of SOM and of carbon inputs at all scales should be explicitly or implicitly considered in the assessment of soil quality. This is particularly true when changes in management to improve soil quality through increased carbon inputs are contemplated. As Kooistra and van Noordwijk (1996) pointed out in their paper on soil architecture and organic matter distribution, "Using larger amounts of organic inputs is not a simple recipe to obtain a better soil structure".

Spatial variability in SOM concentrations at the whole-plant level is often developed and exploited in alley cropping and agroforestry systems to enhance the quality of the soil supporting both an annual and a perennial crop (Nair, 1984). By tapping nutrient stocks which would be inaccessible to shallow-rooted species, deep-rooted perennial crops increase system productivity. In addition to reducing runoff and soil erosion from the annually-cropped areas, the SOM derived from the deep-rooted perennial crop in agroforestry systems provides a supplementary source of nutrients to annual

roots which invade the perennial-dominated microsites. The net increase in nutrient availability may be due to increased nutrient content in the surface soil and/or an SOM-associated increase in cation exchange capacity (Rodella et al., 1995).

IV. Resistance and Resilience

Disturbance, or any event which causes a significant change from the normal pattern in an ecosystem (Forman and Godron, 1986), is increasingly recognized as a key component of both natural and managed systems. Agronomists have long recognized the importance of various types of disturbance, such as cultivation (Eghball et al., 1994). The mechanisms of ecosystem adaptation to disturbance have received serious attention only in the last several decades (Sousa, 1984).

The previous discussion of SOM composition and distribution as critical factors largely ignores disturbance. This perspective is temporally static: it is fixed at the particular point in time that samples are taken or measurements are made. When soils are studied at increasingly long time scales, it becomes clear that the current capacity of a system to perform key processes is not necessarily a good indicator of its capacity to maintain functional integrity over time, particularly following perturbation. Organic matter content, like other soil properties, is determined by the characteristics of the ecosystem within which a soil develops and results from the dynamic equilibrium between soil parent material, climate, topography, and vegetation (Figure 3; Jenny, 1980; van Cleve and Powers, 1995; Huggett, 1995). SOM content is unique because it is one of the most rapidly and readily changed soil properties. As a result, SOM frequently plays a key role in both the resistance of the soil to degradation, and to its resilience or capacity to rapidly recover its functional integrity.

A. Relative Importance of Factors

The relative importance of SOM composition and spatial distribution, the structure and integrity of soil food webs, and the resistance and resilience relative to disturbance depend on the function and time scale of interest, and on the anticipated disturbance regime. For example, over relatively short time periods in the absence of major disturbance, soil physical integrity should be closely related to the composition and spatial distribution of SOM. These factors, which are related to aggregate stability and soil strength, also contribute to the resistance of the soil to compactive and erosive disturbances (Soane, 1990; National Research Council, 1993). Over longer periods of time, the resilience, or capacity of the system to recover physical integrity after disturbance, becomes more important as the probability that a major disturbance event will occur increases. Recovery of soil structure, including soil aggregates and macropores, frequently depends on soil biotic integrity and even on the presence of specific components of the soil biota such as earthworms (Blanchart, 1992; Edwards and Bater, 1992) or termites (Elkins et al., 1986; Herrick and Lal, 1995).

Similarly, the pre- and post-disturbance capacity of the soil to supply plant nutrients also depends on SOM composition, spatial distribution, and on the structure and integrity of soil food webs. However, it is SOM content and SOM turnover rates which appear to control the capacity of the soil to continue to supply plant nutrients after repeated harvests (Tiessen et al., 1994). Turnover rates, in turn, are controlled by climate, soil biota, soil structure, the nature of the disturbance, and organic matter composition. Based on organic matter turnover rates, the predicted length of time that existing litter and soil organic matter could supply nutrients to support agriculture without external inputs ranged from three years for a tropical forest soil in the Amazon to six years for a tropical semiarid forest soil and 65 years for a temperate grassland soil (Tiessen et al., 1994). Changes in nutrient supply rates associated with a switch to agriculture may lag several years due to immobilization processes (Burke et al., 1995). Different organic matter sources within a system can also affect turnover rates.

Based on stable carbon-isotope work in Nebraska, Cambardella and Elliott (1992) suggested that wheat-derived particulate organic matter may have a higher turnover rate than organic matter from grass in an undisturbed grassland. These turnover rates are positively correlated with both plant nutrient content and soil nutrient status (Cheshire and Chapman, 1996). Turnover and accumulation rates are particularly important when catastrophic losses of SOM are possible. A single rainfall event can remove SOM accumulated over thousands of years, substantially reducing the inherent nutrient-supplying capacity of one site while enriching another.

The resilience of a soil with respect to its capacity to retain and supply nutrients, therefore, depends on both SOM pool characteristics, including content and turnover rates, and on the nature of the disturbance. Tillage can lead to reductions in SOM, particularly the physically protected fraction, while erosion can cause across-the-board reductions in all fractions.

B. Disturbance Regimes

The response of a system to a particular disturbance, and whether or not a particular disturbance has a catastrophic impact on soil function, depends on the historic disturbance regime under which the system evolved and on the other stresses to which it is currently exposed. Disturbance regimes are defined in terms of disturbance type and the frequency, seasonality, intensity, and predictability or regularity, of each event. While a system may function satisfactorily and have a relatively high level of resistance and resilience under one disturbance regime, it may collapse in response to the introduction of a new disturbance, or in response to an increase in the intensity and/or frequency of existing disturbances (Belnap, 1995). For example, it is believed that Chihuahuan Desert grassland ecosystems became established and persisted under a regime of unpredictable, episodic, large-scale drought disturbances, and more regular small-scale animal-induced soil surface and grazing disturbances. Although bison may have entered the region occasionally in small groups, there is little evidence to suggest that they played a significant role in the evolution of the system.

Based on observations and limited data from remnant grassland areas, soil organic matter, while limited, was relatively homogeneously distributed and was present in sufficient quantities to help stabilize even relatively erodible sandy loams. With the introduction of cattle and technologies for stock-water development, however, the intensity of grazing disturbances increased. This, together with simultaneous invasion of the sandy grassland soils by a shrub (*Prosopis glandulosa*), is hypothesized to have caused the breakdown of the system during severe droughts, including a net loss of soil carbon and nitrogen, redistribution of the remaining SOM to areas under the shrubs, and reductions in soil stability (Schlesinger et al., 1990; Virginia et al., 1992). Thus, soil quality, as defined by function, resistance and resilience, could be regarded as high under the historic disturbance regime; however, resistance turned out to be quite low in the context of the new disturbance regime. A decline in soil quality is evidenced by both reductions in soil stability in the shrub-dominated systems (J.E. Herrick, unpubl. data) and the failure of the grassland to return even where cattle have been excluded for over 50 years (R.P. Gibbens, unpubl. data). Similar examples can be found for many soils which have experienced a change in the disturbance regime, including Amazonian rainforests (Tiessen et al., 1994) and midwestern prairies (Robinson et al., 1996).

Row crop agriculture, which is based on a temporally regular or predictable tillage disturbance, has led to degraded soil function in some systems, but not others. The differences cannot be easily attributed to differences in historical disturbance regimes, as few, if any, North American landscapes evolved under regimes analogous to annual tillage. Climate, including storm characteristics and fundamental soil properties, such as soil texture and mineralogy, more readily explain these differences. Striking examples of system loss of functional integrity are associated with the increased erosion and SOM loss following cultivation of weakly-structured soils in sloping landscapes, such as many soils of the Appalachian piedmont (Bruce et al., 1995). Conversely, SOM levels and soil

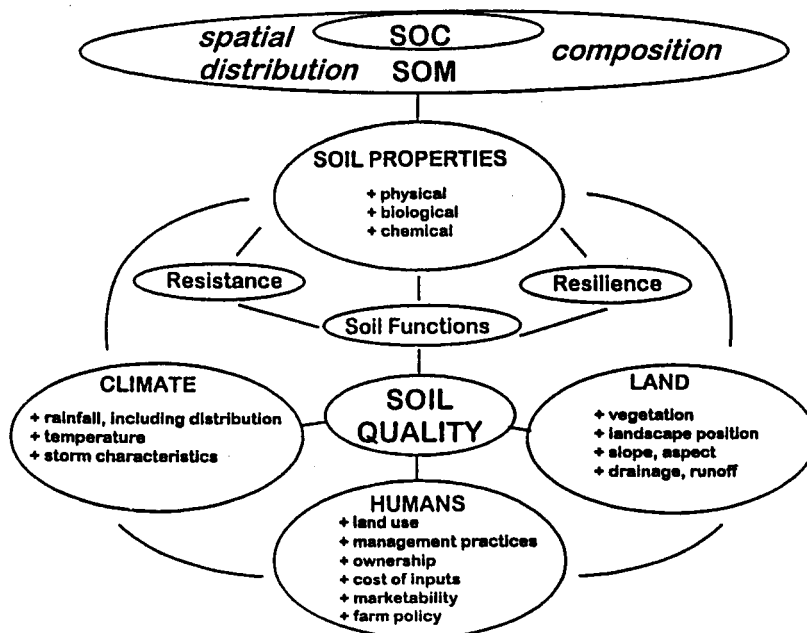


Figure 4. Conceptual model of the relationship between soil organic carbon and soil quality, expanded to include additional linkages. (Modified from Figure 2 and Arshad and Coen, 1992.)

structure can be maintained at desirable levels by using cover crops and applications of animal manures and/or composts.

The positive contribution of SOM to the resilience of cropped soils following cessation of tillage has been demonstrated by work on Conservation Reserve Program (CRP) land (Gebhart et al., 1994; Burke et al., 1995). At least one study showed that soil resilience, as indicated by increases in aggregate stability, was highest on CRP land with the highest levels of SOM at the time the land was taken out of annual crop production (Rasiah and Kay, 1994). Breland (1995) showed that improvements in soil structure on CRP land were rapidly erased when CRP land was returned to annual cropping practices. This suggests that while SOM may enhance resilience, the resistance of the improved structure to subsequent tillage disturbances can be quite low.

The proposed relationships between resistance, resilience, SOM, and soil quality is illustrated in Figure 4 in the context of linkages with the land, climate, and humans. The figure emphasizes the complexity of the interactions between SOM and soil quality. To define resistance and resilience, we must consider the time scale of interest, the nature of the disturbance(s), the level of recovery expected, and the type and quantity of inputs which are expected to be added to the system to support recovery. One criterion which is frequently applied to the assessment of rangeland condition is whether or not the system is likely to recover with a reasonable level of inputs. An informal survey of professionals active in developing rangeland assessment tools indicated that there is relatively little consensus on what constitutes a reasonable level. The same question is being asked in agricultural systems where cover crops, long-term rotations, use of manures, and reduced tillage systems are implemented only where they are perceived to be profitable. Even though resistance and resilience are likely to prove even more difficult to define than "a reasonable level of inputs," they add a key dimension to the discussion: system sustainability. Resistance and resilience must be considered, together with current soil functional integrity, in any but the most short-term assessments of soil quality.

As demands and stresses on soil resources grow, it becomes increasingly important that we understand the relationships between SOM composition and distribution and the functional integrity of specific systems. Key elements of soil quality vary among systems (Cole, 1994). The resistance and resilience of individual systems, contributions of SOM to resistance and resilience, and the relationship between SOM composition and distribution and soil function should receive special attention in the future.

V. Summary and Conclusions

A general relationship between SOM and soil quality has been confirmed by over 100 years of formal experimentation and by thousands of years of formal and informal observations and on-farm trials. This relationship is supported by both correlations and process-based mechanistic studies showing that, for most soils, physical integrity, fertility, and environmental quality are positively correlated with total SOM content. The exact nature of each of these relationships, however, is best understood in a site- and ecosystem-specific context. Within each ecosystem, the biochemical composition of SOM and its spatial distribution (microaggregate to landscape) are key factors in determining the ultimate impacts of SOM on current soil functional integrity and, therefore, on soil quality for a particular ecosystem.

The relationship between SOM and soil quality is not limited to current functional integrity, however. SOM plays a unique role in the maintenance and recovery of soil functions following disturbance for at least two reasons. First, it is relatively dynamic and, unlike mineral components, can be quickly regenerated when lost. Second, it supports activity by a wide variety of soil organisms, which themselves contribute to the restoration of soil functions.

While there is a plethora of research supporting the general relationship between SOM and soil quality, many of the mechanisms discussed or alluded to in this chapter remain poorly understood. As competition for organic inputs increases, it will become increasingly important to develop management approaches which optimize the impacts of these inputs on soil quality, and which tend to conserve the most important SOM fractions. These management techniques should ideally be based on an understanding of the mechanistic relationships between SOM and soil functions, and on interactions between organic matter and the soil food webs which are largely responsible for the fate of organic inputs. Unfortunately, many of the relationships and the SOM-food web interactions are poorly understood. Future research on soil quality-soil carbon relationships should, therefore, be increasingly biological and process-based, while maintaining clearly identifiable links to potential management practices for agricultural, range and forest soils.

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