Soil Quality for Sustainable Land Management: Organic Matter and Aggregation Interactions that Maintain Soil Functions

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ABSTRACT

Soil quality concepts are commonly used to evaluate sustainable land management in agroecosystems. The objectives of this review were to trace the importance of soil organic matter (SOM) in Canadian sustainable land management studies and illustrate the role of SOM and aggregation in sustaining soil functions. Canadian studies on soil quality were initiated in the early 1980s and showed that loss of SOM and soil aggregate stability were standard features of unsustainable land use. Subsequent studies have evaluated SOM quality using the following logical sequence: soil purpose and function, processes, properties and indicators, and methodology. Limiting steps in this soil quality framework are the questions of critical limits and standardization for soil properties. At present, critical limits for SOM are selected using a commonly accepted reference value or based on empirically derived relations between SOM and a specific soil process or function (e.g., soil fertility, productivity, or erodibility). Organic matter fractions (e.g., macro-organic matter, light fraction, microbial biomass, and mineralizable C) describe the quality of SOM. These fractions have biological significance for several soil functions and processes and are sensitive indicators of changes in total SOM. Total SOM influences soil compactibility, friability, and soil water-holding capacity while aggregated SOM has major implications for the functioning of soil in regulating air and water infiltration, conserving nutrients, and influencing soil permeability and erodibility. Overall, organic matter inputs, the dynamics of the sand-sized macro-organic matter, and the soil aggregation process are important factors in maintaining and regulating organic matter functioning in soil.

Soil quality is not a new topic. Early scientific endeavors recognized the importance of categorizing soil type and soil variables or properties in regard to land or soil use, especially for agricultural purposes (Carter et al., 1997). The impetus to define and assess soil quality is in many ways derived from outside of the scientific community, being related to the concern of society with the overall quality or health of the environment. However, due to concerns with soil degradation and the need for sustainable soil management in agroecosystems, there has been renewed scientific attention to characterize soil quality. Placing a value on soil in regard to a specific function, purpose, or use leads to the concept of soil quality.

The basic idea of fitness for use in regard to agricultural use of soil, which was reflected in early and ongoing attempts at classifying soil suitability or land capability, is seen as a basic premise of soil quality (Larson and Pierce, 1991, 1994). If a soil is not suitable for a specific use, then it is not appropriate to attempt to assign or describe quality for that specific use or function. In many cases, however, it is not possible to make a perfect match between the soil and its intended use. Under these circumstances, quality must be built into the system using best management scenarios.

Ecosystem concepts such as function, processes, attributes, and indicators, have proved to be a useful framework to describe soil quality (Larson and Pierce, 1991, 1994; Doran and Parkin, 1994; Doran et al., 1996; Carter et al., 1997; Karlen et al., 1997). However, a precise definition of soil quality proves to be elusive. This is probably related to the innate difficulty in defining soil itself and to the multifaceted nature (i.e., scientific, personal, and social) of environmental concerns. Carter and MacEwan (1996) suggested that although soil quality describes an objective state or condition of the soil, it also is subjective, i.e., evaluated partly on the basis of personal and social determinations. The above framework of soil quality has utility when it is directed or focused towards the manipulation, engineering, and/or management of the soil resource. Thus, soil quality is a technology, an applied science, directed towards better soil management.

The objective of this paper is to review the context and approach to soil quality, with specific emphasis on soil organic matter (SOM) and soil aggregation. Specific objectives are to (i) trace the origins of soil quality research in the concern for sustainable land management in Canada, (ii) differentiate between descriptive and functional approaches used to characterize soil quality, (iii) evaluate the role and limitations of utilizing SOM as a key attribute of soil quality, and (iv) assess the factors that regulate SOM functioning in soil.

SUSTAINABLE LAND MANAGEMENT AND SOIL QUALITY

Soil quality is considered a key element of sustainable agriculture (Warkentin, 1995). The latter refers to productivity, economic, social, and environmental components of land use systems (Smyth and Dumanski, 1995). Although sustainability issues are much broader than soil quality, the strong emphasis on maintaining the natural-resource base ensures that maintaining good soil quality is an integral part of sustainable agriculture (Miller and Wali, 1995).

Abbreviations: SOM, soil organic matter.
Although all of the above components must be satisfied to meet the goal of sustainable land use, it is recognized that sustainability has a time scale and that the time scale may differ for each component. Even though loss of sustainability of any one component would classify the land use system as unsustainable, in reality, short-term economic viability can be sustained by inputs to the system even when use of the natural-resource base has become nonsustainable. This latter scenario has serious implications for SOM and the sustainability of intensive farming systems, as most economic models utilized to describe sustainability in agriculture often disregard or marginalize the natural-resource component.

Use of the Concept of Soil Quality in Canada

Early work in Canada to assess the quality of agricultural soils was conducted within the context of sustainable land use. A series of papers in the Canadian Journal of Soil Science summarized the effects of intensive cultivation on soil quality in different regions of the country. Ketcheson (1980) noted that intensive agriculture, especially monoculture and row crops, had resulted in a deterioration of SOM levels and soil physical properties in southern Ontario. An increase in the use of grass-legume forages was seen as a solution to this problem. In Quebec, Martel and MacKenzie (1980) compared the effect of different land use practices on soil quality and showed that the conversion of forest soils into agricultural soils was accompanied by a loss in both SOM and structural stability and, under some conditions, an increase in soil compaction. Use of continuous grass (>5 yr), however, tended to reverse the decline in soil quality. Saini and Grant (1980) reviewed the deleterious effect of continuous potato (Solanum tuberosum L.) culture in New Brunswick and the neighboring state of Maine (USA) and identified decreases in soil structural stability, porosity, and SOM as characteristic features of declining soil quality. All of these studies recognized, mainly through qualitative assessment of soil properties, the major role that SOM plays in the maintenance of soil quality.

Interest in soil quality was further developed by a series of technical bulletins published by Agriculture Canada to describe key parameters that can be used to measure soil quality in different regions of the country. Acton (1991) identified soil pH, salinity, sodicity, SOM, and other attributes for use in western Canada while Coote (1991) listed soil erosion, acidification, and compaction processes in eastern Canada. The effects of SOM on soil quality in relation to soil structure, water retention, nutrient availability, and other functions were covered by Schnitzer (1991). The especial importance of SOM for soil quality in intensively row-cropped sandy soils in eastern Canada was assessed by Mathur (1991).

More recently, Angers and Carter (1996) described the positive relationship between SOM and water-stable aggregates in eastern Canada.

Soil Erosion and Landscape Studies

In many regions of Canada, concerns about soil degradation related to erosion have been the impetus for much soil quality evaluation. Soil quality indicators in landscapes influenced by soil erosion have been studied where the relationship between land use and soil quality is difficult to characterize because of the complexity of soils and spatial variability. In Saskatchewan, Anderson and Gregorich (1984) assessed the effects of erosion and cultivation on soil quality attributes while Verity and Anderson (1990) characterized the influence of erosion on changes in soil quality attributes, including the relationship between soil quality and crop production. Pennock et al. (1994) assessed soil redistribution in landscapes of southern Saskatchewan with different cultivation histories and showed that SOM was the major soil quality indicator influenced by erosion. Other studies in Saskatchewan have characterized soil quality in different farming systems and noted the benefits of continuous cropping and frequent additions of crop residues on soil quality in general and SOM quality in particular (Boehm and Anderson, 1997). In New Brunswick, Cao et al. (1994) assessed the cumulative effect of soil erosion and redistribution under intensive potato production and found that both soil loss and gain (i.e., deposition) were related to SOM. Gregorich et al. (1998) recently reviewed the relation between soil erosion and deposition processes and distribution and loss of SOM using the Century model.

Soil Quality and Crop Production

Studies have also been conducted in other regions of Canada to elucidate soil quality in the context of sustainable land use and management. Olson et al. (1996) used a field assay based on removing soil and subsequent deposition of soils with diverse properties to identify key soil quality attributes that could also be related to crop productivity in southern Alberta. Significant relationships between crop yield and SOM, carbonate concentration, and pH were obtained. Studies in more northern regions of Alberta have assessed the influence of integrated cropping systems on soil quality. Combinations of herbicide application, crop rotation, and tillage systems were found to influence several soil quality attributes, especially SOM quality (Soon and Darwent, 1998). Wani et al. (1994) found that adopting green manures and organic amendments in crop rotations provided a measurable increase in SOM quality and other soil quality attributes compared with continuous cereal systems.

Soil Quality and Forest Soils

Several studies have assessed soil quality indicators in forest soils. Pennock and van Kessel (1997) evaluated the effect of clear-cut harvest practices on forest soils in Saskatchewan and established that although there was a decline in soil quality attributes, the values were within the natural or undisturbed range, except for SOM, which had declined below the natural range. McBride et al. (1990), using apparent electrical conductivity measurements as an indicator of forest soil quality on nonsaline forest soils in Ontario, found that variations in some soil chemical attributes and total N, that
Table 1. Sequential framework to evaluate soil quality for specific purpose or fitness of use (after Carter et al., 1997; Carter, 2000).

<table>
<thead>
<tr>
<th>Sequence steps</th>
<th>Sequential framework</th>
<th>Questions implied by the framework</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Purpose</td>
<td>What will the soil be used for?</td>
</tr>
<tr>
<td>2</td>
<td>Functions</td>
<td>What specific role is being asked of the soil?</td>
</tr>
<tr>
<td>3</td>
<td>Processes</td>
<td>What key soil processes support each function?</td>
</tr>
<tr>
<td>4</td>
<td>Properties or attributes</td>
<td>What are the critical soil properties for each process? What are their critical or threshold levels?</td>
</tr>
<tr>
<td>5</td>
<td>Indicators, surrogates, or pedotransfer function</td>
<td>When the attribute is difficult to measure or not available, which indirect or related property or properties can be used in its place?</td>
</tr>
<tr>
<td>6</td>
<td>Methodology standardization</td>
<td>What methods are available to measure the attribute? Technical rules and protocols for soil sampling, handling, storage, analysis, and interpretation of data.</td>
</tr>
</tbody>
</table>

were major determinants of forest productivity, accounted for most of the variation in apparent electrical conductivity of bulk soil.

**DESCRIPTIVE AND FUNCTIONAL APPROACHES TO SOIL QUALITY**

The above Canadian studies generally provide a descriptive approach to soil quality based on changes in soil properties and components rather than a functional approach based on the value or fitness of a soil for a specific use. In response to the need to characterize the functional approach, Anderson and Gregorich (1984) proposed that soil quality be defined as “the sustained capability of a soil to accept, store, and recycle water, nutrients, and energy.” Other studies also emphasized the need to assess soil quality on the basis of soil functions (Larson and Pierce, 1991, 1994; Doran and Parkin, 1994; Doran et al., 1996; Karlen et al., 1994, 1997). On the recognition that agriculture is part of a much broader ecological system, Acton and Gregorich (1995) stressed environmental concerns by defining soil quality as “the soil’s capacity or fitness to support crop growth without resulting in soil degradation or otherwise harming the environment.” Carter et al. (1997) summarized the evolution and development of the approaches used in defining soil quality. Present-day approaches generally use an ecological framework to evaluate soil quality based on the following sequence: functions, processes, attributes or properties, attribute indicators, and methodology (Table 1).

Soil quality has two parts: an intrinsic part covering a soil’s inherent capacity for crop growth and a dynamic part influenced by the soil user or manager. The distinction between inherent and dynamic soil quality can also be characterized by the genetic (or static) pedological processes vs. the kinetic (or dynamic) processes in soil as proposed by Richter (1987).

**Inherent Soil Quality**

The quality of any soil depends in part on the soil’s natural or inherent composition, which is a function of geological materials and soil-state factors or variables (e.g., parent material and topography). Attributes of inherent soil quality, such as mineralogy and particle size distribution, are mainly viewed as almost static and usually show little change over time.

Characterization of inherent soil quality for crop production also involves consideration of extrinsic factors, those factors apart from soil that influence crop yield, such as climatic (i.e., precipitation, evaporative demand, and air temperature), topographic, and hydrologic parameters. Generally, inherent soil quality for crop production cannot be evaluated independently of extrinsic factors. For example, a high clay content may be favored in a semiarid region, where soil moisture retention is an advantage, but may be undesirable in humid conditions in which poor internal drainage may limit yields (Janzen et al., 1992). In similar fashion, a certain soil bulk density can be optimal under a semiarid moisture regime but deleterious under a humid moisture regime due to changes in relative saturation and subsequent poor soil aeration (Carter, 1990). Because of these considerations, there is no universally applicable set of inherent soil quality criteria and optimum values.

Inherent soil quality can be assessed using national land resource or soil survey inventories. MacDonald et al. (1995) developed an inherent soil quality index for some Canadian soils based on soil drainage status, water-holding capacity, cation exchange capacity, physical rooting conditions (soil depth, crust and compact layers), and chemical rooting conditions (pH and salinity). Land resource databases were further utilized to characterize areas where inherent soil quality was at risk based on soil and landscape indicators and indicators that reflect intensive agricultural practices, both of which feature SOM.

**Dynamic Soil Quality**

Dynamic soil quality encompasses those soil properties that can change over relatively short time periods (e.g., SOM, labile SOM fractions, soil structural components, and macroporosity) in response to human use and management and that are strongly influenced by agronomic practices. Soil organic matter is both inherent, as total SOM is related to particle size distribution, and dynamic, as it is related to ongoing inputs of organic material to the soil.

**SOIL QUALITY AND SOIL ORGANIC MATTER**

Soil organic matter is considered to be a key attribute of soil quality (Larson and Pierce, 1991; Gregorich et al., 1994) and also environmental quality (Smith et al., 2000). It is involved in and related to many soil chemical, physical, and biological properties. Thus, information is needed on the multifunctional role of SOM in soil qual-
Table 2. Selected attributes of soil organic matter (SOM) that are sensitive to soil management and indicate change in total SOM.

<table>
<thead>
<tr>
<th>Organic matter attribute</th>
<th>Percent of soil organic C†</th>
<th>Methodology</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macroorganic matter C and N (particulate C and N)</td>
<td>15–45</td>
<td>Soil dispersion or sieving</td>
<td>Sand-sized organic material consisting mainly of fine roots and large organic debris.</td>
</tr>
<tr>
<td>Light fraction C and N</td>
<td>3–45</td>
<td>Soil densimetric fractionation</td>
<td>Composed mainly of plant and microbial residues. A transitory pool of organic material between fresh residues and humidified SOM.</td>
</tr>
<tr>
<td>Microbial biomass C and N</td>
<td>1–3</td>
<td>Soil fumigation or extraction</td>
<td>The dynamic, living microbial component of the soil, which regulates the transformation of SOM and functions as both a sink and source of plant nutrients.</td>
</tr>
<tr>
<td>Mineralizable C and N</td>
<td>3–30</td>
<td>Soil incubation</td>
<td>Reflects metabolic activity of heterotrophic microbes and provides an integrated, direct measure of SOM turnover.</td>
</tr>
</tbody>
</table>

† Estimates compiled from data in Carter and Rennie, 1982; Carter et al., 1998.

Soil Quality and Soil Organic Matter Attributes and Indicators

Soil quality attributes can be defined as measurable soil properties that influence the capacity of the soil to perform a specific function (Acton and Padbury, 1993). In many cases, the specific property may be difficult to measure directly, so an indicator is used to serve as an indirect, practical measure of the attribute. For dynamic soil quality, indicators are most useful when they indicate or measure change in the attribute.

Various studies have attempted to identify sets of attributes or properties that can characterize a soil process or processes in regard to a specific soil function. Arshad and Coen (1992) identified several soil physical and chemical properties that could serve as attributes of soil quality. More recently, Topp et al. (1997) provided a detailed assessment of soil physical attributes based on the ability of the soil to store and transmit liquids, solutes, gases, and heat; water parameters; aeration; strength; and structure. Soil biological attributes were categorized by Visser and Parkinson (1992) and Gregorich et al. (1994, 1997).

Measurement of SOM is relatively straightforward, so there is little need for an indicator to assess its status in soil at any one time. However, it is difficult to measure small changes in soil organic matter against a relatively large background mass, so indicators (e.g., major attributes of SOM) are needed that are more sensitive to change in organic matter inputs than the total mass that will indicate the direction of change in total mass of organic matter (Table 2).

Identifying key soil attributes that are sensitive to soil functions allows the establishment of minimum data sets that will provide a practical assessment of one or several soil processes of importance for a specific soil function (Larson and Pierce, 1991, 1994). For the multifaceted role or function of SOM, different minimum data sets can be developed to provide a compilation of subattributes (Gregorich et al., 1994).

Sensitivity of Soil Organic Matter Attributes

In many cases, soil quality assessment requires a monitoring system to provide regular surveillance of soil quality attributes or indicators over time. Wang et al. (1997) describes such a nation-wide system established in Canada. Larson and Pierce (1994) and Pierce and Gilliland (1997) identify both computer models (which use attributes as variables) and statistical (i.e., temporal pattern of attribute mean and standard deviation) control as a means to assess soil quality change over time. Other approaches are use of archived soil and plant samples from long-term experiments and use of geostatistical methods (Wendroth et al., 1997).

One major area of recent research has been the evaluation of the sensitivity of SOM fractions or attributes to changes in total SOM. Early studies showed that SOM attributes (e.g., microbial biomass and mineralizable C) were very sensitive to changes in total SOM and could be utilized, based on their relative simple and straightforward methodology, as indicators of change (Carter and Rennie, 1982). More recently, a greater range of labile SOM attributes (e.g., light fraction and macroorganic matter), along with a relatively simple measure of soil structural stability (e.g., aggregate stability), have been evaluated on their sensitivity to change in total SOM (Campbell et al., 1989, 1997, 1998a, 1998b; Biederbeck et al., 1998; Bolinder et al., 1999; Angers et al., 1999) (Table 3). Macroorganic matter and light fraction (Gregorich and Janzen, 1996) and soil microbial biomass (Carter et al., 1999) are highly responsive to changes in C inputs to the soil and can provide a measurable change before any such change in the total SOM. However, the validity of this approach to indicate the direction of SOM is restricted under conditions where climate impedes adequate C inputs or suppresses the rate of decomposition (Janzen et al., 1998).

Table 3. Comparison of sensitivity analysis of several attributes or fractions of soil organic matter (SOM) to changes in total SOM in eastern and western Canada.†

<table>
<thead>
<tr>
<th>MO-C</th>
<th>MO-N</th>
<th>LF-C</th>
<th>LF-N</th>
<th>MIN-C</th>
<th>MIN-N</th>
<th>MB-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td>1.6</td>
<td>–</td>
<td>–</td>
<td>1.5</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>1.6</td>
<td>1.7</td>
<td>–</td>
<td>–</td>
<td>1.8</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1.6</td>
<td>1.4</td>
<td>–</td>
<td>1.3</td>
</tr>
<tr>
<td>–</td>
<td>–</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

† MO, macroorganic matter; LF, light fraction; MIN, mineralizable; and MB, microbial biomass. Sensitivity analysis is based on ratio of a specific C fraction under conservation system (e.g., crop residues retained, use of forages in rotation) to that under conventional cropping system (i.e., low return of generation of organic matter). The sensitivity ratio for total SOM was 1.1 to 1.2 in all of the above studies.
Other approaches have taken a wider approach using organic matter molecular components, molecular biology, and soil microbial diversity to complement measurement of SOM fractions (Monreal et al., 1997a). However, the utility of such measurements in evaluating soil organic matter quality is not so clear. Kay et al. (1997) assessed the sensitivity of soil structural characteristics to changes in SOM.

### Limitations in Assessing Soil Organic Matter Quality

The ecological framework used to evaluate soil quality (Table 1) can also be utilized to assess SOM quality. The main limitations to this approach are the setting of critical limits, or threshold values, and standardization in methodology.

### Critical Limits or Threshold Values for Soil Organic Matter

Critical (threshold, trigger, baseline, or reference) limits in soil quality assessment refer to the specific value or range of a soil property or indicator that is required to ensure that a soil process or function is not restricted or adversely influenced. Based on the primary concept of *fitness for use* for soil quality, critical limits denote the boundary values, or margins of tolerance, required for soil indicators that are associated with optimum soil functioning and indicate if a soil is *fit* for a specific use (Larson and Pierce, 1994). Few attempts have been made to characterize critical values for key soil quality indicators, such as SOM (Arshad and Martin, 2001), while limiting values, or thresholds, for fractions and components of SOM are generally not known (Carter et al., 1999). Soil organic matter serves many soil functions (Gregorich et al., 1994), so the critical value or range would vary according to function. Generally, at present, two main approaches are utilized:

1. Most studies advocate use of average or baseline SOM values under local soil conditions and soil types (e.g., MacDonald et al., 1995; Gomez et al., 1996) to establish an initial reference level of threshold (Arshad and Martin, 2001) based on general consensus.
2. Some studies have set or characterized critical levels for total SOM based on empirically derived relations between SOM and specific soil processes and conditions. Close relations have been quantified between SOM and soil fertility indices (Feller et al., 1996), crop productivity (Bauer and Black, 1994; Reeves, 1997), soil erodibility (Feller et al., 1996; Fig. 1), and soil aggregation (Angers and Carter, 1996; Jastrow and Miller, 1997; Kay, 1998; Fig. 2).

The above relationships suggest that critical levels could be established for specific soil types and soil management scenarios. Generally, critical levels for total SOM would be soil or site specific, related to a single soil process or function, and based on a range rather than a set value.

### Standardization for Soil Organic Matter

Standardization concerns the technical protocol for the sampling, storage, laboratory methods, and interpretation of soil properties, attributes, and indicators as a means to provide reliable and comparable methodology for soil quality assessment (Nortcliff, 1997). At present, there is a need to develop acceptable standard sampling and measurement protocols to monitor and evaluate change in SOM. Estimates of SOM status and change are still mainly based on C concentration rather than mass, and comparisons between treatments are derived from unequal soil depth, densities, or soil mass (Ellert and Bettany, 1995).

Generally, there is no well-accepted operational definition of SOM (Agric. Soils Working Group, unpublished, 1999). It is not clear if a measure of SOM should include plant litter, crop residues, or root material. Estimated annual straw and root C inputs of cereal crops in eastern Canada (Bolinder et al., 1997) ranged from 2 to 5% of the total (0–60 cm depth) SOM (Carter et al., 1998) and is probably higher for grasses and legumes. Crop-derived C in SOM estimates has implications for...
Table 4. Functions of soil organic matter (SOM) in both whole and aggregated soil and relations to soil processes and conditions.

<table>
<thead>
<tr>
<th>Location of SOM</th>
<th>Function or processes involved</th>
<th>Some resulting soil conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Related to SOM in the whole soil</td>
<td>Compactibility and strength (Soane, 1990)</td>
<td>Increased resistance to soil compaction pressures (Soane, 1990)</td>
</tr>
<tr>
<td></td>
<td>Water-holding capacity (Hamblin and Davies, 1977)</td>
<td>Potential increase in plant available water (Johnston, 1986; Hudson, 1994)</td>
</tr>
<tr>
<td></td>
<td>Soil friability (Christensen and Johnston, 1997; Watts and Dexter, 1998)</td>
<td>Improve soil workability and decrease draft requirements (Low and Piper, 1973)</td>
</tr>
<tr>
<td>Related to SOM in particles and aggregates</td>
<td>Conservation of nutrients and energy (Christensen, 1996; Hassink, 1997)</td>
<td>Reduced turnover time for SOM and increased retention of nutrients (see Table 5; Kay and Angers, 2000)</td>
</tr>
<tr>
<td></td>
<td>Soil physical processes (Kay, 1998)</td>
<td>Stabilized pore size distribution; improved infiltration of water in soil and aeration status (Thomasson, 1978; Kay and Angers, 2000)</td>
</tr>
<tr>
<td></td>
<td>Erodibility (Feller and Beare, 1997; Gregorich et al., 1998)</td>
<td>Enhances stability of soil aggregation and decrease in loss of fine soil particles (Feller et al., 1996)</td>
</tr>
</tbody>
</table>

soil-handling protocols after sampling. Use of sieving methods to separate crop residue and macroorganic matter would be beneficial for SOM characterization.

**FACTORS THAT REGULATE ORGANIC MATTER FUNCTIONING IN SOIL**

A major component of sustainable land use is to sustain and improve the quality of the soil resource base. Monitoring is important, but the usefulness of the data will only be realized if it is used in management decisions to correct deficiencies or improve the quality of the soil resource (Pierce, 1996). In regard to SOM, monitoring would indicate if levels in a specific soil are in decline or too low to adequately support those functions or processes that are SOM dependent. Evidence of low SOM could result in the following soil management decisions: (i) Assess if the soil management system is capable of producing or providing adequate organic matter inputs (i.e., inputs of crop residue, organic amendments, or both) to prevent a decline in SOM and (ii) assess if present management strategies allow the best use or placement of organic matter inputs.

Factors that regulate SOM functioning in soil are related to organic matter additions or inputs, which influence particulate or macroorganic matter, and the relation between SOM and soil aggregates. Functions of SOM, differentiated on the basis of total SOM or aggregated SOM, are given in Table 4.

**Influence of Organic Matter Inputs on Soil Functions**

Increasing organic matter inputs via agricultural management is the key to increasing SOM quantity (Janzen et al., 1997). If the initial level of SOM is below the capacity of a specific soil to store organic matter, then SOM levels increase linearly with increasing input levels although the slope of the line may differ, reflecting the various influences of climate, soil type, and soil management (Fig. 3). The major management strategies to increase SOM quantity are increasing primary production (e.g., perennial crops, plant nutrition, and organic amendments) and increasing the proportion of primary production returned to or retained by the soil (e.g., crop residue retention and placement). Placement of residues at depth can also allow a relative increase in stored SOM (Carter et al., 1998). In some cases, vegetative differences and quality of crop residue (e.g., lignin, N, and C/N ratio) can also influence the quantity of SOM (Juma, 1993).

Addition of organic matter to the soil, in the form of crop residues or organic amendments, increases the level of low-density macroorganic matter, which can represent up to 45% of total SOM (Carter et al., 1998; Kay, 1998). This form of SOM functions in improving the mechanical properties of soil (Table 4).

**Influence of Aggregated Organic Matter on Soil Functions**

The capacity of a soil to store organic matter is related to the association of SOM with clay and clay plus silt (2–20 μm diam.) particles, soil microaggregates (20–250 μm diam.) and macroaggregates (>250 μm diam.), and the fraction of sand-sized macroorganic matter (Christensen, 1996; Tisdall, 1996). Soil mineralogy and particle size distribution regulate the capacity of a soil to preserve organic matter and control soil aggregation. The interrelation between soil aggregation and SOM constrains both decomposition (e.g., separate C substrate from decomposer organisms) and predation (e.g., separate microbes from predators) processes, and consequently results in the conservation and stabilization of SOM (Juma, 1993).

Arable soils contain less organic matter than adjacent...
Grassland soils, but the amount of SOM associated with the clay plus silt (i.e., 2–20 μm diam.) can be similar (Hassink, 1997). More than 80% of the organic matter in temperate soils can be associated with <20-μm-diam. organomineral particles (Christensen, 1996). However, the capacity of a soil to protect and accumulate SOM in organomineral particles is not always positively related to the clay and silt content per se but rather to the degree to which this capacity level is filled (Hassink and Whitmore, 1997). Once the clay plus silt is saturated with organic matter, additional SOM would be found in macroaggregates (Angers and Carter, 1996; Franzluebbers and Arshad, 1996), probably as sand-sized macroorganic matter. Figure 4 illustrates the above differences in the association of soil organic C in whole soil, organic matter fractions, and aggregates for a Charlottetown fine sandy loam (Haplorthod) under two cropping systems in eastern Canada and indicates the importance of these processes on changes in water-stable aggregates.

Grassland and forest soils, which can contain relatively high amounts of organic matter, generally have more sand-sized organic matter than arable soils (Carter et al., 1998). In well-aggregated soils, most of the SOM can be found in macroaggregate complexes (Angers and Carter, 1996; Jastrow and Miller, 1997). Figure 5 illustrates, using a conceptual model, the SOM content and proportion in soil particles and aggregates of a Charlottetown fine sandy loam, from Prince Edward Island, and different types of SOM capacity levels related to organic matter inputs and aggregation. Clay plus silt serve as a fixed capacity level (Hassink, 1997; Hassink and Whitmore, 1997) while the combination of aggregated C and macroorganic C provide an additional variable capacity. The former is soil specific while the latter tends to be contingent on both soil type and management (i.e., C inputs).

The formation of aggregates in most temperate soils distributes organic matter into fractions with an increasing susceptibility to decomposition as follows: within clay plus silt particles, within microaggregates (i.e., intramicroaggregate), within macroaggregates but external to microaggregates (i.e., includes light fraction, macroorganic matter, and microbial biomass), and free macroorganic matter (Carter, 1996; Christensen, 1996). The aggregation process itself is a means to both conserve and protect SOM and allow the stored organic matter to function as a reservoir of plant nutrients and energy. This is illustrated by the turnover time for SOM fractions and SOM in aggregates based on various isotopic studies (Table 5). Aggregated SOM functions in regulating air and water infiltration and soil stability, and thus can serve as an indicator associated with the

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**Fig. 4.** Association of soil organic C in whole soil, organic matter fractions, and aggregates, and changes in water-stable aggregates in a Charlottetown fine sandy loam (Haplorthod) under two cropping systems. Organic C in clay plus silt particles estimated using the model of Hassink and Whitmore (1997). Error bars indicate standard error.

**Fig. 5.** Conceptual model of soil organic matter (SOM) content and proportion in soil particles and aggregates of a Charlottetown fine sandy loam (Haplorthod) illustrating different measurable capacity levels. OM, organic matter.
### Table 5. Estimates of turnover time for soil organic matter in different fractions and in soil aggregates (after Carter, 2000).†

<table>
<thead>
<tr>
<th>Type of organic matter</th>
<th>Estimated turnover time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic matter in fractions</td>
<td>years</td>
</tr>
<tr>
<td>Litter, crop residue</td>
<td>0.5–2</td>
</tr>
<tr>
<td>Microbial biomass</td>
<td>0.1–0.4</td>
</tr>
<tr>
<td>Macroorganic matter</td>
<td>1–8</td>
</tr>
<tr>
<td>Light fraction</td>
<td>1–15</td>
</tr>
<tr>
<td>Organic matter in aggregates</td>
<td></td>
</tr>
<tr>
<td>Nonaggregated soil</td>
<td>1–7</td>
</tr>
<tr>
<td>Macroaggregates (&gt;250 μm diam.)</td>
<td>1–23</td>
</tr>
<tr>
<td>Microaggregates (20–250 μm diam.)</td>
<td>3–80</td>
</tr>
<tr>
<td>Silt plus clay (&lt;20 μm diam.)</td>
<td>5–1000</td>
</tr>
</tbody>
</table>

† Compiled from data in Carter, 1996; Gregorich and Janzen, 1996; Collins et al., 1997; and Monreal et al., 1997b.
‡ Organic matter in macroaggregates but external to microaggregates (i.e., interaggregate).

### REFERENCES


Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under...


