U.S. Department of Agriculture Agricultural Research Service and Natural Resources Conservation Service. 1998. Soil quality kit guide [Online]. Available with updates at http://www.statlab.iastate.edu/survey/SQI/kit2.html (verified 26 Sept. 2001).

U.S. Department of Agriculture Natural Resources Conservation Service. 1999. Soil quality card design manual: A guide to develop locally adapted conservation tools [Online]. Available with updates at http://www.statlab.iastate.edu/survey/SQI/cardguide.html (verified 27 Sept. 2001).

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 nonsustainable 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).

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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).

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

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, crusting, 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.

Organic matter attribute	Percent of soil organic C†	Methodology	Comments
Macroorganic matter C and N (particulate C and N)	15–45	Soil dispersion or sieving	Sand-sized organic material consisting mainly of fine roots and large organic debris.
Light fraction C and N	3–45	Soil densimetric fractionation	Composed mainly of plant and microbial residues. A transitory pool of organic material between fresh residues and humidified SOM.
Microbial biomass C and N	1–3	Soil fumigation or extraction	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.
Mineralizable C and N	3–30	Soil incubation	Reflects metabolic activity of heterotrophic microbes and provides an integrated, direct measure of SOM turnover.

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

ity, including the setting of critical values and standardization.

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.†

MO-C	MO-N	LF-C	LF-N	MIN-C	MIN-N	MB-C
	Grain and forage sequences, 3 to 67 yr (Bolinder et al., 1999)					
1.3	1.5	1.5	1.6	–	–	1.5
	Potato cropping sequences, 9 yr (Angers et al., 1999)					
–	–	1.6	1.7	–	–	1.8
	Grain sequences, 11 yr (Campbell et al., 1997)					
–	–	–	–	1.6	1.4	1.3
	Grain–green manure sequences, 6 yr (Biederbeck et al., 1998)					
–	–	1.3	–	1.4	1.6	–

† 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.

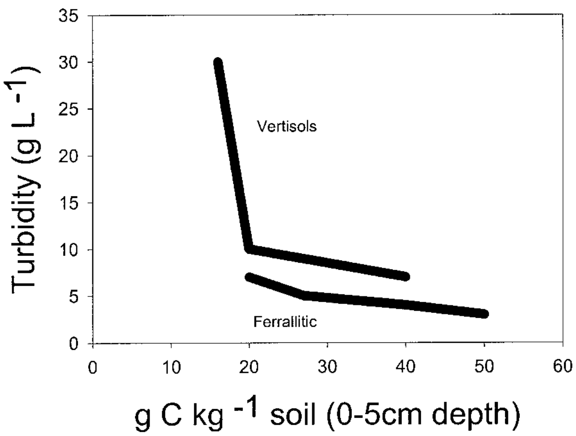

Fig. 1. Relation between soil organic C and soil erodibility (i.e., turbidity) in a Vertisol (Cryert) and Ferrallitic (Oxisol) soil. There is a critical limit of >20 g C kg^{-1} to reduce erodibility in the Vertisols. Data derived from Feller et al. (1996).

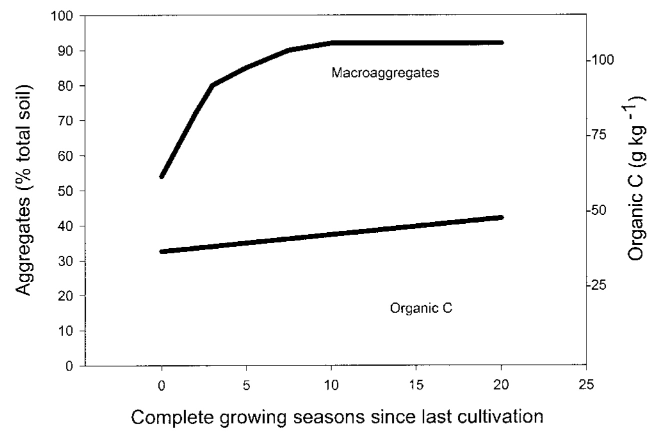

Fig. 2. Relation between soil organic C and macroaggregation over time in a Chernozemic (Boroll) soil. Maximum macroaggregation is >40 g C kg^{-1}. Data derived from Jastrow and Miller (1997).

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.

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

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

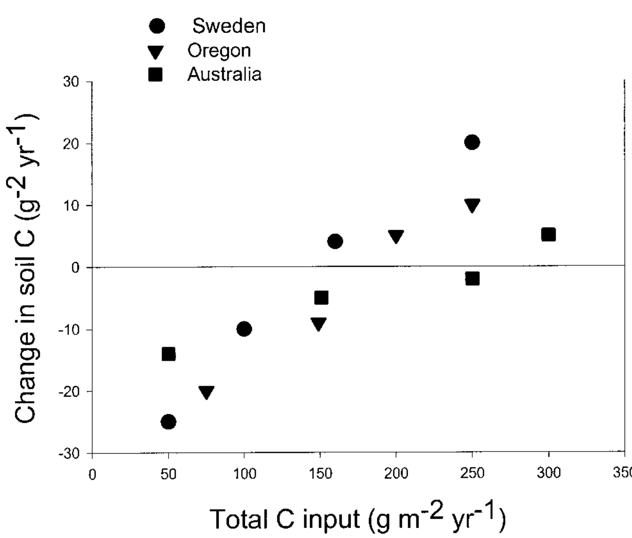

Fig. 3. Comparison of change in soil organic C in relation to total organic C inputs at three different locations (after Parton et al., 1996).

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.

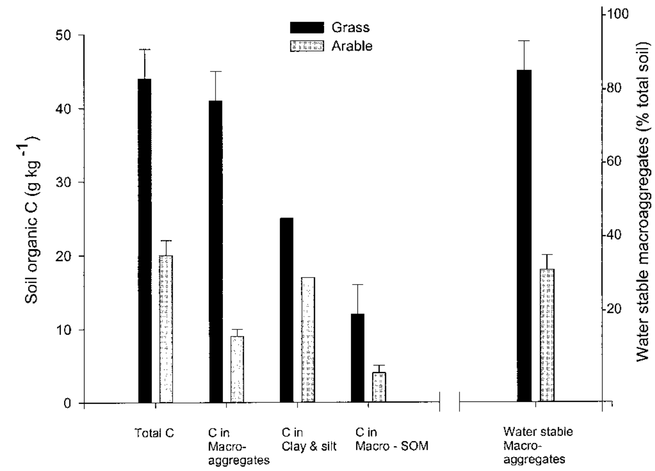

Fig. 4. Association of soil organic C in whole soil, organic matter fractions, and aggregates, and changes in water-stable aggregates in a Charlottetown fine sandy loam (Haplorthod) under two cropping systems. Organic C in clay plus silt particles estimated using the model of Hassink and Whitmore (1997).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

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

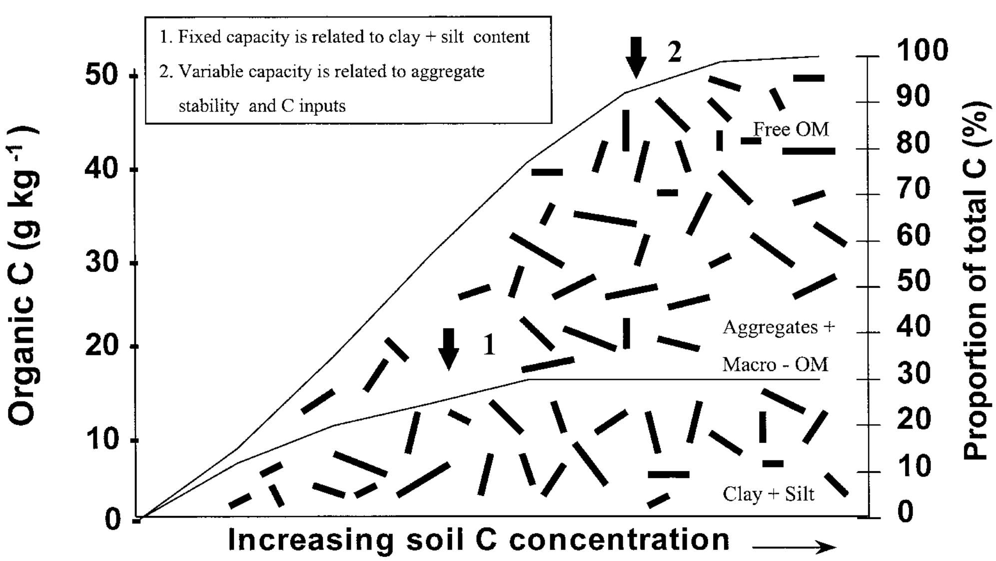

Fig. 5. Conceptual model of soil organic matter (SOM) content and proportion in soil particles and aggregates of a Charlottetown fine sandy loam (Haplorthod) illustrating different measurable capacity levels. OM, organic matter.

Table 5. Estimates of turnover time for soil organic matter in different fractions and in soil aggregates (after Carter, 2000).†

Type of organic matter	Estimated turnover time
Organic matter in fractions	**years**
Litter, crop residue	**0.5–2**
Microbial biomass	**0.1–0.4**
Macroorganic matter	**1–8**
Light fraction	**1–15**
Organic matter in aggregates	
Nonaggregated soil	**1–7**
Macroaggregates‡ (>250 μm diam.)	**1–23**
Microaggregates (20–250 μm diam.)	**3–80**
Silt plus clay (<20 μm diam.)	**5–1000**

† 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).

processes of soil permeability and erodibility (Feller and Beare, 1997).

CONCLUSIONS

A wide range of land management studies in Canada and elsewhere, conducted over the last two decades, have established that SOM and aggregate stability are important indicators to assess sustainable land use. Ecosystem concepts such as functions, processes, attributes, and indicators as well as methodology provide a useful framework to assess SOM quality although the impediment of setting critical limits for SOM and standardization in methodology still remain. At present, critical limits are mainly established by consensus based on reference values derived from soil resource inventories although the development of empirical relations between SOM and specific soil processes and functions offer the promise of more precise estimates in future studies. Sensitivity analyses have shown that several SOM fractions have the potential to indicate change in total SOM. Sand-sized macroorganic matter functions by enhancing soil water-holding capacity and moderating or reducing soil compactibility while aggregated SOM functions in regulating air and water infiltration and conserving plant nutrients. Overall, organic matter inputs, the dynamics of the sand-sized macroorganic matter, and the soil aggregation process are important factors in soil functioning.

REFERENCES

Acton, D.F. 1991. Concepts and criteria of soil quality in the context of western Canada. p. 2–4. *In* S.P. Mathur and C. Wang (ed.) Soil quality in the Canadian context—1988 discussion papers. Tech. Bull. 1991-1E. Res. Branch, Agric. Canada, Ottawa, ON.

Acton, D.F., and L.J. Gregorich. 1995. The health of our soils—towards sustainable agriculture in Canada. Cent. for Land and Biol. Resources Res., Res. Branch, Agric. and Agri-Food Canada, Ottawa, ON.

Acton, D.F., and G.A. Padbury. 1993. A conceptual framework for soil quality assessment and monitoring. p. 2–10. *In* A program to assess and monitor soil quality in Canada: Soil quality evaluation summary. Res. Branch, Agric. Canada, Ottawa, ON.

Anderson, D.W., and E.G. Gregorich. 1984. Effect of soil erosion on soil quality and productivity. p. 105–113. *In* Soil erosion and degradation. Proc. Annu. Western Provincial Conf. on Rationalization of Water and Soil Res. and Manage., 2nd, Saskatoon, SK, Canada.

Angers, D.A., and M.R. Carter. 1996. Aggregation and organic matter storage in cool, humid agricultural soils. p. 193–211. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Angers, D.A., L.M. Edwards, J.B. Sanderson, and N. Bissonnette. 1999. Soil organic matter quality and aggregate stability under eight potato cropping sequences in a fine sandy loam of Prince Edward Island. Can. J. Soil Sci. 79:411–417.

Arshad, M.A., and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. Am. J. Altern. Agric. 7:25–30.

Arshad, M.A., and S. Martin. 2001. Identifying critical limits for soil quality indicators in agroecosystems. Agric. Ecosyst. Environ. (in press).

Bauer, A., and A.L. Black. 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Sci. Soc. Am. J. 58:185–193.

Biederbeck, V.O., C.A. Campbell, V. Rasiah, R.P. Zentner, and G. Wen. 1998. Soil quality attributes as influenced by annual legumes used as green manure. Soil Biol. Biochem. 30:1177–1185.

Boehm, M.M., and D.W. Anderson. 1997. A landscape-scale study of soil quality in three prairie farming systems. Soil Sci. Soc. Am. J. 61:1147–1159.

Bolinder, M.A., D.A. Angers, and J.P. Dubac. 1997. Estimating shoot to root ratios and annual carbon inputs in soils from cereal crops. Agric. Ecosyst. Environ. 63:61–66.

Bolinder, M.A., D.A. Angers, E.G. Gregorich, and M.R. Carter. 1999. The response of soil quality indicators to conservation management. Can. J. Soil Sci. 79:37–45.

Campbell, C.A., V.O. Biederbeck, M. Schnitzer, F. Selles, and R.P. Zentner. 1989. Effect of 6 years of zero tillage and N fertilizer management on changes in soil quality of an Orthic Brown Chernozem in southwestern Saskatchewan. Soil Tillage Res. 14:39–52.

Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zentner, D. Curtin, and M.R. Peru. 1998a. Long-term effects of tillage and fallow-frequency on soil quality attributes in a clay soil in semiarid southwestern Saskatchewan. Soil Tillage Res. 46:135–144.

Campbell, C.A., B.G. McConkey, V.O. Biederbeck, R.P. Zentner, S. Tessier, and D.L. Hahn. 1997. Tillage and fallow frequency effects on selected soil quality attributes in a coarse-textured Brown Chernozem. Can. J. Soil Sci. 77:497–505.

Campbell, C.A., A.G. Thomas, V.O. Biederbeck, B.G. McConkey, F. Selles, D. Spurr, and R.P. Zentner. 1998b. Converting from no-tillage to pre-seeding tillage: Influence on weeds, spring wheat grain yields and N, and soil quality. Soil Tillage Res. 46:175–185.

Cao, Y.Z., D.R. Coote, H.W. Rees, C. Wang, and T.L. Chow. 1994. Effects of intensive potato production on soil quality and yield at a benchmark site in New Brunswick. Soil Tillage Res. 29:23–34.

Carter, M.R. 1990. Relative measures of soil bulk density to characterize compaction in tillage studies. Can. J. Soil Sci. 70:425–433.

Carter, M.R. 1996. Analysis of soil organic matter storage in agroecosystems. p. 3–11. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Carter, M.R. 2000. Organic matter and sustainability. p. 9–22. *In* R.M. Rees et al. (ed.) Sustainable management of soil organic matter. CAB Int., Wallingford, UK.

Carter, M.R., E.G. Gregorich, D.W. Anderson, J.W. Doran, H.H. Janzen, and F.J. Pierce. 1997. Concepts of soil quality and their significance. p. 1–19. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Carter, M.R., E.G. Gregorich, D.A. Angers, M.H. Beare, G.P. Sparling, D.A. Wardle, and R.P. Voroney. 1999. Interpretation of microbial biomass measurements for soil quality assessment in humid regions. Can. J. Soil Sci. 79:507–520.

Carter, M.R., E.G. Gregorich, D.A. Angers, R.G. Donald, and M.A. Bolinder. 1998. Organic C and N storage, and organic C fractions, in adjacent cultivated and forested soils of eastern Canada. Soil Tillage Res. 47:253–261.

Carter, M.R., and R.J. MacEwan. 1996. Summary and conclusions. p. 3–4. *In* R.J. MacEwan and M.R. Carter (ed.) Proc. Symp. on Soil Quality for Land Manage.: Science, Practice and Policy. Univ. of Ballarat, Ballarat, VIC, Australia.

Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587–597.

Christensen, B.T. 1996. Carbon in primary and secondary organomineral complexes. p. 97–165. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Christensen, B.T., and A.E. Johnston. 1997. Soil organic matter and soil quality—lessons learned from long-term experiments at Askov and Rothamsted. p. 399–430. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Collins, H.P., E.A. Paul, K. Paustian, and E.T. Elliott. 1997. Characterization of soil organic carbon relative to its stability and turnover. p. 51–72. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. CRC Press, Boca Raton, FL.

Coote, D.R. 1991. Soil quality in the context of eastern Canada. p. 5–15. *In* S.P. Mathur and C. Wang (ed.) Soil quality in the Canadian context—1988 discussion papers. Tech. Bull. 1991-1E. Res. Branch, Agric. Canada, Ottawa, ON.

Doran, J.W., and T.B. Parkin. 1994. Defining and assessing soil quality. p. 3–21. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. ASA and SSSA, Madison, WI.

Doran, J.W., M. Sarrantonio, and M.A. Lieberg. 1996. Soil health and sustainability. Adv. Agron. 56:1–54.

Ellert, B.H., and J.R. Bettany. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can. J. Soil Sci. 75:529–538.

Feller, C., A. Albrecht, and D. Tessier. 1996. Aggregation and organic matter storage in kaolinitic and smectitic tropical soils. p. 309–359. *In* M.R. Carter and B.A. Stewart. (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Feller, C., and M.H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116.

Franzluebbers, A.J., and M.A. Arshad. 1996. Water stable aggregation and organic matter in four soils under conventional and zero tillage. Can. J. Soil Sci. 76:387–393.

Gomez, A.A., D.E. Swete Kelly, K.J. Syers, and K.J. Coughlan. 1996. Measuring sustainability of agricultural systems at the farm level. p. 108–113. *In* R.J. MacEwan and M.R. Carter (ed.) Proc. Symp. on Soil Quality for Land Manage.: Science, Practice and Policy. Univ. of Ballarat, Ballarat, VIC, Australia.

Gregorich, E.G., M.R. Carter, D.A. Angers, C.M. Monreal, and B.H. Ellert. 1994. Towards a minimum data set to assess soil organic matter quality in agricultural soils. Can. J. Soil Sci. 74:367–385.

Gregorich, E.G., M.R. Carter, J.W. Doran, C.E. Pankhurst, and L.M. Dwyer. 1997. Biological attributes of soil quality. p. 81–113. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Gregorich, E.G., K.J. Greer, D.W. Anderson, and B.C. Liang. 1998. Carbon distribution and losses: Erosion and deposition effects. Soil Tillage Res. 47:291–302.

Gregorich, E.G., and H.H. Janzen. 1996. Storage of soil carbon in the light fraction and macroorganic matter. p. 167–190. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Hamblin, A.P., and D.B. Davies. 1977. Influence of organic matter on the physical properties of some East Anglia soils of high silt content. J. Soil Sci. 28:11–22.

Hassink, J. 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant Soil 191:77–87.

Hassink, J., and A.P. Whitmore. 1997. A model of the physical protection of organic matter in soils. Soil Sci. Soc. Am. J. 61:131–139.

Hudson, B.D. 1994. Soil organic matter and available water capacity. J. Soil Water Conserv. 49:189–194.

Janzen, H.H., C.A. Campbell, B.H. Ellert, and E. Bremer. 1997. Soil organic matter dynamics and their relationship to soil quality. p. 277–291. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Janzen, H.H., C.A. Campbell, E.G. Gregorich, and B.H. Ellert. 1998. Soil carbon dynamics in Canadian agroecosystems. p. 57–80. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Janzen, H.H., F.J. Larney, and B.M. Olsen. 1992. Soil quality factors of problem soils in Alberta. p. 17–28. *In* Proc. Annu. Alberta Soil Sci. Workshop, 29th, Lethbridge, AB, Canada. 18–20 Feb. 1992. Dep. of Soil Sci., Univ. of Alberta, Edmonton, AB, Canada.

Jastrow, J.D., and R.M. Miller. 1997. Soil aggregate stabilization and carbon sequestration: Feedback through organomineral associations. p. 207–223. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Johnston, A.E. 1986. Soil organic matter, effects on soils and crops. Soil Use Manage. 2:97–105.

Juma, N.J. 1993. Interrelationships between soil structure/texture, soil biota/soil organic matter and crop production. Geoderma 57:3–30.

Karlen, D.L., M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. Soil Sci. Soc. Am. J. 61:4–10.

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L. Jordahl. 1994. Long-term tillage effects on soil quality. Soil Tillage Res. 32:313–327.

Kay, B.D. 1998. Soil structure and organic carbon: A review. p. 169–197. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. CRC Press, Boca Raton, FL.

Kay, B.D., and D.A. Angers. 2000. Soil structure. p. 229–276. *In* M.E. Sumner (ed.) Handbook of soil science. CRC Press, Boca Raton, FL.

Kay, B.D., A.P. da Silva, and J.A. Baldock. 1997. Sensitivity of soil structure to changes in organic carbon content: Predictions using pedotransfer functions. Can. J. Soil Sci. 77:655–667.

Ketcheson, J.W. 1980. Long-range effects of intensive cultivation and monoculture on the quality of southern Ontario soils. Can. J. Soil Sci. 60:403–410.

Larson, W.E., and F.J. Pierce. 1991. Conservation and enhancement of soil quality. p. 175–203. *In* Evaluation for sustainable land management in the developing world. IBSRAM Proc., 12th, Bangkok, Thailand. Vol. 2. Int. Board for Soil Res. and Manage., Jatujak, Thailand.

Larson, W.E., and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. p. 37–51. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Low, A.J., and F.J. Piper. 1973. Some examples of the effect of soil physical conditions on the tractive effort required during ploughing. J. Sci. Food Agric. 24:1011–1020.

MacDonald, K.B., W. Frazer, G. Lelyk, and F. Wang. 1995. A geographic framework for assessing soil quality. p. 19–30. *In* D.F. Acton and L.J. Gregorich (ed.) The health of our soils—towards sustainable agriculture in Canada. Cent. for Land and Biol. Resources Res., Res. Branch, Agric. and Agri-Food Canada, Ottawa, ON.

Martel, Y.A., and A.F. MacKenzie. 1980. Long-term effects of cultivation and land use on soil quality in Quebec. Can. J. Soil Sci. 60: 411–420.

Mathur, S.P. 1991. Some comments on loss or accumulation of soil organic matter and their effects on soil quality. p. 50–53. *In* S.P. Mathur and C. Wang (ed.) Soil quality in the Canadian context—1988 discussion papers. Tech. Bull. 1991-1E. Res. Branch, Agric. Canada, Ottawa, ON.

McBride, R.A., A.M. Gordon, and S.C. Shrive. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. Soil Sci. Soc. Am. J. 54:290–293.

Miller, F.P., and M.K. Wali. 1995. Soils, land use and sustainable agriculture: A review. Can. J. Soil Sci. 75:413–422.

Monreal, C.M., H. Dinel, M. Schnitzer, D.S. Gamble, and V.O. Biederbeck. 1997a. Impact of carbon sequestration on functional indicators of soil quality as influenced by management in sustainable agriculture. p. 435–457. *In* R. Lal et al. (ed.) Soil processes and the carbon cycle. Lewis Publ., CRC Press, Roca Baton, FL.

Monreal, C.M., H.-R. Schulten, and H. Kodama. 1997b. Age, turnover and molecular diversity of soil organic matter in aggregates of a Gleysol. Can. J. Soil Sci. 77:379–388.

Nortcliff, S. 1997. Standardisation for soil quality attributes. p. 187–201. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Olson, B.M., H.H. Janzen, F.J. Larney, and L.J. Selinger. 1996. A proposed method for measuring the effect of soil quality on productivity. Agron. J. 88:497–500.

Parton, W.J., D.S. Ojima, and D.S. Schimel. 1996. Models to evaluate soil organic matter storage and dynamics. p. 421–448. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Pennock, D.J., D.W. Anderson, and E. De Jong. 1994. Landscape-scale changes in indicators of soil quality due to cultivation in Saskatchewan, Canada. Geoderma. 64:1–19.

Pennock, D.J., and C. Van Kessel. 1997. Clear-cut forest harvest impacts on soil quality indicators in the mixedwood forest of Saskatchewan, Canada. Geoderma 75:13–32.

Pierce, F.J. 1996. Land management: The purpose for soil quality assessment. p. 53–58. *In* R.J. MacEwan and M.R. Carter (ed.) Proc. Symp. on Soil Quality for Land Manage.: Science, Practice and Policy. Univ. of Ballarat, Ballarat, VIC, Australia.

Pierce, F.J., and D.C. Gilliland. 1997. Soil quality control. p. 203–219. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Reeves, D.W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res. 43:131–167.

Richter, J. 1987. The soil as a reactor. Catena Verlag, Cremlingen, Germany.

Saini, G.R., and W.J. Grant. 1980. Long-term effects of intensive cultivation on soil quality in the potato-growing areas of New Brunswick (Canada) and Maine (U.S.A.). Can. J. Soil Sci. 60:421–428.

Schnitzer, M. 1991. Soil organic matter and soil quality. p. 33–49. *In* S.P. Mathur and C. Wang (ed.) Soil quality in the Canadian context—1988 discussion papers. Tech. Bull. 1991-1E. Res. Branch, Agric. Canada, Ottawa, ON.

Smith, O.H., G.W. Petersen, and B.A. Needelman. 2000. Environmental indicators of agroecosystems. Adv. Agron. 69:75–97.

Smyth, A.J., and J. Dumanski. 1995. A framework for evaluating sustainable land management. Can. J. Soil Sci. 75:401–406.

Soane, B.D. 1990. The role of organic matter in soil compactability: A review of some practical aspects. Soil Tillage Res. 16:179–201.

Soon, Y.K., and A.L. Darwent. 1998. Effect of integrated management of couch grass (*Elytrigia repens*) on soil quality and crop nutrition. J. Agric. Sci. 130:323–328.

Thomasson, A.J. 1978. Towards an objective classification of soil structure. J. Soil Sci. 29:38–46.

Tisdall, J.M. 1996. Formation of soil aggregates and accumulation of soil organic matter. p. 57–96. *In* M.R. Carter and B.A. Stewart (ed.) Structure and organic matter storage in agricultural soils. Lewis Publ., CRC Press, Boca Raton, FL.

Topp, G.C., W.D. Reynolds, F.J. Cook, J.M. Kirby, and M.R. Carter. 1997. Physical attributes of soil quality. p. 21–58. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Verity, G.E., and D.W. Anderson. 1990. Soil erosion effects on soil quality and yield. Can. J. Soil Sci. 70:471–484.

Visser, S., and D. Parkinson. 1992. Soil biological criteria as indicators of soil quality: Soil microorganisms. Am. J. Altern. Agric. 7:33–37.

Wang, C., B.D. Walker, and H.W. Rees. 1997. Establishing a benchmark system for monitoring soil quality in Canada. p. 323–337. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.

Wani, S.P., W.B. McGill, K.L. Haugen-Kozyra, J.A. Robertson, and J.J. Thurston. 1994. Improved soil quality and barley yields with fababeans, manure, forages and crop rotation on a Gray Luvisol. Can. J. Soil Sci. 74:75–84.

Warkentin, B.P. 1995. The changing concept of soil quality. J. Soil Water Conserv. 50:226–228.

Watts, C.W., and A.R. Dexter. 1998. Soil friability: Theory, measurement and the effects of management and organic carbon content. Eur. J. Soil Sci. 49:73–84.

Wendroth, O., W.D. Reynolds, S.R. Vieria, K. Reichardt, and S. Wirth. 1997. Statistical approaches to the analysis of soil quality data. p. 247–276. *In* E.G. Gregorich and M.R. Carter (ed.) Soil quality for crop production and ecosystem health. Elsevier, Amsterdam.