Effects of Soil and Crop Management Practices on Soil Quality

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Abstract

Developing the concept of soil quality may help identify the soil and crop management practices required for environmentally, socially, and economically sustainable agriculture. Objectives of this paper are (1) to review current efforts to define soil quality, (2) to discuss factors and processes which influence soil quality, (3) to identify, soil and crop management practices that affect processes influencing soil quality, and (4) to demonstrate a method for evaluating soil quality. A common focus among all proposed soil quality definitions is that the soil must reflect its ability to “function” in numerous ways at the present time and in the future. Soil and crop management practices that add or maintain soil carbon appear to be among the most important for restoring, maintaining, or improving soil quality. This includes utilizing reduced tillage, producing green manures or cover crops where climate and water resources will support the practice, applying supplemental animal or poultry manures or composted materials when available, and enhancing biological diversity to facilitate nutrient cycling and maintain soil structure. The soil quality assessment method that has been developed does not provide a definitive answer with regard to the measurements or specific functions which should be included in a soil quality index, but it uses specific measurements that describe soil functions and it is dynamic. Therefore, research focusing on the development of a soil quality index is justified and should be continued.

Introduction

The concept of soil quality has been suggested by several authors (Lal, 1991; Granatstein and Bezdicek, 1992; Sanders, 1992; Karlen et al., 1992; Papendick and Parr, 1992; Parr et al., 1992; Acton and Padbury, 1993) as a tool for assessing long-term sustainability of agricultural practices at local, regional, national, and international levels. This suggestion was reinforced by a recent report from the National Academy of Sciences, National Research Council (1993) recommending that the United States adopt a national policy which seeks to conserve and enhance soil quality as a fundamental first step to environ-mental improvement. My objectives for this report are (1) to review current efforts to define soil quality; (2) to discuss factors and processes which influence soil quality; (3) to identify soil and crop management practices that affect processes influencing soil quality; and (4) to demonstrate a potential method for evaluating soil quality.

Doran and Paikill (1994) suggested that soil quality assessments could be used as a management tool or aid to help farmers select specific management practices and as a measure of sustainability. They also suggested that approaches used to define and assess soil quality should be tailored for specific applications such as sustainable production, environmental quality, and animal or human health. Soil quality may also provide a focal point or vocabulary for communication between scientists and non-scientists, if the concept can be clearly defined.

Several definitions have been proposed in an attempt to define soil quality, but unlike air quality or water quality for which the U.S. has established standards through legislation, the concept remains difficult to define and quantify. Doran and Parkin (1994) stated that a common link among all proposed soil quality definitions was the capacity of soil to “function” effectively at the present time and in the future. They proposed defining soil quality as:

The capacity of a soil to function within the ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote animal health.

Acton and Padbury (1993) proposed that the definition of soil quality should be based on two critical soil functions, each representing major expectations placed on soils by farmers and agricultural or other resource managers. These functions are (1) to ensure sustainable crop production or the capacity to produce crops; and (2) to ensure environmental sustainability or the capacity of soil to serve as an environmental buffer, to accept, hold and release water to plants, streams, and groundwater, and to function as a source or sink for gaseous materials and the capacity to exchange those materials with the above ground atmosphere. With this general background, several factors and processes which may influence soil quality will be examined.

Factors Influencing Soil Quality

Karlen et al. (1992) stated that inherent interactions among the five basic soil forming factors [parent material, climate (including water and temperature effects), macro- and micro-organisms, topography and time] identified by Jenny (1941) create a relatively stable soil quality that has distinct physical, chemical, and biological characteristics in response to prevailing natural or non-anthropogenic factors. However, humankind, the anthropogenic force described as a sixth soil forming factor in the basic model for describing a soil (SSSA, 1987), interacts with the non-anthropogenic factors and influences soil quality both negatively and positively. Soil and crop management practices imposed on land resources by humankind thus determine whether inherent soil quality will be lowered, sustained, or improved over relatively short time intervals. The relative importance of anthropogenic or management factors compared to non-anthropogenic physical, chemical, or biological factors will generally be determined by the function or application for which a soil quality assessment is made.

Several biological attributes, including microbial biomass, respiration, amino acids, soil enzymes, and earthworm activity have been suggested as factors which influence soil quality. Water-filled pore space, a physical condition that influences biological activity, has also been identified as a factor affecting soil quality. Water-filled pore space and many of the biological indicators are much more temporally, and perhaps spatially, dependant than physical or chemical indicators of soil quality such as bulk density or cation exchange capacity (CEC). However, those factors can be very responsive to soil and crop management practices (Doran et al., 1990; Linn and Doran, 1984a,b).

Aggregate stability and size distribution are two physical measurements that have been suggested as indicators of soil quality, especially for evaluating effects of soil and crop management practices such as no-tillage (Arshad and Coen, 1992). These measurements were suggested because they reflect resistance of soil to erosion (Luk, 1979). Soil carbon content has been suggested as a soil quality indicator because decreases in this parameter can be directly related to decreased water stability of both macro- and micro-aggregates (Tisdall and Oades, 1982; Churchman and Tate, 1987; Pojasok and Kay, 1990).

Earthworm activity can increase the water stability of soils through the production of casts (Lee, 1985) and by excreting materials from their bodies (Piearce, 1981). Earthworms can affect infiltration, water transport, and plant root development by creating macropores. Increased earthworm activity has therefore been suggested as an indicator of soil quality (Berry and Karlen, 1993).

Microbial biomass, respiration, and ergosterol concentrations are biological indicators that have also been suggested as being useful for assessing long-term soil and crop management effects on soil quality (Karlen et al., 1992). Periodic assessments of soil-test properties have been suggested as essential for evaluating the chemical aspects of soil quality (Arshad and Coen, 1992; Karlen et al., 1992).

Use of a minimum data set (MDS) for assessing the health or quality of world soils was proposed by Larson and Pierce (1991). They suggested that standardized methodologies and procedures be established to assess changes in soil quality. Soil attributes and measurements selected for their MDS (Table 1) were dictated by a need to be (1) sensitive to various soil and crop management practices; (2) detectable following relatively short. But variable periods of time; and (3) accessible to most people through direct measurement or pedotransfer functions (Bouma, 1989).

Table 1. Factors Recommended by Larson and Pierce (1991) for Inclusion in a Minimum Data Set for Assessment and Monitoring of Soil Quality.

Soil Quality Factor	Measurement Technique
Texture or particle size	Pipette or hydrometer
Soil structure	Bulk density using intact cores or from water retention curves
Soil strength	Bulk density or penetration resistance
Maximum rooting depth or soil volume above root restrictive layers	On-site characterization for various crops or standard rooting estimates
Plant available water retention	Field measurements or estimation from water retention curves
Soil acidity or pH	pH meter with glass and reference electrodes
Electrolytic conductivity	Conductivity meter
Nutrient availability	Analytical soil test procedures (perhaps plant tissue analyses)
Total organic carbon (C)	Dry- or wet-combustion techniques
Labile organic C	CO_2-C release from hot KCI digests

Doran and Parkin (1994) adapted the MDS recommendations and proposed several soil physical, chemical, and biological characteristics that should be included as basic indicators of soil quality (Table 2). They also provided a rationale for selecting these characteristics, and emphasized the importance of defining ecosystem mechanisms and control processes that respond to soil and crop management practices and ultimately determine soil quality.

Table 2. Soil Physical, Chemical, and Biological Characteristics Proposed by Dorul and Parkin (1994) as Basic Indicators of Soil Quality.

Soil Characteristic	Relationship to Soil Condition or Function	Rationale for Selection as Priority Measurement
	Physical Characteristics	
Soil texture	Retention and transport of water and chemicals	Process modeling, erosion, and productivity estimates
Profile, topsoil and rooting depth[1]	Productivity and erosion estimates	Normalization of landscape and geographic variables
Bulk density and water infiltration[1]	Leaching, productivity, and erosivity estimates	Physical characteristic and for adjustment of measurements to volumetric basis
Water retention capacity[1]	Water retention, transport, and erosivity	Water available for plant and microbial processes
	Chemical Characteristics	
Total organic C and N	Soil fertility, stability, and erosion status	Process modeling and normalization of site characteristics
pH	Biological and chemical activity thresholds	Process modeling
Electrical conductivity	Plant and microbial activity thresholds	Productivity and environmental quality indicators
Extractable N, P, and K	Potential N loss and plant available nutrients	
	Biological Characteristics	
Microbial biomass C and N	Microbial catalytic potential and capacity for C and N retention	Process modeling and early indicator of adverse practices affecting soil organic matter content
Potentially mineralizable N	Soil productivity and N supplying potential	Process modeling and surrogate indicator for microbial biomass
Soil respiration, water	Microbial and sometimes plant content, and temperature[1] activity	Process modeling and estimate of microbial biomass activity

[1] Measurements made in the field to account for variations in row orientation, traffic patterns, and related management practices.

Processes Influencing Soil Quality

Hendrix et al. (1992) identified three types of ecosystem processes that were relevant to environmental quality and agricultural sustainability. These were (1) soil structure, including form, stability, and resiliency to respond to stress; (2) nutrient cycling, involving transformations such as mineralization and immobilization; and (3) biological interactions, including trophic relations within food webs. These processes may influence soil quality because they are easily influenced by soil and crop management inputs into agroecosystems. Tillage, fertilization, practices, and pest control were identified by Hendrix et al. (1992) as practices capable of influencing soil structure, nutrient cycling, and biological interactions, respectively. They also stated that by understanding agroecosystem processes, it would be possible to identify practices or mechanisms to mitigate environmental degradation through surface water eutrophication, groundwater contamination, soil erosion, sedimentation, and contamination by pesticide residues.

Soil structure is very sensitive to human activities and influences crop yield. It can be affected by plant genetics (Elkins, 1985) and influences crop response to anthropogenic management of weeds, insects, diseases, soil fertility, and water (Kay, 1990). Effects of various soil and crop management practices on soil structure can be measured over several time scales ranging from hours to centuries. Soil structure is an important component of soil quality; therefore, management factors and time scales that affect soil structure presumably affect soil quality.

Kay (1990) described soil structure in terms of form, stability and resiliency. Structural form describes the heterogeneous arrangement of solid and void space that exists at any given time and refers to the (1) arrangement of primary soil particles into hierarchical structures; (2) total porosity; (3) pore size distribution; and (4) continuity of the pore system. Soil stability is defined as the ability to retain solid and void space arrangement when exposed to different stresses such as compaction. Resiliency has not been specifically used in relation to soil structure, but Kay (1990) suggested that it provides a single term to describe processes such as tilth-mellowing, self-mulching, and age-hardening.

The characteristics of soil stability are specific with respect to the form and type of stress being applied (Kay, 1990). For example, the resistance of a pore system to compressive stresses (wheel traffic) will be different than resistance of clay particles to dispersion by osmotic stresses (salinity). Soil and crop management practices that alter the stresses to which soil is exposed can thus change structural characteristics which in turn, can subsequently affect hydrologic characteristics of soil and influence plant growth. Structural stability and soil resiliency thus determine the rates at which cropping sequences and till-age practices will cause changes in soil structure.

Biological, chemical, and physical processes influencing soil quality affect nutrient cycling by influencing two basic soil structure components, the formation of water stable aggregates and biopores. The primary process linking nutrient cycling and soil structure, and therefore, influencing soil quality, appears to be soil organic matter transformations.

Soil aggregates are composed of mineral and organic particles held together by a variety of factors (Boyle et al., 1989). At fine scales, organic inputs from root exudates, plant residues, or organic amendments stimulate microbial production of polysaccharides and other compounds that bind mineral soil particles into micro-aggregates. At coarser scales, macro-aggregates are formed when fungal hyphae and fine roots entangle micro-aggregates and large mineral and organic particles, and when soil fauna such as earthworms produce fecal pellets or casts that consist of mixtures of mineral particles and organic materials of various sizes and in various stages of decay (Hendrix et al., 1992).

The formation of pores or spaces between the aggregates is closely associated with the aggregation process. Biological activity, including penetration of plant roots or movement of soil fauna, creates channels which may be a major factor in macropore formation (Hendrix et al., 1992). These macropores may affect nutrient cycling by influencing water conductivity and leaching of solutes such as nitrate. Micropores within the soil structure matrix contain water films that provide suitable habitats for the microflora and microfauna including bacteria, protozoa, and nematodes. The degree to which the pores are filled by water influences the relative proportions of aerobic and anaerobic microbial activity within the soil (Doran and Smith, 1987).

The stability of soil aggregates depends on soil physical and chemical characteristics, but their formation appears to be primarily a function of biological activity within the soil. Soil and crop management practices affect soil quality by determining the supply of organic matter at the soil surface and by manipulating the physical and chemical environment for soil biology.

Management Practices Influencing Soil Quality

Management practices that influence soil organic matter content are the most important with respect to soil quality; because soil organic matter was the component that showed the greatest decline when virgin prairie was first broken for cultivation (Bradfield, 1937; DeTurk, 1937;

Waksman, 1937; Melsted, 1954; Bauer and Black, 1981). Soil organic matter continues to decline more rapidly with cropping systems involving fallow periods than with continuous cropping (Unger, 1982). As a result of these types of observations, Boyle et al. (1989) stressed the need for more emphasis on soil organic matter and suggested that returning carbon to the soil may be "a necessary expense that insures a sustainable harvest." The use of management strategies that add or maintain soil carbon, therefore, appear to be needed to improve the quality of our soil resources (Karlen et al., 1992).

In the U.S., crop residues and animal or poultry manures constitute the largest proportion of organic materials available for increasing soil organic matter levels (Follett et al., 1987; King, 1990; Hendrix et al., 1992). Animal and poultry manures represent an important organic amendment that can be applied to improve soil quality. These materials can increase water stability of soil aggregates, decrease susceptibility to crust formation, and increase the proportion of large pores.

Crop and weed residues produced *in situ* provide the largest organic input for most agroecosystems. A critical factor that determines how effective these materials will be with regard to formation of soil organic matter and their influence on soil quality is the type of management that these residues receive. If they are incorporated, and especially if tillage operations are quite intensive, there will be minimal impact on soil organic matter. Green manuring and use of cover crops are often suggested as practices that can be used to increase soil organic matter, but the effectiveness of these practices may be negated unless they are accompanied by reduced tillage practices (MacRae and Mehuys, 1985; Bruce et al., 1991). Plant selection, sequence or rotation, and frequency of harvesting are management practices that can influence soil quality by forming biopores and influencing the amount and distribution of organic materials in the soil. .

Management of soil organic matter to improve soil quality through practices such as mulching can provide a food source for the soil biota, enhance nutrient availability for subsequent crops, and maintain or improve surface structural properties. The critical amount of biomass required to achieve these goals will differ depending upon crop-ping sequences, soil conditions, degree of incorporation, temperature, and water regimes. However, in general, input rates must equal decomposition rates to maintain soil organic matter levels, or exceed them to increase soil organic matter levels. Where climate and water resources will support the practice, growing cover crops between cash or grain crops is a management strategy that may be useful for adding supplemental organic matter and thus improving soil quality.

Organic matter quality is also an important factor affecting organic matter management and soil quality. The carbon and nitrogen (C:N) ratios, lignin, and polyphenolic content of plant material can significantly affect its decomposition rate (Coleman et al., 1989). More rapid decomposition of soybean residue and lower soil aggregate stability after a 5-year period, as reported by Bruce et al. (1990), probably reflected higher nitrogen and lower lignin content in soybean residues than in grain sorghum. The soybean residues presumably provided a higher-quality food source for the soil biota and resulted in a more rapid and extensive decomposition than the grain sorghum residues.

Reduced tillage practices that are tailored to local soil and climatic conditions may be one of the best strategies for improving soil quality (Karlen et al., 1992). With regard to soil structure, tillage effects are determined primarily by the soil water content when operations are performed (Kay, 1990). After the soil water content exceeds a critical minimum, which is determined for each soil by clay content, exchangeable Ca:Mg ratios, and clay mineralogy (Emerson, 1983), the amount of clay dispersed by tillage operations increases as water content increases. Tillage also causes sorting of aggregates with smaller ones tending to sink to the bottom of the tilled layer and larger ones tending to rise to the surface. Continuity of pores within the tilled layer (Ball, 1981) and between tilled and untilled zones (GOSS et al., 1984) is diminished by tillage (Kay, 1990). Tillage can create a compacted zone at the base of the tillage layer (Bowen, 1981). It enhances mineralization of organic stabilizing materials and often results in a flush of microbial activity (Elliott, 1986). Surface tillage also disrupts earthworm burrows, increases the susceptibility of earthworms to predation by birds, and can reduce crop residue at the ground surface, thus increasing the potential for water runoff and soil erosion.

Hendrix et al. (1992) suggested that maintenance of biodiversity of the soil biota may be a useful strategy for sustainable agriculture. Biodiversity may also be an important factor affecting soil quality. For example, earthworms influence nutrient cycling and soil structure, but different species respond to management practices in different ways (Berry and Karlen, 1993) and have different effects on the soil (Lee, 1985; Lavelle, 1988). Species such as *Lumbricus terrestris* L. form deep burrows and can affect solute transport and may increase the potential for rapid movement of surface-applied agricultural chemicals through the soil profile (Tyler and Thomas, 1977; Barraclough et al., 1983; Edwards et al., 1989). Shallow-burrowing species such as *Aporrectodea trapezoides* Duges, *A. turgida* Eisen, *A. tuberculata* Eisen and *Octolasion tyrtaeum* Savigny are geophageous earthworms that mix mineral soil and organic matter in the upper soil layers, perhaps stimulating nutrient mineralization and immobilization processes in the soil. Litter dwellers, such as *L. rubellus* L., may consume and increase decomposition rates of particulate organic matter on the soil surface.

Soil and crop management practices such as reduced tillage, increased input of carbon, and reduced pesticide applications may promote earthworm diversity and thus enhance the effects of earthworms on soil properties. Management practices that include polycultures, crop rotations, hedgerows, buffer strips, or reduced tillage may favor biodiversity and result in a number of benefits including an increased abundance of predators and beneficial parasites, and provide increased microhabitat diversity for microbial activity and processes (Hendrix et al., 1992).

Soil Quality Evaluation

Evaluating soil quality is difficult because it is much more site- and soil-specific than air or water quality. To meet this challenge, Larson and Pierce (1991) proposed five soil quality attributes, and suggested that the combined physical, chemical, and biological properties of a soil enable it to perform three functions. The soil functions are (1) to provide a medium for plant growth, (2) to regulate and partition water flow through the environment, and (3) to serve as an environmental filter. They also stated that soil quality describes how effectively soils:

1. accept, hold, and release nutrients and other chemical constituents;
2. accept, hold, and release water to plants, streams, and groundwater;
3. promote and sustain root growth;
4. maintain suitable soil biotic habitat; and
5. respond to management and resist degradation.

Karlen and Stott (1994) proposed a framework for evaluating soil quality relative to water erosion that was based on soil processes and properties that were sensitive to soil and crop management practices. They identified four critical functions as (1) accommodating water entry into the soil, (2) facilitating water transport and absorption, (3) increasing resistance to soil erosion, and (4) supporting plant growth.

Table 3. Soil Quality Functions and Indicators Related to Surface Soil Quality as affected by Various Crop Residue Management Treatments on Silt Loam Soil in Southwestern Wisconsin.

FUNCTION	Weight	INDICATOR					
		Level I	Weight	Level II	Weight	Level III	Weight
Accommodate water entry	0.20	Aggregate stability	0.60				
		Surface 75mm porosity	0.20				
		Earthworms	0.20				
Facilitate water transfer and absorption	0.20	Upper 500 mm porosity	0.60				
		Upper 600 mm total carbon	0.20				
		Earthworms	0.20				
Resist degradation	0.20	Aggregate stability	0.60				
		Microbial processes	0.40	Microbial biomass	0.30		
				Respiration	0.30		
				Ergosterol	0.20		
				Surface 75 mm total carbon	0.10		
				Surface 75 mm total nitrogen	0.10		
Sustain plant growth	0.40	Rooting depth	0.30	Surface 75 mm bulk density	0.20		
				Earthworms	0.10		
				Upper 500 mm bulk density	0.50		
				Plant available water (PAW)	0.20		
		Water relations	0.30	PAW	0.25		
				Surface 75 mm porosity	0.25		
				Upper 500 mm porosity	0.40		
				Upper 600 mm total carbon	0.10		
		Nutrient relations	0.30	pH	0.30		
				CEC	0.20		
				Upper 600 mm total nitrogen	0.10		
				Upper 600 mm total carbon	0.10		
				Nutrient cycling	0.30	Microbial biomass	0.10
						Respiration	0.10
						WFPS	0.25
						Ergosterol	0.05
						Surface 75 mm total N	0.25
						Surface 75 mm total C	0.25
				Chemical barriers (pH or acidity)	0.10		

In subsequent studies, Karlen et al. (1994a) modified the framework to assess surface soil quality as affected by various crop residue and tillage treatments. Each biological, chemical, or physical measurement that was used to compute the soil quality index (Table 3) was normalized to a value between 0 and 1 using standardized scoring functions (Wymore, 1993). The values chosen to normalize each soil quality measurement were derived from literature values for each parameter. Values selected for normalizing soil aggregation data were based on studies by Wilson and Browning (1945), while those for bulk density were as suggested by Singh et al. (1992) for their tilth index. Water-filled pore space normalization was based on information published by Doran et al. (1990) and Linn and Doran (1984a,b). For plant available water in silt loam soils, we utilized relationships suggested by Hudson (1993). Total carbon and total nitrogen scaling were based on experience with Rozetta and Palsgrove silt loam soils, while cation exchange capacity, microbial biomass, respiration, ergosterol concentrations, and earthworm populations were normalized based on literature reviewed by Eash (1993).

After normalizing or scoring each measurement used for the proposed soil quality index, scores were multiplied by the appropriate weighting factor (Table 3). The products were then summed to give a weighted value. For factors such as nutrient relationships, weighted values for nutrient cycling (1evel 3) were computed and then used as the “score” for that factor at level 2. Similarly, all level 2 factors (pH, CEC, total N, total C, and nutrient cycling) were then multiplied by their respective weighting factor so that products could be summed to give weighted scores for each level 1 factor. Weighted scores for each function were then summed to give an overall soil quality index as shown in equation [1].

Soil Quality (Q) = ${}^{q}\text{we}\ (\text{wt}) + {}^{q}\text{wta}\ (\text{wt}) + {}^{q}\text{rd}\ (\text{wt}) + {}^{q}\text{spg}\ (\text{wt})$ [1]

Where:

${}^{q}\text{we}$ = Level 1 rating for accommodating water entry

${}^{q}\text{wta}$ = Level 1 rating for water transport and absorption

${}^{q}\text{rd}$ = Level I rating for resisting degradation

${}^{q}\text{spg}$ = Level I rating for supporting plant growth

wt = Weighting factor for each factor

Karlen and Stott (1994) demonstrated how a soil quality index might be calculated using data from a study comparing alternate and conventional farming practices. The alternative farming practices, which included a 5-year corn, soybean, corn, oats, and meadow rotation; application of a mixture of animal manure and municipal sludge during the first 3-years of each rotation; and the use of ridge-tillage, resulted in a higher soil quality rating (0.73) than conventional practices (0.54), which consisted of a 2-year corn-soybean rotation without carbon input in excess of the crop residues. Using the framework shown in Table 3, Karlen et al. (1994a) computed soil quality index values showing that removal, maintenance, or doubling crop residues for 10 years with no-till production practices resulted in ratings of 0.45, 0.68, and 0.86, respectively. In another study (Karlen et al., 1994b), the same procedure indicated that the surface soil quality ratings after 10 years of plow, chisel, and no-till treatments were 0.47, 0.48, and 0.70, respectively. The relative ranking of the plow and no-till treatments in this study was confirmed by measuring soil loss with a sprinkling infiltrometer.

These initial studies have demonstrated the feasibility of developing a useful and perhaps valuable procedure for assessing surface soil quality. The procedure appears to be sensitive and can discern long-term crop residue management and tillage treatment effects. The proposed soil quality assessment method, although tested only for non-glaciated silt loam soils, does not provide a definitive answer with regard to measurements or specific functions which should be included in a soil quality index. However, it is based on actual soil measurements that describe specific soil functions and provides a framework for an even more dynamic soil quality index. Development of soil quality concepts is warranted and should enhance our efforts to achieve a more sustainable agriculture and environment.

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