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FRAMEWORK FOR SUSTAINABLE SOIL MANAGEMENT

LITERATURE REVIEW AND SYNTHESIS

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The Soil and Water Conservation Society (SWCS) is a nonprofit scientific and educational organization that serves as an advocate for natural resource professionals and for science-based conservation policy. SWCS fosters the science and art of soil, water, and environmental management on working lands to achieve sustainability. SWCS members promote and practice an ethic that recognizes the interdependence of people and their environment.

Contents

Introduction

"Soil scientists must … adopt a positive approach to natural resource management. They must think about soil conservation rather than erosion, soil fertility enhancement rather than nutrient depletion and imbalance, soil restoration rather than degradation and desertification, and judicious use of input rather than low input systems" (Rattan Lal 1998a).

Scope and objective

This paper was prepared to help inform the Soil and Water Conservation Society's (SWCS) ongoing efforts to foster the science and art of soil management. SWCS has a vital interest in enhancing the ability of conservationists and landowners to manage soil in ways that sustain productivity and protect the environment. Effective soil management is essential to the long-term sustainability and commercial viability of agriculture. It is also the foundation of effective environmental management of farming systems. The need for more effective and comprehensive soil management has become even more urgent as a means to both mitigate and adapt to the effects of climate change. The restoration of soil quality has become an important strategy for addressing world food security.

The goal for this paper was to document the state of the current science on the concept of constructing a practical and useful framework for evaluating the potential effects of management and conservation practices on soil quality. The long-term goal is a framework that is both scientifically sound and usable by producers and the advisors who recommend alternative management and conservation systems for their operations. There is controversy and disagreement in some quarters regarding the concept of soil quality and its applicability to soil management. We have attempted to document those disagreements but have not tried to resolve them in this paper.

The paper reviewed scientific literature in the following areas: (1) definitions of soil quality, (2) soil functions, (3) soil attributes and indicators, (4) attempts to set threshold levels for indicators, and (4) attempts to construct frameworks for more comprehensive soil management.

The literature was limited to North America to reduce the scope and challenge of such a literature review.

Criteria for an ideal system

Research on soil quality has advanced to the degree that the potential exists for the creation of a framework or tool that allows growers, regulators, and researchers to monitor and assess positive and negative changes in soil quality. The number of soil sensors available and forthcoming is large and make it possible to address the challenges posed by spatial and temporal variability in soil properties and soil quality. Although a complete consensus has not been reached regarding definitions of soil quality or its measurement, enough knowledge has accumulated that broad agreement on a workable instrument can be established in the foreseeable future. The objective is to have an equation or framework that reasonably predicts the effects of management practices on the improvement or degradation of soil quality. This application must enable soil conservationists to recommend changes in soil management that will help attain economic and environmental objectives, as well as provide recommendations that will sustain or enhance options for future generations.

The framework envisioned should consist of a minimum set of soil functions selected because they strongly influence the capacity to achieve the objectives stated above; a minimum set of soil indicators that are sensitive to changes in management and strongly influence soil function; indices or process models that can predict at least the direction (and hopefully magnitude) of the change associated with changes in soil management practices or systems; thresholds for soil management indicators needed to achieve, via their effect on soil function, the stated objectives; and a tool or framework that packages enough information to allow field personnel to consistently evaluate the positive and negative aspects of the soil management and farming system recommendations they make. This approach seeks to move beyond a mindset or paradigm that emphasizes maximum production at any cost to one that recognizes the full suite of functions that soils provide in agro-ecosystems.

Definitions of soil quality

Many researchers focus on the functional approach to measuring soil quality and thus define soil quality in that light. Gregorich et al. (1994) defines soil quality as "a composite measure of both a soil's ability to function and how well it functions, relative to a specific use." Karlen et al. (1997) describe soil quality as "the fitness of a specific soil to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation." This definition is similar to Acton and Gregorich (1995), Doran and Parkin (1994), and Larson and Pierce (1991), and allows for quantification of soil quality as well as for innate differences among soil orders. Harris and Bezdicek (1994) tie soil quality to soil health by stating that together they "reflect the fitness of a soil body, within land use, landscape and climate boundaries, to protect water and air quality, sustain plant and animal productivity and quality, and promote human health." In an article focusing on the protection of urban soil quality, Hanks and Lewandowski of the USDA Natural Resources Conservation Service (NRCS) (2003) state that "soil quality is the ability of soil to perform certain functions, such as (1) effectively cycling nutrients, minimizing leaching and runoff, while making them available to plants (2) maximizing water-holding capacity and minimizing runoff and erosion (3) adsorbing and filtering excess nutrients, sediments, and pollutants (4) providing a healthy root environment and habitat, and (5) providing a stable foundation for (man-made) structures." Others have recommended that soil resilience be included as an important consideration in defining soil quality (Lal et al. 1997) Singer and Ewing (2000) note that outside of the United States, especially Canada and Europe, many industrial nations consider contaminant levels and their effects critical to any measure of soil quality, citing Moen (1988), Denneman and Robberse (1990), Cairns (1991), and Sheppard et al. (1992).

Singer and Ewing (2000) state that in the United States, the concept of soil quality includes soil fertility, potential productivity, resource-sustainability, and environmental quality. They also observe that the existence of multiple definitions of soil quality suggests that the concept continues to evolve. Cook and Hendershot (1996) assert that soil quality guidelines are intended to protect the ability of ecosystems to function properly. The whole thrust of soil quality research arose from the recognition that soils are a vital component of and provide necessary services to the ecosystem (Daily et al. 1997), and that the ability of soils to continue to provide those services is threatened by degradation (Parr et al. 1992). Letey et al. (2003) would prefer that soil quality not be defined, but that if it must be, then a rigorous and technical definition is needed. They argue that what is needed is not management of soil quality but quality soil management. Following is a list of definitions of soil quality published in the literature.

Doran and Parkin (1994): The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

Gregorich et al. (1994): A composite measure of both a soil's ability to function and how well it functions, relative to a specific use.

USDA NRCS (2003): Soil quality is the ability of soil to perform certain functions, such as (1) effectively cycling nutrients, minimizing leaching and runoff, while making them available to plants (2) maximizing water-holding capacity and minimizing runoff and erosion (3) adsorbing and filtering excess nutrients, sediments, and pollutants (4) providing a healthy root environment and habitat, and (5) providing a stable foundation for (man-made) structures.

Harris and Bezdicek (1994): Soil quality and soil health reflect the fitness of a soil body, within land use, landscape and climate boundaries, to protect water and air quality, sustain plant and animal productivity and quality, and promote human health.

Karlen et al. (1997): The fitness of a specific soil to function within its capacity and within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation.

Larson and Pierce (1991): The capacity of a soil to function within the ecosystem boundaries and interact positively with the environment external to that ecosystem.

Letey et al. (2003): The chemical, physical, and biological properties of soil that affect its use. (use is emphasized, as opposed to function)

Moen (1988): A "clean" soil is one which poses no harm to any normal use by humans, plants or animals; not adversely affecting natural cycles or functions; and not contaminating other components of the environment.

Power and Myers (1989): The ability of soil to support crop growth which includes factors such as degree of tilth, aggregation, organic matter content, soil depth, water holding capacity, infiltration rate, pH changes, nutrient capacity, and so forth.

Soil Science Society of America (SSSA 1987): Soil qualities—inherent attributes of soils that are inferred from soil characteristics or indirect observations (e.g. compactibility, erodibility, and fertility).

SSSA (1997): The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation (In Letey et al. 2003).

The Functions of Soil

The original scientific concept of soil quality arose out of the classification of soils based on the factors that influenced their formation (Dokuchaev 1883; Jenny 1941; Simonson 1959). These pioneers of soil science noted that soils were inherently different based on the environment in which they formed. Milne (1936a, 1936b) coined the term catena to describe how a repeating sequence of soils that occurs from the top of a hillslope to the adjacent valley bottom changed. The practical consequence of how different soils influenced agricultural production was a principal consideration guiding the description and delineation of soils, and the goal was to determine which soils were better for which uses. Lal (1998b) noted that "farmers worldwide have learned through experience that not all soils are created equal—some are more productive than others while still others are more vulnerable to erosion and degradation." Thus, soil quality as it described agricultural yield became associated with crop productivity, and soil classification delineations often implied differences in productivity.

More recently, research focused on ecosystems and how they function, combined with a growing concern that current agricultural practices that maximize short-term productivity often lead to soil degradation, has shifted the concept of soil quality to describe how well a soil functions (Larson and Pierce 1991; Gregorich et al. 1994; Karlen et al. 1997). This redefining of the term was an attempt to broaden the scientific understanding of the roles soils play beyond influencing crop yields and lead to a focus on soil management—how to work with the soil to overcome barriers and sustain or improve a soil's capability to perform key functions. An early version of this definition of soil quality can be found in the work of Yoder (1937). Karlen and Stott (1994) chronicled Yoder's discussion of soil tilth, with its emphasis on soil structure that would lead to minimum resistance to root penetration, permit free intake and moderate retention of rainfall, provide an optimum soil-air supply with moderate gaseous exchange between soil and atmosphere, promote microbiological activity, and perform other functions.

More recently, Daily et al. (1997) described six services performed by soil for the larger ecosystem: (1) buffering and moderation of the hydrological cycle, (2) physical support of plants, (3) retention and delivery of nutrients to plants, (4) disposal of wastes and dead organic matter, (5) renewal of soil fertility, and (6) regulation of major element cycles. Singer and Ewing (2000) documented the soil functions they found appearing frequently in soil science literature: soil (1) maintains biological activity/productivity; (2) serves as a medium for plant/crop growth; (3) supports plant productivity/yield; (4) supports human/animal health; (5) partitions and regulates water/solute flow; (6) serves as an environmental buffer/filter; (7) maintains environmental quality; and (8) cycles nutrients, water, energy, and other elements through the biosphere. In addition, Larson and Pierce (1991) added that soil quality describes how effectively soils respond to management and resist degradation, and Karlen et al. (1997) provided support of socioeconomic structures and protection for archeological treasures associated with human habitation as a soil function. Harris et al. (1996) stated that the quality and health of a soil dictates the fitness of a soil to (1) provide nutritional and physical support for biological production and waste recycling; (2) act as a source of materials for construction and mining; and (3) serve as a living filter mediating the quality of interfacing air, surface water, and ground water. Lal (1998b) listed productivity and sustainability, environmental quality, biodiversity, and human welfare as soil function criteria affecting soil quality. Papendick and Parr (1992) stated that soil quality should serve as an indicator of the soil's capacity to produce safe and nutritious food, enhance human health, and overcome degrative [sic] processes. Carter et al. (1997) focused on soil functions as they relate to crop production, stating that in this role the function of soil is to nurture and sustain plant growth. They divided this function into several components: soil provides a medium of plant growth; regulates and partitions water, gas, and energy flow; and serves as a buffer or filter system. Wang and Gong (1998) summarized the functions soils perform as the ability to supply nutrient and other physico-chemical conditions to plant growth, promote and sustain crop production, provide habitat to soil organisms, ameliorate environmental pollution, resist degradation, and maintain or improve human or animal health.

Hanks and Lewandowski, in a USDA NRCS (2003) publication, provided an urban perspective to soil function by including effective nutrient cycling, minimizing runoff and erosion while maximizing water-holding capacity, adsorbing and filtering excess nutrients, sediments, and pollutants, providing a healthy rooting environment and creating habitat, and providing a stable foundation for structures. The German

Federal Soil Protection Act (BbodSchG 1998) officially recognized soil as a basis for life and habitat for animals, plants, and soil organisms; part of natural systems, especially water and nutrient cycles; and a filter and a buffer. As can be seen in the functions listed above, there is a great deal of overlap and agreement in the literature on soil functions.

The adoption of specifying soil function when defining soil quality is not universally accepted. Sojka, Upchurch, and others (Letey et al. 2003; Sojka and Upchurch 1999) believe strongly that precisely specifying soil use, not function or capacity, should be the primary criteria for soil attribute evaluation. They state that the terms and concepts of capacity and function are the source of operational conflicts in execution of the soil quality concept and use the example that a soil that might be "good" for one function may be "poor" for another function. Recent efforts to quantitatively assess soil quality attempt to overcome this criticism by specifying the management goals of a soil prior to assessing which soil functions to evaluate (e.g., Andrews et al. 2004). Letey et al. (2003) use the example of lower springtime nitrate levels in the soil as positive for soil functioning to protect the environment, but negative for soil functioning to maximize crop productivity. This account highlights the difficulty in creating a single index to measure trends in soil quality. Clearly, the decision to have lower nitrate levels is a management decision that can be measured over time, but appears to force the manager to choose between the management goals of productivity and environmental protection. The manager may ultimately choose to maximize spring nitrate levels to the capacity of the soil to hold nitrates at that time of year without leaching. This balanced approach is an example of what society is beginning to ask of agricultural producers and a tool that measures management decisions that will optimize the balance is what is needed at this time.

A quandary highlighted by Letey et al. (2003) is the potential loss of human ingenuity in solving agricultural problems if the concept of soil function is adopted. They use the example of cropping corn and soybeans on steep slopes in Mississippi to illustrate their point. Soils found on steep slopes may be assumed to function poorly for row-crop agriculture, due to the potential for erosion, with subsequent degradation of soil organic matter, soil structure, infiltration, cation exchange capacity, water quality, and other problems. They point out though, that through judicious application of available techniques and technology, such as no-till, contour planting, and vegetative surface mulching, infiltration actually improved, soil-depth-related water supply problems were reduced, and erosion and runoff decreased. This illustration serves to point out that a tool that estimates or predicts changes in soil quality due to the adoption of certain management practices is a better goal than just mapping soils in order to determine their "best use."

Soil Attributes and Indicators

Influence on soil functions

The challenge of enabling more comprehensive management of soil resources has led scientists to evaluate a host of soil attributes for their influence on soil function. Evaluating chemical, physical, and biological properties and process collectively is thought to provide and better and more complete evaluation of soil management alternatives than looking at any one soil property or process in isolation.

This complex or conglomerate of soil attributes is described in the literature as a minimum data set (MDS) (Larson and Pierce 1991; Gregorich et al. 1994; Doran and Parkin 1994, 1996) Most attributes, also described as properties or indicators, can be categorized as chemical, physical, or biological, and in general are measurements that are familiar to the soil scientific community. Singer and Ewing (2000) note however, that commonly identified soil quality parameters may not always correlate well with yield, citing a publication by Reganold (1988). The Reganold study compared adjacent farms that were farmed either "organically" or conventionally for decades. The results showed significant increases in soil organic matter, polysaccharides, water content, CEC, microflora, and soil granular structure on the organically farmed sites, but winter wheat yields were 8% lower in one location and 13% higher in another location over a five-year period compared to the conventionally-farmed system. Reganold postulated that the ability of the organic farmer to produce yields similar to neighboring conventional farmers, even after almost 80 years of farming without (inorganic, synthetic) fertilizer, may be partly due to a reduction in soil erosion through effective management practices. The author goes on to point out the key difference in management practices that led to the reduction in erosion was the incorporation of a green manure crop in the third year of rotation. This study highlights the fact that much information currently exists in the scientific literature that could be utilized in the construction of a tool that predicts changes in soil quality due to the adoption of certain management practices (Liebig and Doran 1999b; Gilley et al. 2001). Seybold et al, 2003 introduced the concept of use-dependent soil properties as the focus on linking management practices to changes in soil quality.

Minimum data sets

In a review article on biological indicators, Stenberg (1999) cited Doran and Parkin (1996) and Doran and Safley (1997) who listed five criteria to find a set of indicators that is practical for use by everyone from practitioners to scientists and policy makers, and in most ecological and socioeconomic situations. They should (1) be well correlated with ecosystem processes, (2) integrate physical, chemical, and biological properties and processes and serve as basic inputs needed for estimation of soil properties or functions that are more difficult to measure directly, (3) be easy to use under field conditions and be assessable by both specialists and producers, (4) be sensitive to long-term variations in management and climate, and (5) be components of existing soil databases where possible. Brookes (1993) gave an earlier list of microbiological indicators that could be used in soil pollution monitoring with similar criteria.

Singer and Ewing (2000) deem it vital to consider four points concerning the selection and quantification of soil characteristics: soil characteristics may be desirable or undesirable; soil renewability involves judgment of the extent to which soil characteristics can be controlled or managed; rates of change in soil characteristics vary; and significant temporal or spatial variations in soil may exist. Desirable soil characteristics were defined as the presence of a property that benefits soil functions, or the absence of a property that is detrimental to those functions. Undesirable soil characteristics were limited to the presence of contaminants (e.g. heavy metals, pathogens, radiation, growth-inhibiting compounds) or soil characteristics whose values were "out of range" and thus contributed negatively to soil quality (e.g. high soil salinity). Doran and Zeiss (2000) stated that soil quality indicators should fulfill the following criteria: 1) sensitivity to variations in soil management; 2) good correlation with beneficial soil functions; 3) helpfulness in revealing ecosystem processes; 4) comprehensibility and utility for land managers; and 5) cheap and easy to measure.

Larson and Pierce (1991) inventoried certain soil attributes based on their ability to accept, hold, and release nutrients and water, promote growth, provide habitat, and resist degradation. They divided these attributes between those important in the surface horizon and those critical in the (crop) limiting horizon. Surface horizon attributes were total and labile organic matter, nutrient supply, soil texture, surface horizon depth, structure, pH, and electrical conductivity (EC). Attributes important in the limiting horizon were texture, depth, structure, pH, and EC.

Papendick (1991) summarized the work of an international conference on the assessment and monitoring of soil quality that listed infiltration, available water holding capacity (AWC), and soil depth as first-order soil physical properties affecting soil quality and water-stable aggregates, dispersable clay, and bulk density (Db) as second order physical properties. Chemical indicators listed were pH, salinity, CEC, soil organic matter (SOM), and toxicities such as heavy metals, toxic organic compounds, excess nitrate, and radioactive substances (Karlen and Stott, 1994).

Doran and Parkin (1994) proposed using a mixed set of soil physical, chemical, and biological characteristics that included: texture; depth of soil and rooting; (Db) and infiltration; AWC; water retention characteristics; water content; soil temperature; total organic carbon (TOC) and nitrogen (TON); pH; EC; Mineral N (NH4 and NO3), P, and K; Microbial biomass C and N; potentially mineralizable N (N0); soil respiration; biomass C/total organic C ratio; respiration/biomass ratio. The authors modified this approach (Doran and Parkin, 1996) incorporating the work of Larson and Pierce (1994) to include: texture; depth of soil, topsoil, and rooting; infiltration and Db; AWC; SOM; pH; EC; extractable N, P, and K; microbial biomass C and N; N0; and soil respiration, water content, and temperature.

Kennedy and Papendick (1995) list several soil quality indicators that can be included in a minimum data set to characterize soil quality: SOM, aggregation, Db, depth to hardpan, EC, fertility, respiration, pH, yield, infiltration, N0, and AWC.

Karlen et al. (1997) selected organic matter, infiltration, aggregation, pH, microbial biomass, forms of N, Db, topsoil depth, conductivity or salinity, and available nutrients as important indicators of soil quality.

Wang and Gong (1998) used 12 indicators to evaluate changes in soil quality over 11 years at a site in southeast China, selecting soil depth, texture, slope, organic matter, Total N, P, and K, Available N, P, and K, CEC, and pH. They stated that their selection was based on indicators that were considered useful to that particular site, not to any soil at any location.

Carter et al. (1997) noted the difficulty and expense involved in making certain measurements and adapted the use of pedotransfer variables from Larson and Pierce (1991, 1994) as suitable substitutes for certain indicators. Organic matter was recognized for its complexity and its importance in many soil functions, so a minimum data set of sub-attributes of soil organic matter was proposed: total organic C, microbial biomass, carbohydrates to evaluate soil structural stability; total organic N, microbial biomass N, mineralizable N, light fraction and macro-organic matter to evaluate nutrient storage; and microbial biomass, enzymes, and mineralizable C and N to evaluate biological activity.

Karlen and Stott (1994) divided indicators into three levels and weighted the indicators in an attempt to develop a soil quality index equation. They also introduced scoring functions that had different shapes, such as "more is better," "less is better," an "undesirable range,"and an "optimum range." This scoring concept has been adopted by some researchers building working frameworks for soil quality evaluation (e.g. Andrews et al. 2004).

Harris et al. (1996) chose certain physical properties: texture, Db, infiltration, and AWC; chemical properties: total organic C and N, pH, EC, extractable NH4, NO3, P, and K; and biological properties: microbial biomass C and N, N0, and soil respiration for their utility in describing soil functions. Andrews et al. (2004) adds a nematode maturity index, metabolic quotient (proportion of soil respiration and microbial biomass), macro-aggregate stability, and sodium adsorption ratio to those listed in Harris et al. (1996).

Challenges and options

The literature contains a great deal of overlap concerning soil quality indicators. The difficulty in coming to agreement on a "standard" set of indicators is based on the concern that a "one-size-fits-all" approach will lead to inadequate or inaccurate soil quality assessment. Other options besides one single set of indicators include indicators specific to certain soil orders, soil uses, or geographic regions. Alternatively, there is concern among some researchers (e.g. Nortcliff 2002;

Table 1
Soil quality indicators: physical, chemical, and biological.

Soil quality indicator - physical	Reference
Organic matter	Larson and Pierce 1991
Texture	Reganold and Palmer 1995
Soil depth	Larson and Pierce 1991
Soil structure	Larson and Pierce 1991
Aeration	Singer and Ewing 2000
Aggregate stability	Andrews et al. 2004
Bulk density	Karlen et al. 1992
Clay mineralogy	Singer and Ewing 2000
Color	Reganold and Palmer 1995
Consistence	Reganold and Palmer 1995
Depth to root limiting layer	Singer and Ewing 2000
Hydraulic conductivity	Singer and Ewing 2000
Oxygen diffusion rate	Letey 1985
Particle size distribution	Singer and Ewing 2000
Penetration resistance	Reganold and Palmer 1995
Pore connectivity	Singer and Ewing 2000
Pore size distribution	Singer and Ewing 2000
Soil strength	Singer and Ewing 2000
Soil tilth	Singer and Ewing 2000
Structure type	Reganold and Palmer 1995
Temperature	Letey 1985
Total porosity	Karlen et al. 1992
Available water-holding capacity	Andrews et al. 2004
Slope	Wang and Gong 1998
Infiltration	Harris et al. 1996

Soil quality indicator - chemical	Reference
Organic matter	Larson and Pierce 1991
Nutrient supply	Larson and Pierce 1991
pH	Larson and Pierce 1991
EC	Larson and Pierce 1991
Base saturation	Singer and Ewing 2000
CEC	Wang and Gong 1998
Contaminant availability	Singer and Ewing 2000
Contaminant concentration	Singer and Ewing 2000
Contaminant mobility	Singer and Ewing 2000
ESP	Singer and Ewing 2000
SAR	Andrews et al. 2004
Nutrient cycling rates	Karlen et al. 1992
Plant nutrient availability	Singer and Ewing 2000
Plant nutrient content	Singer and Ewing 2000
Potentially mineralizable N	Kennedy and Papendick 1995
Heavy metal concentration	Howard 1993
Organic chemical concentration	Howard 1993
Soil test P	Andrews et al. 2004
Total and available P and K	Wang and Gong 1998
Total organic C	Harris et al. 1996
Total organic N	Harris et al. 1996

Soil quality indicator - biological	Reference
Microbial biomass C	Kennedy and Papendick 1995
Microbial biomass N	Kennedy and Papendick 1995
Total microbial biomass	Andrews et al. 2004
Bacterial biomass	Kennedy and Papendick 1995
Fungal biomass	Kennedy and Papendick 1995
Potentially mineralizable N	Kennedy and Papendick 1995
Soil respiration	Kennedy and Papendick 1995
Enzymes – dehydrogenase	Kennedy and Papendick 1995
Enzymes – phosphatase	Kennedy and Papendick 1995
Enzymes – arlysulfatase	Kennedy and Papendick 1995
Biomass C: TOC	Kennedy and Papendick 1995
Respiration: biomass	Andrews et al. 2004
Microbial community fingerprinting	Kennedy and Papendick 1995
Substrate utilization	Kennedy and Papendick 1995
Fatty acid analysis	Kennedy and Papendick 1995
Nucleic acid analysis	Kennedy and Papendick 1995
Earthworm population	Reganold and Palmer 1995
Invertebrate diversity	Stork and Eggleton 1992
Nematode maturity index	Andrews et al. 2004

Dick et al. 1996) that different investigators using different methods of collection and analysis will produce results that cannot be compared from study to study, or within the same study over time. This becomes a critical issue when contemplating the utilization of any system on a national–or international–basis. Two alternatives to the repeated collection of samples and data are: 1) the use of remote sensing devices that can sample automatically and send data to a central collection point and 2) creation of a model such as the Revised Universal Soil Loss Equation (RUSLE) that relies upon research data to predict an outcome based on certain soil conditions and practices. It is noted that researchers, conservationists, regulators, and growers utilize the RUSLE to modify farming systems even though not a single measurement is made prior to the RUSLE's application. This last option holds out the promise of a method that would be readily adaptable at the farm level and would not be constantly subjected to the question of whether samples were being taken objectively, randomly, frequently, and thoroughly enough to accomplish the goal. An existing model that approaches this concept is the Natural Resource

Conservation Service's Soil Conditioning Index (SCI) (USDA NRCS 2001). This approach attempts to estimate the probability of whether applied conservation practices will result in maintained or increased levels of soil organic matter. The user must provide seven types of information about the field to be evaluated, only one of which requires soil sampling: geographic location, soil texture, crops in the rotation, yields for each crop, applications of organic matter (manures, etc.), field operations such as tillage and inputs, and rate of wind and water erosion (estimated from the RUSLE). Only soil texture must be measured, and it can be argued that it would not need to be measured on a frequent basis.

Attributes that best indicate change in soil quality

The abundance of research articles, such as those listed above, discuss the use of certain soil attributes and indicators but do not highlight which of these indicators best predict changes in soil quality. Karlen et al. (1998) describe a hierarchical framework for soil quality evaluations and describe which indicators are appropriate measures of soil quality at various levels, from point-scale to national and international. Many papers focused on specific indicators, such as soil physical properties or invertebrates (Arshad et al. 1996; Parisi et al. 2005; Blair et al. 1996, etc.) in order to build a body of knowledge that is useful in the construction of frameworks of evaluation. The indicators most often utilized are soil organic matter (Karlen et al. 1997; Liebig and Doran 1999b; Bowman et al. 2000; Brejda et al. 2000b; Kettler et al. 2000; Gilley et al. 2001; Li et al. 2001; Andrews et al. 2002; Andrews et al. 2004), bulk density (Karlen et al. 1997; Liebig and Doran 1999b; Kettler et al. 2000; Gilley et al. 2001; Li et al. 2001; Andrews et al. 2004), and macro-aggregate stability (Bowman et al. 2000; Six et al. 2000). Chemical indicators most often included are pH, EC (or salinity), and forms of N (Romig et al. 1995; Kennedy and Papendick 1995; Karlen et al. 1997; Andrews et al. 2004). Biological indicators most often cited are microbial biomass, microbial respiration, and organic matter mineralization and denitrification (Karlen et al. 1992; Visser and Parkinson 1992; Reganold et al. 1993; Franzleubbers et al. 1995; Yakovchenko et al. 1996; Boehn and Anderson 1997; and Franzleubbers and Arshad 1997; Pankhurst 1997; Liebig and Doran 1999b; Gilley et al. 2001). Some authors assessed soil quality based on soil microfauna populations (Bernini et al. 1995; Iturrondobeitia et al. 1997; van Straalen 1998; Paoletti 1999; Paoletti and Hassal 1999; Jacomini et al. 2000; Parisi 2001; Parisi et al. 2005).

Many frameworks utilize organic matter for a portion of their assessment methods (Andrews et al. 2004; Andrews et al. 2002; Carter 2002; Karlen et al. 1997). Critics (Letey et al. 2003) voice concern that heavy reliance upon the increase in organic matter as a measure of improved soil quality ignores possible detrimental effects caused by the organic matter source (e.g. high P loads from poultry manure) or they suspect that the push to increase organic matter is in reality advocating organic farming systems over conventional systems. Soil organic matter does have the advantage of serving as a proxy for many other indicators. The addition of soil organic matter often increases aggregate stability, infiltration, potentially mineralizable N, C, microbial biomass, and cation exchange capacity. It is relatively easy to sample and store, although sampling consistency can be problematic since samplers are not always consistent in depth of samples taken, and SOM levels can fluctuate dramatically within a field.

Ghani et al. (2003) propose that use of hot-water extractable carbon (HWC) in soils was sensitive enough to discriminate between different fertilization, grazing, and cultivation management regimes. They note that when HWC is extracted, other pools of labile nutrients are extracted along with the C. They suggest a decline in HWC represents a decline in other nutrients such as N, P, and S.

Research on the utility of indicators in assessing soil quality is ongoing. No scientific consensus exists that any one indicator best measures or predicts changes in soil quality. Most frameworks and assessment tools incorporate a combination of physical, chemical, and biological indicators to accomplish their tasks. Arshad and Martin (2002) set out a set of indicators that appear to be a reasonable set for most situations: organic matter, topsoil depth, infiltration, aggregation, pH, electrical conductivity, suspected pollutants, and soil respiration. Crop yield is to be used as an integrator of these indicators. They then state that a minimum data set must be established for each indicator, and that monitoring must take place that reduces the influence of soil heterogeneity, seasonal fluctuations, and analytical uncertainties. The article then sets out guidelines to identify critical limits for key indicators and a procedure for monitoring changes in soil quality trend.

Attempts to Set Thresholds

Comparisons

Many studies compared the effects of management systems or practices on selected soil quality indicators, then made a judgment as to which system or practice best improved overall soil quality (e.g. Acosta-Martinez et al. 2004; Moore et al. 2000; Franzluebbers et al. 1995b). Karlen et al. (1997) cite Doran et al. (1987), Doran and Werner (1990), and Werner and Dindal (1990) who investigated alternative cropping practices and tabulated the effects on organic C content, conductivity, pH, mineralizable N, and other factors. These authors note that sampling time had a measurable and significant impact on the results obtained. One example reported is that earthworm counts on soil treated with animal manure rose from 10 kg ha-1 in samples taken June 1 to 120 kg ha-1 on July 1 to 440 kg ha-1 on July 28. This illustrates the challenges faced by researchers in selecting soil quality indicators that are sensitive enough to measure change over reasonable periods, but not so sensitive as to skew the results based on sampling time. Filip (2002) published research that rates the sensitivity (relative to a control soil) of certain microbiological and biochemical soil quality indicators to 49 different anthropogenically affected soils (table 2).

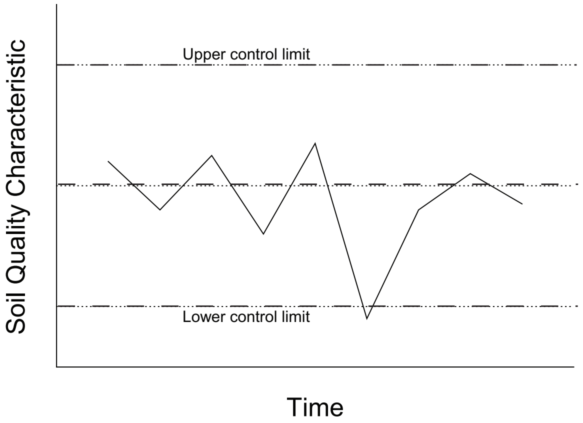
Sarrantonio et al. (1996) provide detailed procedures and calculations to determine values for a select set of soil quality indicators at the farm level, then compare results obtained from two different cropping systems. They do not provide parameters for these values, and evaluation of the results is left to the grower. One example provided by the authors from their study shows high soil nitrate levels in a conventional management system and short infiltration times for those same treatments. They concluded that this system had a high potential for nitrate leaching. This illustrates the importance of training practitioners to make connections and fully evaluate all the data collected for a soil quality assessment.

Cited thresholds

Thresholds, or parameters, are found in several publications on soil quality. The USDA NRCS has published a table of soil quality standards, based on Koenig and Isaman (1997), for urban soils in an on-line publication directed towards developers (NRCS 2003). (table 3, 3a). Larson and Pierce (1994) and Pierce and Larson (1993) suggested using statistical control charts to assist in establishing critical control limits and also monitoring changes in soil quality (figure 1). Critical control limits were defined as upper and lower boundaries for the soil quality characteristic and were selected based on known tolerances, mean variation obtained from average measurements, or personal experience. If values are located within the control limits, the system is considered to be in an acceptable state. Conversely, if the value lies outside the critical control limits, the system is considered to be in a state of degradation. The graphical interface of this design is useful for a few select indicators, but can be cumbersome and difficult to interpret if too many indicators are used.

Figure 1

Concept of a control chart from Pierce and Larson (1993).



Gomez et al. (1996) applied the Framework for the Evaluation of Sustainable Land Management developed by FAO and IBSRAM (Smyth et al. 1993) on two farms in a tropical region and set thresholds for soil depth, organic C, and permanent ground cover (among other parameters) based on values measured in the area. The purpose was to establish a sustainability index, not an index specifically for soil quality, but the method used to make evaluations of soil quality based on values measured in the local area is useful to consider. Sparling and Schipper (2004) took this technique to a national level, in New Zealand, by conducting and reporting a broad survey of selected soil properties based on land use categories. These categories were divided into 1) arable cropping, 2) mixed cropping, 3) drystock pasture, 4) dairy pasture, 5) tussock grassland, 6) plantation forestry, and 6) indigenous forest. In this way, mean and standard error statistics could be recorded so that future evaluation of specific farm-management programs could be compared against this data set.

Another feature of the Gomez et al. (1996) article that may have applicability in the construction of a soil quality index or formula is the use of a radar graph to present the data. This technique has the advantage of being useful for quick analysis with less danger of oversimplification. However, an article published by Andrews et al. (2003) that surveyed grower reaction to different forms of data presentation showed poor grower receptivity to radar graphs.

Harris et al. (1996) used a qualitative data set to rate the fitness of a soil to support the crop-production function of soil health. For example, the authors provide a scoring range of 3.0 to 4.0 for a soil in which all nutrient levels are at the recommended levels or are capable of rapid rotting of residues and manures, but only 0.0 to 1.0 for soils with two or more nutrients very low or residues and manures do not break down in the soil. The scores are then summed for an overall soil-health score. They list several indicators based on nutrient availability, water availability, and rooting environment and give numerical parameters within an "expected range." (table 5). The authors also describe the shapes of the scoring curves based on optimum, more-is-better, or less-is-better functions that they adopted from Wymore (1993). Hussain et al. (1999) adopted this technique and modified the threshold limits to better suit local conditions found in southern Illinois.

Karlen et al. (1994) provide threshold and optimal levels (table 4) based on the research of Wilson and Browning (1945), Hillel (1971), Edwards and Lofty (1977), Tisdall and Oades (1982), Linn and Doran (1984a,b), Arshad and Coen (1992), Singh et al. (1992), Eash (1993), and Hudson (1994).

Andrews et al. (2004) set threshold limits on selected soil quality indicators and gave them functional curves, specifically algorithms and logic statements (table 6), similar to those of Harris et al. (1996). This was a thorough attempt to create a framework that was quantitative in character and applicable to most areas of the country, utilizing studies from the Midwest, the West Coast, and the Southeast.

Arshad and Martin (2002) point out that one particular challenge in setting critical threshold limits on soil quality indicators is that some parameters are crop or environmentally dependent. They use the example that a drop in pH below 6.5 reduces the yield of

Table 2

Relative sensitivity of selected microbiological and biochemical soil quality indicators based on Filip (2002).

Parameter	Relative sensitivity*
Microbial biomass	
Composition of microbial communities	+/++
Copiotrophic bacteria (colony forming units)	+/++
Oligotrophic bacteria	++
Actinomycetes	++
Microscopic fungi	++
Proteolytic spore forming bacteria	–/+
Cellulose decomposer	+/++
N_2-fixing bacteria	++++
Pseudomonads	–/+
Biochemical process-linked activities	
Respiration (CO_2 release)	+++
Ammonification (NH_4^+ release)	++
Nitrification/denitrification	++/+++
Dehydrogenase activity	+++/++++
Humification activity	++

Table 3

Soil tests and parameters for urban topsoil based on Koenig and Isaman (1997).

Topsoil characteristic	Test method	Required final condition
Soluble salts (EC) ds m^{-1} or mmho cm^{-1}	Saturated paste	<2.5
Sodium adsorption ratio (SAR)	Saturated paste	<2
pH	Saturated paste	6.0 to 7.5
Sand (%)	Hydrometer	<70
Silt (%)	Hydrometer	<70
Clay (%)	Hydrometer	<30
Texture class		Must be L, SiL, SCL, SL, or CL
Organic matter	Loss on ignition/ash	≥5
Coarse fragments (%)	Sieving	<10
NO_3-N (mg kg^{-1})	$Ca(OH)_2$ extract	Report level to allow proper fertilization
P mg P kg^{-1}	Olsen $NaHCO_3$	>20
K mg K kg^{-1}	Olsen $NaHCO_3$	>150
Fe mg Fe kg^{-1}	DTPA	>10
C:N ratio	Combustion/Leco instr.	<20:1
On-site tests		
Penetrability	ASAE Soil Testing Spec. of a 20 mm insertion rate s^{-1} with soil moisture at field capacity	<1400 kPa down to 25.4 cm depth
Bulk density		See Table 1a.
Infiltration (cm hr^{-1})	ASAE Soil Testing Spec.	>1.5-5.1
Topsoil depth (cm)		>20.3 cm

Table 3a
Bulk density specifications for urban soils (USDA NRCS).

Soil texture	Ideal bulk densities (g cm–3)	Bulk densities that may affect root growth (g cm–3)	Bulk densities that restrict root growth (g cm–3)
Sands, loamy sands	<1.60	1.69	>1.80
Sandy loams, loams	<1.40	1.63	>1.80
Sandy clay loams, loams, clay loams	<1.40	1.60	>1.75
Silts, silt loams	<1.30	1.60	>1.75
Silt loams, silty clay loams	<1.10	1.55	>1.65
Sandy clays, silty clays, some clay loams (35 to 45% clay)	<1.10	1.49	>1.58
Clays (>45% clay)	<1.10	1.39	>1.47

Table 4
Soil quality indicators and their expected ranges based on Harris et al. (1996).

			Type of curve		
Data set	Parameter	Expected range	Plant production	Environmental quality	Integrated
Nutrient availability	Bray P	7.5 to 150 mg kg–1	Optimum	Optimum	Optimum
	Exchangeable K	45 to525 mg kg–1	Optimum	Optimum	Optimum
	pH	3.5 to 9.5	Optimum	Optimum	Optimum
	Organic C	5 to 65 g kg–1	More is better	More is better	More is better
	NO3-N	3 to 50 mg kg–1	Optimum	Optimum	Optimum
Water availability	Surface residue	1000 to 18000 kg ha–1	Optimum	Optimum	Optimum
	Porosity	20 to 80%	Optimum	Optimum	Optimum
	Organic C	5 to 65 g kg–1	More is better	More is better	More is better
	Aggregate stability	15 to 70%	More is better	More is better	More is better
Rooting environment	pH	3.5 to 9.5	Optimum	Optimum	Optimum
	Bulk density	1.2 to 2.1 g cm–3	Less is better	Less is better	Less is better
	Rooting depth	60 to 250 cm	More is better	More is better	More is better
	Organic C	5 to 65 g kg–1	More is better	More is better	More is better

alfalfa, but that the pH must drop below 4.0 for a reduction in blueberry yields. They suggest that the best science can do is develop a set of guidelines that can help set limits for defined crop/environment situations. The authors do believe it is important to define critical limits for selected indicators in the sense of a certain percentage increase or decrease that is significant. They believe, for example, that a 15% increase or decrease of organic matter over a baseline level seems reasonable. An increase of 15% would indicate that an adopted management practice had a significant impact on soil organic matter content, and conversely, a 15% decrease in organic matter would indicate corrective action should be taken to reverse the trend.

Brejda et al. (2000b) studied to what extent soil quality indicators were correlated on different land uses in the central and southern High Plains. They determined that 87 of 190 attribute pairs were significantly correlated and stated that the high frequency of correlation indicates that some soil attributes can be grouped into factors. They also noted that discriminant-analysis results indicated that soil texture, acidity, and soil P factors did not vary significantly with land use and thus were not useful indicators in monitoring changes in soil quality under different land uses or conservation programs on a regional scale within the central High Plains. Conversely, they determined that total organic C and total N were the most powerful soil attributes in discriminating among different land uses. It should be noted that these attributes were evaluated on land use and not on management practices within one type of land use, but they are an indication of sensitivity to changes that exist due to long-term differences in soil usage. A similar study by the authors in the Northern Mississippi Loess Hills and Palouse Prairies (Brejda et al. 2000c) gave somewhat different specific attributes for different areas of the nation but did reaffirm the notion that certain indicators could be grouped into factors.

Table 5

Parameters used by Karlen et al. (1994) for soil quality assessments of different crop residue treatments.

Parameter	LT	BL	UT	LB	OL	UB
Aggregation (%)	30	45	60	—	—	—
Surface 75 mm porosity (%)	20	—	80	40	50	60
Upper 500 mm porosity (%)	20	—	80	40	50	60
Surface 75 mm bulk density (Mg m–3)	1.3	1.8	2.1	—	—	—
Upper 500 mm bulk density (Mg m–3)	1.3	1.8	2.1	—	—	—
Microbial biomass (mg C kg–1)	75	350	700	—	—	—
Respiration (mg C kg–1)	0.5	3.0	8.0	—	—	—
Ergosterol (µg g–1)	75	350	700	—	—	—
Earthworm population (no. m–2)	25	75	125	—	—	—
Soil pH	4.5	—	9.0	5.3	6.5	7.5
Total C in surface 75 mm (mg cm–3)	15	30	50	—	—	—
Total C in upper 500 mm (mg cm–3)	6	12	20	—	—	—
Total N in surface 75 mm (mg cm–3)	1.5	3.0	5.0	—	—	—
Total N in upper 500 mm (mg cm–3)	0.6	1.2	2.0	—	—	—
Cation exchange capacity (cmol kg–1)	5	10	15	—	—	—
Plant available water (volumetric %)	10	20	30	—	—	—
Water-filled pore space (%)	15	—	105	30	60	90

Table 6

Example of algorithms and logic statements used to interpret indicators in Andrews et al. (2004).

Indicator	Scoring algorithm	Fixed parameters	Site-specific factors
Macroaggrate stability (AGG)	IF AGG>50 AND [y=a+b*cos(c*AGG-d)<1] THEN y=1, ELSE y=a+b*cos(c*AGG-d)	a=–0.8, b=1.799, c=0.0196	d=f((iOM#, texture, Fe2O3)
Available water capacity (AWC)	IF region=arid, THEN y=(a*b+c*AWC)/(b+AWC), ELSE y=a+b*cos(c*AWC+d)	a=0.0114, c=1.088, d=2.182	region, b=f (texture, iOM) d=f(texture)
Microbial biomass carbon (MBC)	y=a/[1+b*exp(-c*MBC)]	a=1.0, b=40.478	c=f(iOM, texture, season)
pH	y=a*exp[-(pH-b)2/2*c2)	a=1.0	b,c=f(crop)

Inherent organic matter levels grouped by suborder (USDA NRCS) 1998.

Frameworks

Comparisons

Bezdicek et al. (1996) note in an article concerning the importance of soil quality to health and sustainable land management that there are two approaches to viewing soil quality. The first is to see soil quality as "an inherent attribute of soils that can be inferred from soil characteristics or indirect observations (e.g. erodibility or compactability)." The second is to view soil quality as a dynamic characteristic or in terms of a soil's "capacity to perform certain productivity, environmental, and health functions." In other words, one can measure the quality of a soil based on a comparison to an ideal soil, or measure it in terms of how well it performs and can continue to perform certain functions. The use of a reference soil (also termed ideal, native, or undisturbed) works best in agricultural soil that was former grassland. The transformation of soil that was historically forested prior to cultivation is too drastic to be able to compare the managed soil to an undisturbed soil. This approach also assumes that agricultural practices only degrade soil and is not well suited for use in a system that attempts to measure managed improvements in soil quality. The authors note two examples of why the first method is so difficult to use, the first being desert soils of the southwestern United States that were initially poor producers and unsustainable for agriculture until effective irrigation management was implemented. In this situation, there is no "ideal" soil to compare against the soil quality of the irrigated cropland. The other example cited is flooded-rice culture on native dryland soil. Soil quality could not be measured or evaluated in reference to the native condition of the soil due to the radical transformation of the vegetative and environmental conditions. A consensus has formed around the concept of viewing soil quality in terms of a soil's sustainable ability to perform certain functions. This approach has its detractors (e.g. Sojka and Upchurch 1999; Letey et al. 2003) who are concerned that defining or describing soils based on their capacity to function discounts humankind's ability to innovate and adapt, thus creating a potential situation where millions of hectares of land will be abandoned to farming due to its vulnerability.

The "functional" approach to assessing soil quality was elucidated by Doran and Parkin (1994) and consists of viewing soil quality through three primary soil functions. The first primary function of a soil, one that most producers are familiar with, is how well a soil maintains productivity. This soil function is the most understood of the three since historically agronomic research has focused on this aspect and contains many soil quality indicators. Bezdicek et al. (1996) note that although most soil scientists agree that in this soil function, soil organic matter is the most important indicator, by itself it is not a sufficient measure of soil quality or health. The second primary soil function that soils must perform is environmental. Agricultural practices that optimize (short-term) productivity may enhance or degrade the environment. The link between soil quality and air and water quality is well understood in the scientific community (Cox 1995; Haberern 1992). Sims et al. (1997) state that soil quality assessment requires a definition of a "clean" soil. This statement highlights the overlap between the environmental function of a soil and the third soil function, which is the promotion of plant, animal, and human health. Different researchers tend to group the second and third functions into one (Moen 1988) with the difference being more on emphasis. The environmental function may focus on water quality degradation or improvement due to soil management practices, while the "health" function may, for instance, focus more on a soil's ability to adsorb or transform a chemical compound toxic to animals or humans. Daily et al. (1997) list important soil functions as including water flow and retention, solute transport and retention, physical stability and support, retention and cycling of nutrients, buffering and filtering of potentially toxic materials, and maintenance of biodiversity and habitat.

Selected frameworks for evaluating soil quality

Carter et al. (1997) suggest a framework for evaluating soil quality that consists of following an ordered procedure: 1) describe each soil function on which quality is to be based, 2) select soil characteristics or properties that influence the capacity of the soil to provide each function, 3) choose indicators of characteristics that can be measured, and 4) use methods that provide accurate measurement of these indicators. They go on to state that application of the management aspect of soil quality control should begin with using the steps just described in assessing whether the soil management system is capable of producing inputs for some sustainable factor (such as soil organic matter), and whether the management system provides the best method for producing and placing the input. If the answer to either is negative, it is an indication that the system is not sustainable and/or calls for better management practices.

Doran (2005a, 2005b) stated that soil and land management practices are primary determinants of soil quality and health. Consequently, indicators of soil quality and health must not only identify the condition of the soil resource but also define the economic and environmental sustainability of land management practices to assist governmental agencies in formulating realistic agricultural and land-use policies. He proposed a framework linking farmer and society needs with resource conservation and environmental considerations and a set of practical indicators that could be used to assess the effect of soil and land management.

Andrews et al. (2004) discuss a Soil Management Assessment Framework (SMAF) based on the impact of soil management practices on soil function. The authors use a three-step process that begins with selecting indicators, followed by indicator interpretation, and finally integration into an index. The user begins the process by answering a series of questions, including the manager's primary goal for the site. Management goals are divided into 1) maximizing productivity, 2) waste recycling, or 3) environmental protection. A table identifies the critical functions for each management goal.

A list of indicators is then associated with each soil function. Indicator interpretation is founded on non-linear curves unique to each indicator. Some indicators follow an asymptotic more-is-better curve, such as potentially-mineralizable nitrogen or microbial biomass carbon. Some indicators follow an asymptotic less-is-better curve, such as bulk density, and others, like soil test phosphorus, use an optimal (Gaussian-related) curve. Integration into an index then, is the sum of the indicator scores divided by the number of indicators used, and the score is considered an overall assessment of soil quality. This research was built on techniques reviewed by Weinhold et al. (2004).

Earlier work by Andrews and co-workers (Andrews et al. 2002) evaluated different indexing techniques to determine which were best for providing information needed for the selection of best management practices. Minimum data sets (MDS) were chosen using expert opinion or principal components analysis as a data reduction technique. Scoring techniques were compared between a linear and non-linear model, with the non-linear model determined to be more representative of system function. Indicator scores were combined using an additive index, weighted additive index, or a decision support system. Their results showed an organic system received significantly higher soil quality index scores than conventional systems, a fact criticized by Letey et al. (2003) due to the ignored potential risks to groundwater associated with high manure application rates necessary to obtain high soil quality index scores.

Gomez et al. (1996) published a framework for evaluating sustainable land management based on the FESLM developed by FAO and ISBRAM (Smyth et al. 1993). This method evaluates sustainability at the on-farm level, uses threshold levels, and is conceptually split between resource conservation and farmer satisfaction. The underlying assumption is that high productivity is the primary factor in farmer satisfaction. The authors stipulate that the procedure for measuring sustainable agriculture should be the same regardless of location. This allows for comparison across farms and is easier to analyze for repeatability. The protocol for measuring is 1) defining the requirements for sustainability, 2) selecting the common set of indicators, 3) specifying the threshold levels, 4) transforming the indicators into a sustainability index, and (5) testing the procedure using a minimum data set. If index scores exceed a threshold level, remedial action is desirable.

Harris et al. (1996) provide a conceptual framework for assessment and management of soil quality and health by using a scorecard approach. They focus on the ecosystem role of soils and define the functions that fulfill those roles. Indicators, which are divided into physical, chemical, and biological categories, are based on function. The scorecard chooses a particular soil property, e.g. soil organic matter, and then gives a score range based on the health status of the soil. In the example using soil organic matter, for instance, a healthy soil status could receive a score in the range of 3.0 to 4.0, where an impaired soil may only receive a score in the range of 1.5 to 2.5, and an unhealthy soil in the range of 0.0 to 1.0. Specific management practices could then be rated, or scored, depending on the heath status of the soil. An example would be narrow row beans on healthy soil might receive a score of 3.6, whereas continuous pasture on healthy soil might receive a 4.0 score.

Hussain et al. (1999) adopted and modified the Harris et al. (1996) framework for the evaluation of three tillage systems in southern Illinois. They concentrated on three soil functions: 1) resistance to erosion, 2) nutrient relations, and 3) rooting relations. Theses functions were scored by more-is-better, less-is-better, and optimum scoring functions with modifications made by changing the weighting factors, threshold limits, or type of scoring function applied to indicators, and the addition of air-filled and water storage porosity to the nutrient and rooting relation functions. The authors stated that adjusting threshold limits for local conditions make the function ratings more or less sensitive to the management practices being evaluated.

An oft-cited model for evaluating soil quality is one posited by Doran and Parkin (1994), called the soil quality index. The index is estimated as the product of weighted subfactors for each of the soil quality functions, and subfactors are estimated from regression equations that are constructed by simulating the relationship between properties of indicators and soil functions. The authors note the "monumental task" of developing relationships between soil attributes and soil functions but suggest the use of algorithms already employed in existing process models such as NLEAP and EPIC should prove a useful starting point. The authors cite nine areas of research that are critical to the development of assessing and improving soil quality, including the standardization of methods and protocols for sampling, the identification of soil quality indicators that can be related to food quality and human health, and the development of precision farming techniques for quality enhancement of soils.

Karlen et al. (1994) developed a soil quality index based on four soil functions, namely 1) infiltration, 2) water holding capacity, 3) degradation resistance, and 4) support of plant growth. This index also used the more-is-better, less-is-better, and optimal characterization of soil properties as described above in Andrews et al. (2004). Each soil function is weighted, and each value ascribed is multiplied by the function weight. Then all four products of weight and function score are summed to obtain the soil quality index.

$$SQI = q1(wt) + q2(wt) + q3(wt) + q4(wt) ,$$

where SQI is soil quality index, and wt is the weight assigned to qn, the soil function.

Karlen et al. (1998) created a framework for evaluating changes in soil quality as a result of enrolling land into the Conservation Reserve Program (CRP). Their on-farm measurements suggested that biological indicators were affected most quickly and to the greatest extent when cultivated land was converted to grassland, and that enrolling land into the CRP program had a positive effect on soil quality.

Larsen and Pierce (1991) were one of the first to clearly articulate that defining soil quality in terms of productivity alone was not sufficient but was more the sum of individual soil attributes and functions. They went on to suggest that a minimum data set (MDS) of soil properties or indicators was required to get a more complete assessment of soil quality. The importance of a MDS is now well established in the literature (Gregorich et al. 1994). The authors were more concerned with changes in soil quality than the baseline condition (or magnitude) of the soil quality. They separated static soil properties, i.e. those that did not change much over time (for instance, soil texture) from dynamic soil properties, or those that were measurable and had the potential to change relatively rapidly. Since changes in soil quality are a function of changes in soil characteristics over time then $dQ/dt \geq 0$ is an indication that soil quality is improving over time. Conversely, if $dQ/dt < 0$, soil quality is degrading over time (Larson and Pierce 1991).

Sparling and coworkers (Lilburne et al. 2004; Sparling and Schipper 2004; Sparling et al. 2004) conducted research over six years throughout New Zealand in order to establish a soil quality monitoring protocol. They derived a framework based on a set of interpreted response curves, which combine production and environmental goals and are specific to particular combinations of land use and soil type (Lilburne et al. 2004). The authors note that at present, the framework is better suited for assessing soil quality on a regional scale, rather than site-specific evaluation.

Other frameworks

Fu et al. (2003) compared a soil quality index to a degradation index (DI) using data gathered from deforested land in the humid, mountainous regions of China. After converting the quality index to a "deduced quality index" the authors note a high correlation between the degradation index and the deduced quality index. They note both methods were efficient in evaluating soil quality levels, but the DI was a simpler method.

Parr et al. (1992) suggest an index based on soil functions, but Singer and Ewing (2000) note that Parr's inclusion of biological diversity, food quality and safety, and management inputs, make this a land quality index as defined by FAO (1997). Snakin et al. (1996) also developed a soil index but one that measures soil degradation. It appears this index would not be readily amenable to measuring or quantifying soil quality improvements. Smith et al. (1993) and Halvorson et al. (1996) use a multiple-variable transformation procedure to combine values and combine this with kriging to develop probability maps that estimate the probability of meeting soil quality criteria at the landscape level. The authors do not define soil quality or specify which soil characteristics are to be used (Singer and Ewing 2000). Zalidis et al. (2002) proposed the development of zonation maps through the subdivision of fields into primary sampling areas, with periodic sampling and monitoring.

An older index that focused primarily on productivity is the Storie Index Rating, or SIR (Storie 1932,1964). Nine soil properties were selected, including soil morphology, surface texture, slope, drainage class, sodicity, acidity, erosion, microrelief, and fertility. The SIR equation multiplied the first three with the product of the last six after the last six had been scored from 1 to 100%. Since the SIR is the product of fractions, it does not readily lend itself to measuring improvements in soil quality. Non-quantitative systems include the USDA Land Capability Class (Klingebiel and Montgomery 1973) that evaluates arable soils separately from non-arable soils, assigning each into classes, subclasses, and units. The system, besides being qualitative, focuses primarily on productivity and may have limited application when evaluating environmental functions of soils.

Cambardella et al. (2004) evaluated soil quality assessment on a watershed scale by removing and evaluating soil cores along transects placed along topographic gradients, then using terrain analysis to group the data into landform classes. This allowed them to evaluate the effect of topographic position on soil quality. They documented soil quality differences by 1) quantification of soil indicator variables, 2) calculation of soil quality indices, and 3) comparison of indicator variable and index results with independent assessment of soil function endpoints such as sediment loss, water partitioning at the soil surface, and crop yield. Other articles have evaluated soil quality indicators from point to region-wide scales (Brejda et al. 2000c, d; Karlen et al. 1999; Liebig and Doran 1999a).

Wang and Gong (1998) utilized GIS technology to develop a relative soil quality index (RSQI) and its difference, or changes in time and space (ΔRSQI). Their purpose was to map and assess soil quality changes in small watersheds. The system depends on an extensive database of soil parameters measured over a moderately extensive time period (11 years). Jaenicke and Lengnick (1999) used data envelopment analysis techniques in the reconciliation of two soil quality indexes with economic concepts of technical efficiency and productivity growth.

Li and Lindstrom (2001) incorporate the use of a tracer element (137Cs) with a tillage erosion prediction model to estimate soil movement on a terraced hillslope. They were able to model and measure the effect of tillage beyond estimating overall soil loss through the RUSLE. This type of detailed information could prove useful in the construction of minimum data sets that form the backbone of a soil quality framework.

Biological approaches

Several studies have focused on the biological components of soils in order to estimate soil health or soil quality (Sicardi et al. 2004; Filip 2002; Stenberg 1998; Kennedy and Smith 1995; Visser and Parkinson 1992). Leirós et al. (1999) investigated the utility of incorporating biological indicators heavy-metal contaminated soils, mine soils, and arable land. Parisi et al. (2005) established an index that they termed "Qualità Biologica del Suolo" or "QBS" index which is based on the concept that the higher soil quality, the higher will be the number of microarthropod groups well adapted to soil habitats. They use techniques that do not require identification of microarthropods at the species level, thus allowing non-specialists the ability to use the system. Some challenges associated with any system that relies solely on the biological component of soil are frequency of testing, timing, and the unknown impacts of pesticides on a biological population.

Models

Harris et al. (1996) list several process models that utilize computer power to go beyond simple mathematical equations. The authors highlight NCSOIL (Molina et al. 1983, 1994) to describe carbon and nitrogen cycling; NLEAP (Shaffer et al. 1991) and the P-Index (Lemunyon and Gilbert 1993) for modeling N and P, respectively; the Attenuation Factor (AF) model for pesticides (Mulla et al. 1996); EPIC for crop productivity (Williams and Renard 1985). RUSLE, an empirically-based field and hill-slope water erosion model, was reviewed by Bussaca et al. (1993). In their review, the authors note that no one model evaluates all functions of soil quality in a comprehensive manner, with the exception of Hawkins et al. (1995), that evaluates the impact of management practices on productivity, environmental quality, and economic profitability using elements of NLEAP, P-Index, AF, RUSLE, and EPIC models. Parton et al. (1987) formulated the CENTURY model that simulates soil organic matter (SOM) formation over various time periods. The active SOM pool turns over in 1-5 years, the slow SOM pool turns over every 20-40 years, and passive SOM turns over every 200-1,500 years. Temperature, soil moisture, soil texture, and lignin content of initial residues are controlling factors or driving variables. Their parameters were established from the literature using a non-linear data fitting procedure. Parton et al. (1994) made improvements to the model, including a revised submodel for surface litter decomposition. Given that soil organic matter plays such a large role in soil quality, CENTURY or other similar models may prove a useful tool in predicting management effects on soil quality.

Associated concepts and views

Some researchers suggest that soil quality literature is generally centered around three main themes: education (Wander et al. 2002; Gomez et al. 1996), assessment (Andrews et al. 2004; Carter et al. 1997), and the test kit concept (Ditzler and Tugel 2002; Liebig et al. 1996). Each theme provides useful insight into the construction of a workable soil quality index. Several frameworks, as described above, have in common 1) the use of a minimum data set (MDS), 2) logical scoring techniques, and 3) score integration or indexing based on mathematical formulae that rely on expert opinions or principal components analysis. A synthesis of ideas and methods that takes into account the heterogeneity of soil, its multiple functions, and the concept that soil quality is measurable and improvable should be within reach. It is not apparent that researchers have attempted to create a "RUSLE-like" equation, other than the USDA NRCS Soil Conditioning Index, that uses in-depth research to create a tool that can predict the effects of management systems on soil quality. That is not to say, however, that the many publications on frameworks and comparisons of systems could not be synthesized to provide the knowledge base necessary for the creation of such an instrument. This body of accumulated research is a strong foundation for such an attempt.

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