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Soil quality: why and how?

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Abstract

The soil quality concept evolved throughout the 1990s in response to increased global emphasis on sustainable land use and with a holistic focus emphasizing that sustainable soil management requires more than soil erosion control. The concept includes two areas of emphasis—education and assessment—both based soundly on principles of soil science. Soil quality test kits, farmer-based scorecards, visual assessment procedures, fact sheets, and video presentations were developed as educational materials because many people have no basis to recognize, understand or appreciate the complexity of soil resources. Assessment tools for indexing soil quality at various scales were pursued to show the multiple functions (e.g. nutrient and water cycling, filtering and buffering of contaminants, decomposition of crop residues and other organic matter sources, and recycling of essential plant nutrients) that soils provide as the foundation for sustainable land management. Worldwide research and technology transfer efforts have increased awareness that soil resources have both inherent characteristics determined by their basic soil formation factors and dynamic characteristics influenced by human decisions and management practices. Soil quality assessment and education are intended to provide a better understanding and awareness that soil resources are truly living bodies with biological, chemical, and physical properties and processes performing essential ecosystem services.

Keywords: Soil quality; Soil health; Sustainability; Land use planning

1. Introduction

Warkentin and Fletcher (1977) suggested developing a soil quality concept because of the multiple functions (e.g. food and fiber production, recreation, and recycling or assimilation of wastes or other by-products) that soil resources must provide. They

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emphasized that (1) soil resources are constantly being evaluated for many different uses; (2) multiple stakeholder groups are concerned about soil resources; (3) society's priorities and demands on soil resources are changing; and (4) soil resource and land use decisions are made in a human or institutional context. They also stated that because of inherent differences among soils, there is no single measurement that will always be useful for evaluating soil quality.

Following its introduction, soil quality per se was not discussed in the literature for nearly a decade because the primary emphasis of soil management was on controlling soil erosion and minimizing the effects of soil loss on productivity (e.g. Pierce et al., 1984). In the mid-1980s, the Canadian Senate Standing Committee on Agriculture prepared a report on soil degradation and revived the concept (Gregorich, 1996). Shortly thereafter, Larson and Pierce (1991) defined soil quality as the capacity of a soil to function within the ecosystem boundaries and to interact positively with surrounding ecosystems. They also proposed a quantitative formula for assessing soil quality and suggested that such assessments could help determine how soils responded to various management practices. Soil quality began to be interpreted as a sensitive and dynamic way to document soil condition, response to management, or resistance to stress imposed by natural forces or human uses (Arshad and Coen, 1992; Haberern, 1992).

1.1. Initial US soil quality activities

From its inception, soil quality was not limited to productivity, emphasizing instead soil management impacts on environmental quality, human and animal health, and food safety and quality (Haberern, 1992). Interest in the concept increased rapidly following publication of *Soil and Water Quality: an Agenda for Agriculture* (NRC, 1993). Several symposia and publications (Doran et al., 1994; Doran and Jones, 1996) followed producing definitions, identifying critical soil functions, and suggesting uses for soil quality assessments (Doran and Parkin, 1994). The concept continued to evolve with sustainable agriculture (NRC, 1989; Gomez et al., 1996) and rangeland health (NRC, 1994) initiatives providing an increasing emphasis on sustainable land use. Soil quality assessment was envisioned as a tool to help balance challenges associated with (1) increasing world demand for food, feed, and fiber, (2) increasing public demand for environmental protection, and (3) decreasing supplies of nonrenewable energy and mineral resources (Pesek, 1994; Doran et al., 1996).

The soil quality concept advanced again when the USDA-Soil Conservation Service was reorganized and the Natural Resources Conservation Service (NRCS) Soil Quality Institute was created. The NRCS recognized that with 100 years of experience with the National Cooperative Soil Survey Program, they knew the geographic location of more than 18,000 soils and had an extensive amount of data on basic soil properties, landscape characteristics, and interpretations for use and management. This database, describing inherent soil properties, was envisioned as a resource to match various land uses with the inherent ability of individual soils to perform critical functions. The NRCS, through the National Resources Inventory (NRI), also had developed a statistical sampling basis for monitoring and assessing soil quality changes with time on regional and national scales. Through its partnership with local Soil Conservation Districts, the NRCS also has an extensive technical delivery system and is positioned to work with private landowners to

promote the maintenance and enhancement of our nation's soil resources. With this foundation the newly created NRCS agreed to: (1) participate in the development of scientific principles supporting the soil quality concept; (2) develop, test, and disseminate tools for monitoring and assessing soil quality; (3) build partnerships with research groups and action agencies [i.e. EPA, Forest Service (FS), Bureau of Land Management (BLM)] to characterize and document effects of current and alternative land management practices on soil quality; (4) enhance awareness by developing educational materials and tools for land managers to monitor and assess the quality of their soils; and (5) develop and provide training materials for agency personnel and others.

The Soil Science Society of America (SSSA) contributed to development of the soil quality concept when the president appointed a 14-person committee (S-581) in 1994 and charged them to define the concept, examine its rationale and justification, and identify the soil and plant attributes that would be useful for describing and evaluating soil quality. This led initially to a simple definition for soil quality: "the capacity (of soil) to function". An expanded version defines soil quality as "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" (Karlen et al., 1997). The SSSA continues to have an active soil quality working group within the Soil Biology and Biochemistry (S3) Division and substantial interest within the Soils and Environmental Quality (S11) Division. Scientists from university, government, nonprofit, private sector, and international organizations are among the many active participants in these groups.

1.2. Current soil quality research and education activities

The soil quality concept evolved with two distinct areas of emphasis—education and assessment—both based soundly on principles of soil science. Educational materials are being developed because most people have no basis for recognizing, understanding or appreciating the complexity of soil resources. They are not aware of how soil literally provides the foundation for sustainable land management through processes such as nutrient and water cycling, filtering and buffering of contaminants, decomposition of crop residues and other organic matter sources, and recycling of essential plant nutrients. Assessment tools including soil quality test kits (Liebig et al., 1996; Sarrantonio et al., 1996), farmer-based scorecards (Romig et al., 1996) and soil resource management programs (Walter et al., 1997) focus on farmer-based evaluations and education regarding various soil and crop management practices and their effects on soil resources. The accuracy, sensitivity, and usefulness of several indicators (Karlen et al., 1999; Liebig and Doran, 1999) and spatial extrapolation techniques (Smith et al., 1993) are also themes for various soil quality studies. Doran et al. (1996) examined the broader linkages between soil quality (or soil health) and sustainability. Finally, various soil quality indexing approaches (Andrews and Carroll, 2001; Andrews et al., 2002a; Hussain et al., 1999; Jaenicke and Lengnick, 1999; Karlen et al., 1998; Wander and Bollero, 1999) were pursued. Collectively these research and education activities focus on two important principles associated with soil quality and its assessment. These are that (1) soil quality is determined by both inherent and dynamic properties and processes interacting within a

living dynamic medium, and (2) that it is holistic, reflecting biological, chemical, and physical properties, processes, and interactions within soils.

Soil quality research and education programs are continuing to be carried out in each of these areas by soil scientists, ecologists, and others around the world. Before giving specific examples, however, it is important to clarify how these efforts differ from traditional soil survey, classification, and interpretation. Soil quality assessment emphasizes both inherent and dynamic soil properties and processes. Traditional soil classification and interpretation are based almost entirely on inherent characteristics determined by basic soil forming factors of climate, parent material, time, topography, and vegetation (Jenny, 1941). The inherent properties determine absolute capabilities of various soils, generally focus on the entire soil profile (~ 2 m deep), and are the reason why there can be no single value describing soil quality for all soil resources and land uses. Dynamic soil quality focuses on the surface 20 to 30 cm and describes the status or condition of a specific soil due to relatively recent land use or management decisions (Fig. 1). It is measured by using various biological, chemical, and physical indicators, including some of the inherent properties (e.g. pH, bulk density, organic matter content) included in most soil profile descriptions. In fact, the ranges provided for the inherent measurements in the traditional soil survey database are often used to establish the boundaries for scoring or quantifying the dynamic measurements associated with soil quality assessment. Traditional soil survey, classification, and interpretation and soil quality assessment are not competing but rather complementary.

1.3. Education thrusts

The Soil Quality Institute (http://soils.usda.gov/SQI) is providing substantial leadership toward promoting public awareness regarding how the soil, water, air, plant, animal and human resources are affected by land use decisions. Soil quality information sheets were one of the first products prepared by the institute (Muckel and Mausbach, 1996). The Soil Biology Primer (SWCS, 2000) and Guidelines for Soil Quality Assessment in Conservation

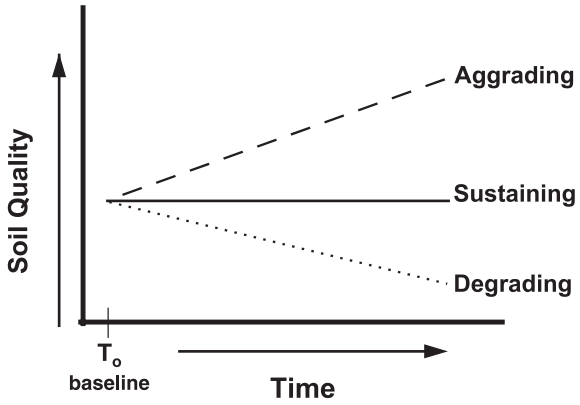

Fig. 1. Possible temporal trends in dynamic soil quality assessments.

Planning (USDA-NRCS, 2001) are two recent publications. An educational website is also being prepared by ARS, NRCS, and University of Illinois partners with partial support from USDA-Sustainable Agriculture Research and Education (SARE).

1.4. Scorecards

Romig et al. (1995) developed a soil health card for Wisconsin conditions that was then adapted for use in several other states. These tools were developed with the aid of soil scientists and are intended to provide a qualitative, self-assessment of a farmer's current soil and crop management practices. The scoring is relatively simple (e.g. poor, fair, good) and based on observations of tilth, earthworms, runoff or ponding of water, plant vigor, ease of tillage, and yield. Two primary reasons for developing scorecards were to promote an increased awareness regarding soil resources and to encourage landowners and operators to "look below ground" when they are evaluating their soil management practices (Karlen et al., 2001).

1.5. Soil quality test kits

The initial soil quality test kit was developed to provide semiquantitative indicator data for the 0 to 7.6 cm depth (Doran, 1994). Bulk density, infiltration rate, water-holding capacity, electrical conductivity, soil pH, soil nitrate, and soil respiration were measured. Evaluations in several locations compared favorably with laboratory analyses (Liebig et al., 1996) and provided a good screening tool for agricultural soil quality (Sarrantonio et al., 1996) and conditions in Central Park of New York City (Norfleet, 2000, personal communication). The kits are commercially available with free guidelines for making and interpreting measurements provided by the Soil Quality Institute (USDA-NRCS, 1998).

Internationally, there are several other soil quality kits being developed to help land managers make better decisions regarding their soil management practices. One example is the Visual Soil Assessment protocol developed for New Zealand conditions (Shepherd, 2000). Site characteristics including land use, soil type, texture, moisture condition, and seasonal weather patterns are included to help with interpretation. Indicators for lowland arable areas include: (1) soil structure as indicated by a 1 m drop/shatter test, (2) soil porosity, (3) soil color, (4) number and color of mottles, (5) earthworm number, (6) evidence of a tillage pan, (7) surface cloddiness, and (8) the apparent susceptibility to wind and water erosion. Plant indicators include: (1) degree and uniformity of emergence, (2) crop height at maturity, (3) size and development of the root system, (4) yield quantity and quality, (5) incidence of root diseases, (6) degree of weed infestation, (7) amount and duration of surface ponding, and (8) relative production costs. Other soil and plant indicators are used for lowland pasture and hill country evaluations. Based on the assessments, various options and recommendations are provided to repair the loss of soil quality. Management suggestions include (1) continued monitoring of soil conditions to ensure that soil resources regain and are maintained in a healthy condition, (2) maintaining or improving soil organic matter levels, (3) utilizing no-till or reduced tillage practices whenever possible, (4) targeting tillage operations and implements to sustain soil structure–including cultivating only when soil water contents are appropriate and using

implements that minimize structural degradation, (5) managing wheel traffic, (6) preventing water and wind erosion, (7) using subsoiling to break hardpans, (8) installing drainage when needed and feasible, (9) rotating crops, and (10) incorporating organic residues and composted materials whenever feasible. An important characteristic of this assessment program is that it uses several traditional morphology and genesis criteria (e.g. structure, porosity, color, and mottling) as well as plant response as key indicators of soil quality.

1.6. Indicator evaluations

The most prevalent soil quality research theme focuses on indicator selection and evaluation. Numerous studies are being conducted worldwide to examine the accuracy, sensitivity, and usefulness of various soil properties and processes at scales ranging from single points to entire land resource areas (Karlen et al., 1998; Beare et al., 1999; Brejda et al. 2000a,b,c; Elmholt et al., 2000a; Islam and Weil, 2000). This is also a dominant theme in this issue with several papers focusing on one or more soil quality indicators and how they respond to various treatments or land management scenarios. Although indicator research is a critical component of soil quality assessment, it is not an end in itself. Unfortunately, emphasis on single indicators of soil quality has sometimes been reported as ''measuring soil quality'' even though the intent from its inception (Warkentin and Fletcher, 1977) was for soil quality to be evaluated based on multiple biological, chemical, and physical attributes and their interactions.

One aspect of soil quality indicator research that may help reassure skeptics that the concept is science based is the role that pedotransfer functions can have. Larson and Pierce (1994) discussed their usefulness and application in detail during one of the first US soil quality symposia. These tools can be very useful when data for an important indicator may not be available but other related measurements have been collected. Potential soil quality indicators for which pedotransfer functions have been published include (1) phosphate-sorption capacity, (2) cation exchange capacity, (3) change in organic matter content, (4) bulk density, (5) water retention, (6) random roughness, (7) porosity, (8) hydraulic conductivity, (9) seal conductivity, (10) saturated hydraulic conductivity, (11) soil productivity, and (12) rooting depth (Larson and Pierce, 1991).

The complexity of soils, spatial and temporal variability, and effects of external factors such as climate were recognized as major challenges to overcome at a conference in Ås, Norway (Bouma, 2000; Elmholt et al., 2000b; Karlen and Andrews, 2000). Participants agreed that to obtain a better understanding of soil quality, interdisciplinary studies are needed to understand how soil properties and processes interact within ecosystems. Unfortunately, the primary research focus for most participants was on individual properties or processes such as denitrification, redox potential, organic matter, earthworms, biotic and abiotic binding processes, tillage systems, crop rotation, or management of organic wastes. Only a few were actually participating in interdisciplinary, holistic programs.

1.7. Indexing soil quality

Traditional soil survey, classification and interpretation activities have defined Land Capability Classes, a Storie Index, and other Land Inventory and Monitoring indices based

primarily on inherent soil properties (Karlen et al., 1997). Each is important and useful for certain applications, but none are the same as indexing dynamic soil quality. The latter builds upon the former but not vice versa. The inherent differences among soils, complexity of environments within which soils exist, and the variety of soil and crop management practices being used around the world currently preclude establishing a specific rating or value against which all soils can be compared. What can be developed is a framework or indexing procedure that can be easily modified for different soils and used to enumerate dynamic soil quality ratings, determine trends in those ratings, and thus used to quantify long-term effects of alternate land uses or soil management decisions (Karlen et al., 2001).

Indexing dynamic soil quality involves three steps. The first is selecting appropriate soil quality indicators to efficiently and effectively monitor critical soil functions (e.g. nutrient cycling; water entry, retention, and release; supporting plant growth and development) as determined by the specific management goals (Fig. 2) for which an evaluation is being made. Collectively these indicators form a minimum data set (MDS) that can be used to determine how well critical soil functions associated with each management goal are being performed. Each indicator is then scored, often using ranges established by the soil's inherent capability to set the boundaries and shape of the scoring function. This step is required so that biological, chemical, and physical indicator measurements with totally different measurement units can be combined [e.g. earthworms per unit area, pH (unitless), and bulk density (g cm^{-3})]. Indicator scoring can be accomplished in a variety of ways (e.g. linear or nonlinear, optimum, more is better, more is worse) depending upon the function (Fig. 3). For some management goals the same indicator may be included under different functions and even scored in different ways (e.g. "more is better" for NO_3–N supporting plant growth but "less is better" with regard to leaching). The unitless values are combined into an overall index of soil quality (Fig. 3) and can be used to compare effects of different practices on similar soils or temporal trends on the same soil. Finally, to understand the complete value of dynamic soil quality assessment, Andrews and Carroll (2001) suggested that it be viewed as one of the components needed to quantify agroecosystem sustainability (Fig. 4). Process and mechanistic soil science research thus provide critical information for soil quality assessment and in our opinion, make soil quality an important theme for the advancement of soil science.

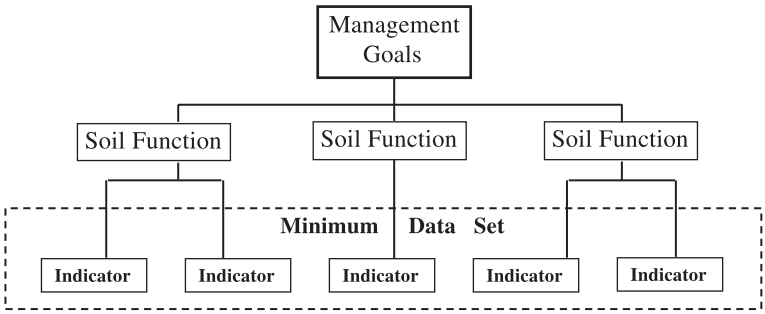

Fig. 2. A framework for selecting indicators for a minimum data set.

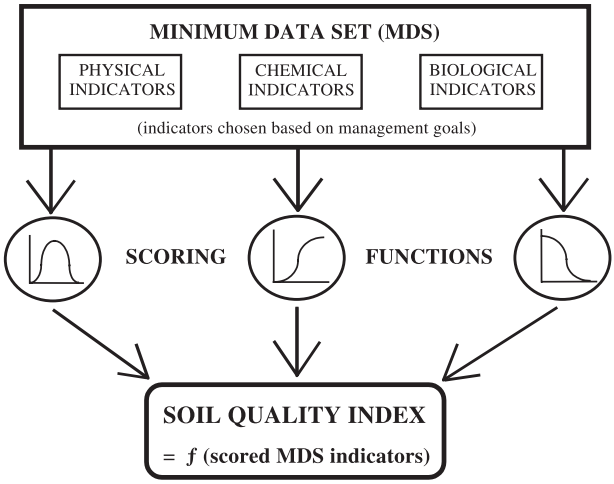

Fig. 3. Conceptual model for converting minimum data set indicators to index values (adapted from Andrews, 1998).

1.8. Reservations regarding soil quality

The soil quality concept has not been universally accepted (Sojka and Upchurch, 1999), even though efforts to develop and use soil quality assessment as a tool to evaluate sustainability are based on a belief that soil scientists must take a more active

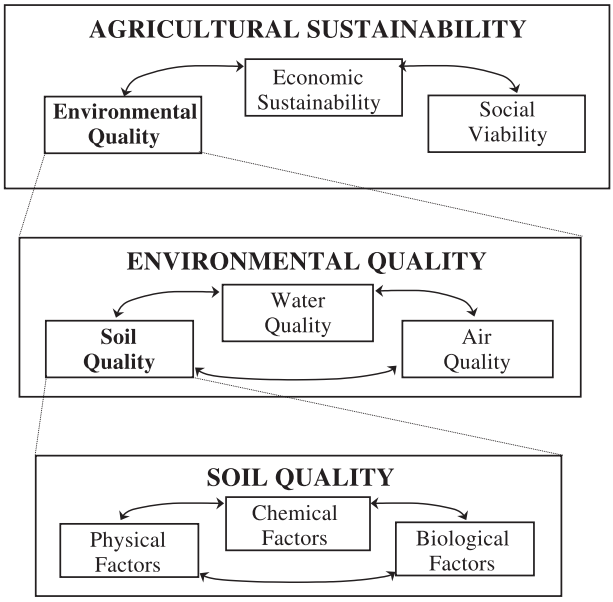

Fig. 4. Hierarchical relationship of soil quality to agricultural sustainability (adapted from Andrews, 1998).

role in balancing production and environmental quality within agroecosystems (Karlen et al., 2001). One concern expressed regarding soil quality assessment was that it placed too much emphasis on production agriculture rather than including all potential land uses in the US. Singer and Ewing (2000) supported this concern stating that internationally soil quality efforts have focused more on contaminant levels and their potential effects on soil function than in the US. We agree that this occurred during the 1990s even though the need to apply the soil quality concept to activities such as mining and smelting, refining, landfilling, forest and range management, urban compaction, recreation (e.g. parks and athletic fields), and other nonagricultural land uses was recognized (Karlen et al., 1997). We attribute the initial narrow focus to the disciplinary bias of the early adopters (Karlen et al., 2001) and their research focus on tillage and crop production. However, Sims et al. (1997), a Soil Science Society of America symposium in 2000, and other publications are addressing this broader soil quality need by demonstrating that frameworks developed for production issues can be easily adapted for issues such as poultry litter management (Andrews and Carroll, 2001) or vegetable crop production (Andrews et al., 2002a).

Sojka and Upchurch (1999) suggested there was very little if any parallel between soil, air, and water quality. We argue that all three resources have a plethora of definitions based on current or anticipated use. Indeed, water can exist in a pure state whereas soil cannot, but under natural conditions water is not pure. If it were pure, single-celled organisms would be lysed and the habitat would be unsuitable or of "low quality". For applications involving environmental and human interactions (e.g. allergy ratings, odors, suitability for swimming, fishing or drinking), air and water quality are defined based on current or intended use. It is with that parallel in mind that these three entities can be equated into sustainability indices.

Sojka and Upchurch (1999) also stated that there was a regional or taxonomic bias in soil quality efforts. We disagree and have conducted studies in the irrigated central valley of California (Andrews et al., 2002a,b) and Georgia Piedmont (Andrews and Carroll, 2001) demonstrating that soil quality indexing can be a useful tool for assessing sustainability of soil and crop management practices for a wide variety of soils. This can be done because the nonlinear scoring functions (Fig. 3) can be easily modified to accommodate soil differences due to their inherent characteristics (e.g. Mollisols in the Midwestern US will typically have higher soil organic matter levels than Ultisols in the Southeast). Furthermore, the relative index of inherent soil quality (Sinclair et al., 1996), criticized by Sojka and Upchurch (1999) as being biased toward US Midwestern Mollisols, is an accurate reflection of the soil resource potential in the absence of human intervention and external input of energy resources (i.e. fossil fuel and water). The lack of correlation between inherent soil quality and economic value of the products produced is expected because high productivity in areas with low inherent soil quality can only be achieved by creating a highly rated dynamic soil quality by investing in external energy inputs and producing high-value crops. This type of situation is why measuring sustainability by evaluating soil quality requires precise measurements, accurate interpretations, and a thorough understanding of both inherent and dynamic soil properties and processes. It is also why substantial effort has been devoted to developing educational materials using rigorous principles of edaphology. Without such holistic efforts, we argue that too many decisions will continue to be made with a

shortsighted yield- or economically based focus and that the resulting actions will continue to literally treat soil like "dirt" (Gibbons and Wilson, 1984).

2. Summary and conclusions

We conclude that soil quality has become an internationally accepted science-based tool for advancing the assessment, education and understanding of soil resources. Two of the most important factors associated with the soil quality concept are that (1) soils have both inherent and dynamic properties and processes and that (2) soil quality assessment must reflect biological, chemical, and physical properties, processes and their interactions. We stress that there is no ideal or magic index value, but soil quality assessments can be made using a framework that prioritizes management goals, identifies critical soil functions necessary for achieving those goals, and selecting indicators that provide useful information regarding how a specific soil is functioning. Undoubtedly, the soil quality concept will continue to evolve, but rather than continuing to disagree about terminology, we hope that others will join the effort so that we can truly ensure that our children and grandchildren will be well-fed and that they will have woods to walk in and streams to splash in (Sojka and Upchurch, 1999).

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