1-1-2008

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Karlen, Douglas L.; Andrews, Susan S.; Wienhold, Brian J.; and Zobeck, Ted M., "Soil Quality Assessment: Past, Present and Future" (2008). *Publications from USDA-ARS / UNL Faculty.* Paper 1203.
http://digitalcommons.unl.edu/usdaarsfacpub/1203

Journal of Integrative Biosciences 6:1 (2008)

Soil Quality Assessment: Past, Present and Future

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ABSTRACT

Soil quality assessment may be one of the most contentious topics ever debated by the soil science community. Our objective is to examine the history, present status, and potential for using soil quality assessment as a tool to monitor soil physical, chemical, and biological effects of management decisions that may affect soil and water resources. Differences between inherent and dynamic soil quality and various approaches for assessment are identified and discussed. Four assessment indices, the Agroecosystem Performance Assessment Tool (AEPAT), Soil Conditioning Index (SCI), Cornell Soil Health Test, and Soil Management Assessment Framework (SMAF) are examined. The SCI predicts changes in soil organic matter (SOM) and is a good first step toward more comprehensive assessment, but it focuses only on a single indicator. The AEPAT, Cornell Soil Health Assessment, and SMAF offer a more comprehensive soil quality assessment by including biological, chemical, and physical indicators. One SMAF study showed that including at least three years of forage resulted in higher index values than growing continuous corn (*Zea mays* L.) because the latter had lower soil pH, decreased macro-aggregate stability, and lower microbial biomass carbon. Another study within the Iowa River South Fork watershed showed that overall, soils were functioning at 87% of their full potential. The lowest indicator score was associated with SOM (0.60) because the average value was only 28.4 g kg^{-1}. A third study showed that the SMAF could separate cropping groups not recognized by the SCI. Opportunities for collaboration to further improve the SMAF are discussed with the long-term goal being to provide tools to help guide soil management and use decisions and thus ensure long-term sustainability of our soil, air and water resources.

Keywords: Soil Management Assessment Framework (SMAF); Soil Health; Soil Conditioning Index (SCI), Soil Restoration

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J. Integr. Biosci. 6(1):3-14.

INTRODUCTION

The concepts of soil quality, soil health, and soil quality/health assessment are highly contentious within the soil science community, because many believe those terms have generalized and over-simplified the collective knowledge and wisdom developed through several centuries of intensive, in-depth, global studies of soil resources (Letey et al., 2003; Sojka et al., 2003; Sojka and Upchurch, 1999). Critics cite writings on sustainability by Cato during Roman times, prominent scientists and politicians from the 19th and 20th centuries, Nobel Laureates and other prestigious global award winners in support of their arguments. A common theme is that soil quality/health assessments are impossible and meaningless because of the complexity of soil resources. They suggest research and education should be focused on developing quality soil management practices rather than on soil quality or soil health. Proponents of soil quality argue that although soil scientists have long recognized the many unique and important properties and processes provided by fragile soil resources, outside the agricultural community, soils remain largely an under-valued resource (Karlen et al., 2003). The assessments are viewed as tools intended to alert users, in a manner analogous to a "consumer price index," that soil resource problems have or may be occurring.

We contend that both groups really want the same outcomes – an improved public awareness of the importance of soil resources and a better understanding of how short-term economic decisions impact long-term properties and processes. Both camps embraced a 2004 special section in *Science* (11 June 2004) recognizing soil as "The Final Frontier" in order to highlight the importance of this resource and to draw attention to our incomplete knowledge of soil properties, processes and functions. The articles illustrated how processes occurring in the top few centimeters of Earth's surface are the basis of all life on dry land, but concluded that the opacity of soil has severely limited our understanding of how it functions (Sugden et al., 2004).

Being among the proponents for soil quality/health assessment, it is impossible to fully comprehend and represent our counterparts' viewpoints. Our goal for this paper is to focus and clarify our perception of soil quality/health and the need for periodic assessment. Hopefully this will help address their concerns and incorporate suggestions for improvement into an assessment framework that will ultimately lead to quality soil management and improved decisions regarding fragile soil resources throughout the world.

Why is Soil Quality Assessment Necessary?

Periodic assessment is needed to identify the condition of soil resources at all scales – within a lawn, field, farm, watershed, county, state, nation, or the world. Why? Because historically, humankind has neglected its soil resources more than once – often ending in failure of the dominant society and culture (Lowdermilk, 1953; Hillel, 1991). Even after more than 1,000 years of abandonment, soils of the Tikal rain forest have not recovered from the Maya occupation (Olson, 1981). Similarly, the catastrophic land management failures of the 1930's began with ignorance of the Great Plains' soil resource, which was described as "indestructible and immutable" in the 1909 Bureau of Soils Bulletin 55 (Whitney, 1909). Implementation of a wheat (*Triticum aestivum* L.) – fallow cropping system and use of intensive tillage throughout the Great Plains contributed to the "Dust Bowl" that fostered Hugh Bennett's 1933 indictment of Americans as "the great destroyers of land" (Baumhardt, 2003).

Despite this well-documented history, degradation of the earth's soil resources is still among the most serious and widespread threat to humankind. With very little effort, we can find gullies cutting large fields into small parcels, road ditches that have to be cleaned out, silt-laden streams, lakes being choked by sediment, and windstorms with blowing soil darkening western skies and cutting off young cotton (*Gossypium* spp.), wheat or soybean [*Glycine max* (L.) Merr.] plants. These are such visible signs of soil degradation that it is no surprise tolerable soil loss or T, defined as the maximum amount of erosion at which the quality of a soil as a medium for plant growth can be maintained, became the primary tool used to assess sustainability of soil resources. However, focusing on T, using the Revised Universal Soil Loss Equation (RUSLE2) (Lightle, 2007) or the Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965; Sporcic et al., 1998) alone or in combination, fall short as assessments for estimating impacts of management on the long-term sustainability of soil resources. These tools address only one aspect of soil degradation – erosion. Soils can also be degraded by salinity, sodicity, excess water, compaction, heavy metals, acidification, and loss of nutrients and organic matter. Since these degraded conditions exist on millions of hectares worldwide (Oldeman, 1994), it is essential that more robust assessment tools be developed.

Current efforts to define soil quality/health and develop multi-factor assessment protocols can be traced to publications from the 1970s (Alexander, 1971; Warkentin and Fletcher, 1977). This coincided with increased emphasis on "Sustainable Agriculture" during the mid- to late 1980s (e.g. NRC, 1989) that brought public attention to the increasing degradation of soil resources and the implications for environmental health. In Canada, the Canadian Soil Quality Evaluation Program was one of the first national efforts focused specifically on soil quality assessment. As discussion of and interest in the concepts of soil quality and soil health spread worldwide (Karlen et al., 1997; 2001), many questions were raised regarding the sustainability of current soil and crop management decisions (Pesek, 1994). Several ideas for assessment evolved following publication of quantitative formula for assessing soil quality (Larson and Pierce, 1991) and efforts to relate changes in various indicators to soil management practices (e.g. Karlen et al., 1994a,b).

Interest in soil quality among natural resource conservationists, scientists, farmers and policymakers increased even more after the U.S. National Academy of Sciences published the book entitled *Soil and Water Quality: An Agenda for Agriculture* (NRC, 1993). This report stated that more holistic research was needed to ensure soil resources were sustained, water quality was protected, and money invested in conservation was well spent. Among the responses to those challenges were the reorganization of the USDA-Soil Conservation Service (SCS) to the USDA-Natural Resources Conservation Service (NRCS), creation of several Institutes including the USDA-Soil Quality Institute, development of user-oriented soil quality scorecards and test kits (Romig et al. 1996; Sarrantonio et al., 1996), and several symposia (e.g. Doran et al., 1994; Doran and Jones, 1996) that defined soil quality, identified critical soil functions, and proposed applicable assessment methods (Doran and Parkin, 1994).

What Is Soil Quality?

The Soil Science Society of America (SSSA) has defined soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (SSSA, 1997). Challenges and controversies associated with this definition are accentuated when strategies are proposed and implemented to make this definition operational. Often the perception is given that assessment is to be relative to soils from another region (Letey et al., 2003; Sojka et al., 2003; Sojka and Upchurch, 1999) or that practices such as conservation tillage would be discounted because they often involve the use of herbicides. Examples of herbicide retention by high organic matter soils are given as a reason not to penalize low organic matter soils. These points are recognized but actually misrepresent the points made in the initial development of soil quality assessment strategies (Karlen et al., 1994a, b; 1997)

During the 1990s, one of the first methods used to assess soil quality was through the development and use of soil quality scorecards (Harris et al., 1996; Romig et al., 1996; Shepherd, 2000; Shepherd et al., 2000). These cards and guidelines for developing them were among the first products developed by the NRCS-Soil Quality Institute (USDA NRCS, 1999). They were developed and promoted primarily to build a basic awareness of soils and to help non-technical persons document efforts being used to improve them. Other approaches included the use of soil pits and the soil quality test kit developed by J.W. Doran, M. Sarantonnio and others (Sarantonnio et al., 1996) to provide a "hands-on" understanding of how soil physical, chemical, and biological properties and processes change over time and from location to location. The kits are used to measure water infiltration, bulk density, soil respiration at field capacity, soil water content, water holding capacity, water-filled pore space, soil temperature, soil pH, electrical conductivity, and soil nitrate. Once again, the use of soil pits and visual examination was not a new soil assessment approach, but when combined with a soil test kit that emulated the "doctor's black bag", many conservationists, soil and crop consultants, and other users found them to be very useful for education and building an awareness of spatial and temporal variability among soil resources (Doran et al., 1996; Liebig et al., 1996; USDA-NRCS, 1999).

More recently, the USDA-NRCS has recognized the importance of soil quality by incorporating the Soil Conditioning Index (SCI), a linear predictive tool to assess trends in soil organic carbon in crop management systems, into several policies and programs. The SCI was developed from data associated with a 12 year field study (1948-1959) conducted near Renner, TX (Laws, 1961). Released initially for regional planning, the NRCS Soil Quality Institute further validated it during the 1990s using data from long-term carbon studies (USDA NRCS, 2003). One evaluation using nine long-term C studies showed positive trends in soil C were reflected by positive trends in the SCI, while negative SCI trends were associated with negative soil C trends (Hubbs et al., 2002). In another study using data from 52 sites in west Texas, Zobeck et al. (2007) found SCI values were not strongly correlated with total soil organic carbon. However, they were more strongly correlated with a specific soil C fraction known as particulate organic matter carbon (POM-C). Obviously, this is an area of research that needs additional efforts for many different regions and cropping systems.

Following passage of the 2002 U.S. Farm Bill, the SCI was adopted nationally as one factor for determining eligibility for the USDA Conservation Security Program (CSP) and the Environmental Quality Incentives Program (EQIP). One of the major changes prior to this national release was the addition of a soil texture correction factor to the original SCI. This increased the model accuracy by requiring more biomass production to maintain the level of soil organic matter in coarser textured soils (NRCS, 2003). However, one limitation of the SCI is that it focuses only on potential changes in soil organic matter. This is justified because if only one indicator is to be used, soil organic matter is often agreed upon to be the best choice because of the multitude of soil physical, chemical, and biological properties and processes it influences (USDA-NRCS, 2003).

The Soil Management Assessment Framework (SMAF), as described by Andrews et al. (2004), is another approach for implementing the concepts of soil quality, health and their assessment. This tool evolved from studies applying principles of systems engineering (Karlen et al., 1994a, b) and ecology (Andrews and Carroll, 2001) to interpret soil physical, chemical, and biological data collected from various soil management studies. The SMAF provides a consistent approach or framework for evaluating all types of indicators and, if desired, combining the ratings into an overall assessment of dynamic (responsive to current or recent management decisions in contrast to "inherent soil quality" determined by basic soil forming factors and relatively unresponsive to recent management) soil quality (Andrews et al., 2002a,b; 2004). A similar approach has also been incorporated into the Agroecosystem Performance Assessment Tool (AEPAT) and the Cornell Soil Health Test program.

The AEPAT is a computer program designed to assess agronomic and environmental performance of soil and crop management practices (Liebig et al., 2004). Measured indicators are assigned by the user to various functions (*e.g.* food/feed production, nutrient cycling, etc.). The functions are weighted by the user and individual function scores are combined into an index. It was recently used to compare cropping system effects on soil quality using information from several long-term studies throughout the Great Plains (Wienhold et al, 2006).

The Cornell Soil Health Test is a new program that was implemented in 2007 (see http://soilhealth.cals.cornell.edu/index.htm). Its primary purposes are to facilitate education about soil health, guide farmers and land managers in their selection of soil management practices, provide monitoring for the NRCS, and indirectly increase land values by providing information regarding the soil's overall condition. It too uses biological, chemical, and physical indicators. Measured values are interpreted using various linear response curves. The tool has been found to be sensitive to soil and crop management practices (e.g. tillage, crop rotation, and animal manure), relevant to what's been defined as the critical functions (Doran and Parkin, 1994), consistent and reproducible, easy to sample for, and economical for soil-testing laboratories to implement (Harold van Es, personal communication, 2007).

For all three applications (SMAF, AEPAT, and the Cornell Soil Health Test), an important foundation is that the emphasis for all three tools is on "dynamic soil quality." This describes the soil status or condition and reflects current or past management decisions, rather than "inherent soil quality" (Fig. 1) which reflects the basic soil forming factors of climate, parent material, time topography and vegetation on soil attributes and includes soil attributes that are relatively unresponsive to recent management.

Establishing a Baseline for Soil Quality Assessment

Figures 1 and 2 illustrate two important points with regard to soil quality assessment. The first emphasizes soil differences and that meaningful comparisons can be made only by soil series, for a specific location, with a known management history. Comparisons between different soils are almost meaningless because of differences in the inherent soil forming factors. The fluctuation about either soil A or B reflects the dynamic effects and is intended to show that there will be variance in temporal assessments. Figure 2 addresses the controversial issue of what baseline condition (e.g. native prairie, fencerow, cemetery, pasture, cultivated field, etc.) to use for soil quality/health assessment. We suggest that since it is not possible to go back in time, repeat assessments across time are most useful for examining long-term trends for the same soil within the same management unit. The important baseline is the condition or quality of the soil resource when the first measurements are made, and the assessment is the trend in response to subsequent soil management decisions. Measurements over time (often every 3 to 5 years) will show whether the practices being used

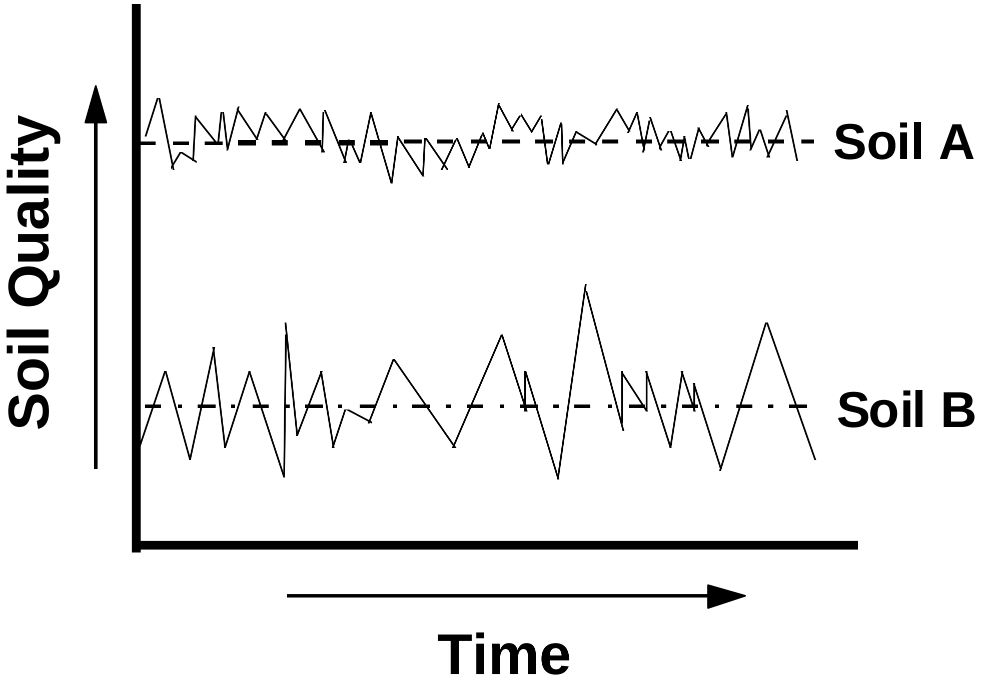

Fig. 1. Conceptualization of inherent soil quality differences between two soils. Adapted from Karlen et al., 2001.

are causing the indicators to improve, decline, or remain stable.

Understanding a SMAF Assessment

The SMAF consists of three steps: indicator selection, indicator interpretation, and integration into a soil quality index (Andrews et al., 2004). The indicator selection step uses an expert system of decision rules to recommend indicators for inclusion in the assessment based on the user's stated management goals, location and current practice. For instance, if the user is adding manure, soil test P is suggested as one indicator to include in the assessment. In the indicator interpretation step, observed indicator data is transformed into a unitless score based on clearly defined, site-specific relationships to soil function. The soil functions of interest include crop productivity, nutrient cycling, physical stability, water and solute flow, contaminant filtering and buffering, and biodiversity. The indicator interpretation step use various factors (*i.e.* organic matter, texture, climate, slope, region, mineralogy, weathering class, crop, sampling time, and analytical method) to adjust threshold values in the scoring curves that are then used to assign a relative value of 0 to 1 for each type of data being collected. The integration steps allows for the individual indicator scores to be combined into a single index value. This can be done with equal or differential weighting for the various indicators depending upon the relative importance of the soil functions for which they are being measured. The SMAF is still under development, but it currently includes the following indicators:

Soil organic matter – because of its important roles for crop production including the biological functions associated with growth and support of beneficial microorganisms and micro-, meso-, and macro-fauna (e.g. earthworms); chemical functions associated with cycling and supplying essential plant nutrients (especially N, P, and S); and physical functions associated with soil structure, tilth, surface crusting, runoff, and water as well as air entry, retention and transmission (Stevenson, 1986; Sikora and Stott, 1996). Soil organic matter status is influenced by management practices such as tillage intensity, crop residue management, and cropping intensity and diversity (e.g. Varvel, 1994).

Soil aggregation – which reflects the arrangement of the primary sand-, silt-, and clay-sized particles into structural units defined as peds. Within their inherent limits (*i.e.* sands will always have fewer aggregates and lower aggregate stability than loam, clay loam, or clay soils), soils with an optimum level of aggregation will be more resistant to surface sealing, thus allowing more rapid water and air penetration. Soils with good aggregation will generally provide better soil – seed contact, which will result in more rapid transmission of water to the seed, quicker germination, and generally better and more uniform establishment of the desired crop. Soil aggregation is primarily influenced by tillage intensity and residue

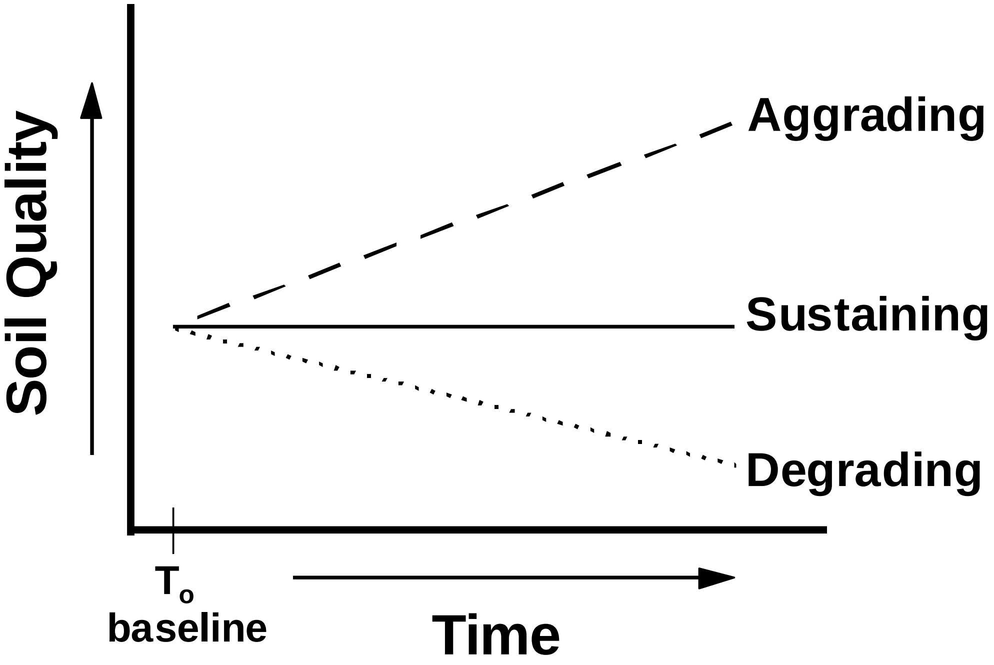

Fig. 2. Conceptualization of dynamic soil quality trends from time zero (T_0). Adapted from Seybold et al., 1998.

management (Tisdall and Oades, 1982).

pH – because of its effect on nutrient availability (e.g. P amd Zn) and both toxicities (e.g. Al or Mn) and deficiencies (e.g. Mn, Fe, and Zn), ammonification and nitrification processes, microbial habitat, and plant root growth and development. Soil pH is also a good indicator of the attention being given to effects of management practices such as the use of ammonium fertilizers, liming, and animal manure application.

Electrical conductivity (EC) – has generally been associated with determining soil salinity, but it can also serve as a measure of soluble nutrients – both cations and anions (Smith and Doran, 1996). Within a specific range, EC can be used to indicate the status of nutrient availability for plants, with the low end indicating nutrient poor soil that is structurally unstable and disperses readily. High EC values often reflect poor plant growth conditions and the potential for salinity problems.

Salinity and **SAR** are generally more important in arid or semi-arid areas where excessive transpiration can result in a buildup of salts in the near surface horizons. They can also help detect the presence of seeps where water that infiltrated at higher landscape positions has flowed along impervious layers and now intersects the surface once again.

Plant available P is important because of it role in supporting plant growth, but must also be monitored to ensure that it does not become an environmental hazard if surface runoff occurs (Sharpley et al., 1996). Management practices can influence available P through fertilizer and animal manure applications as well as by maintaining a near neutral pH.

Nitrate-N (NO_3-N) – reflects the residual effects of a many practices including crop rotation, fertilization strategies, and use of animal manure. It provides insight regarding the potential for leaching and contamination of groundwater or surface water sources and for release of nitrous oxides (NO_x) emissions (Rice et al., 1996; Allan and Killorn, 1996).

Microbial biomass carbon – provides a measure of the biological activity within a soil. It reflects nutrient cycling processes that are essential for meeting crop growth. It is also influenced by management practices such as tillage intensity, crop type (annuals versus perennials) and crop residue management strategies.

Bulk density (BD) – defined as the mass of dry soil per unit volume is an important soil quality indicator because of its potential effects on plant root development, exploration, and thus the volume of soil that each plant can draw upon to meet their water and nutrient needs. Management practices such as tillage, wheel-traffic patterns, timing of field operations (because of the interaction with soil water content) and residue management influence bulk density (Arshad et al, 1996).

The next set of scoring curves being developed for the SMAF are for water-filled pore space as an indicator of the type of microbial functioning to expect (aerobes vs anaerobes), soil-test K, and β-glucosidase activity. Many other potential indicators have been suggested (Karlen et al., 1997) and for some scoring functions will be developed and incorporated into future versions of the SMAF.

An Assessment Example

Tables 1 and 2 show the type of information the SMAF and SCI (through RUSLE2) assessment tools can provide. Wind erosion was not considered in this application of SCI. This data was collected during autumn 2003 and spring 2004 within two transects established across the Iowa River South Fork Watershed. The sampling was designed to include all major soil associations, landforms, and cropping systems within the watershed. One 32-ha tract was randomly selected from each 259 ha (640 acre) section along each transect. Landowners and tenants were contacted for permission to collect soil samples and to obtain data on crop management history from each area.

Soil samples were collected by soil map unit (SMU) from 29 of the 32 ha areas where permission was granted by the land owners and operators. Samples were not collected from areas without prior permission. Large areas of the same SMU were subdivided into approximately equal areas so that overall, each sample represented an area of approximately 3.6 ha (9 acres). This approach resulted in a total of 220 samples being collected for this study. For more information about the original study, please see Karlen et al. (2008).

After laboratory analyses were completed, the data were interpreted using the SMAF (Andrews et al., 2004). As previously described, scoring curves within the SMAF are based on inherent soil properties and are therefore adjusted for each soil series. For situations where scored values are not the same even though measured mean values were, this reflects variation associated with the means for each landscape group (i.e. hilltop, sideslope, toeslope, or depression) and tillage practices (*e.g.* Table 1, EC and pH for hilltop and sideslope sites in 2005). But, neither salinity (EC) nor acidity (pH) appear to be problems within this watershed since both scored very close to 1.0. The P data illustrates the mid-point optimum scoring curve (Andrews et al., 2004) with low (Depression 2003/04) and high (Depression 2005) mean values having similar scores. For both samplings, soil-test P was neither limiting crop

Table 1. Soil quality indicator data collected for various landscape positions within the Iowa River South Fork Watershed.

Landscape Group	EC	EC score	pH	pH score	P	P score	SOC	SOC score	Soil Loss	N-Leaching Index	STIR Rating	SCI	SMAF score
2003/04 sites	ds m^{-1}				mg kg^{-1}		g kg^{-1}		Mg ha^{-1}				
Hilltop	0.25	0.95	6.6	0.98	38	0.95	18.9	0.40	8.7	5.0	69	0.31	82
Sideslope	0.26	0.98	6.4	0.98	45	0.98	24.1	0.60	5.0	4.9	69	0.36	87
Toeslope	0.36	0.97	7.1	0.95	38	0.97	30.8	0.66	3.8	1.7	69	0.52	89
Depression	0.44	0.92	7.8	0.89	22	0.92	47.1	0.93	2.2	1.4	66	0.43	94

2005 sites	EC	EC score	pH	pH score	P	P score	SOC	SOC score	MBC	MBC score	BD	BD score	SMAF score
	ds m^{-1}				mg kg^{-1}		g kg^{-1}		μg C g^{-1}		g cm^{-3}		
Hilltop	0.28	0.98	6.2	0.98	92	0.90	22.4	0.50	334	0.74	1.51	0.59	78
Sideslope	0.28	0.99	6.2	0.99	96	0.96	28.7	0.62	362	0.68	1.49	0.37	77
Toeslope	0.32	0.99	6.3	0.99	97	0.97	29.9	0.62	454	0.71	1.43	0.43	78
Depression	0.47	1.00	6.6	0.99	124	0.95	90.3	0.86	715	0.88	1.14	0.67	89

[1] Electrical conductivity, EC; Soil Organic Carbon, SOC; Soil Tillage Intensity Rating, STIR; Soil Conditioning Index, SCI; Soil Management Assessment Framework, SMAF; Microbial Biomass Carbon, MBC; Bulk Density, BD

growth nor a major environmental concern. However, the higher mean values for 2005 sampling sites do indicate a portion of the South Fork Watershed does need to be closely monitored for increasing soil-test P levels. We suggest this reflects increased swine manure applications associated with the high density of consolidated animal feeding operations.

The means and scored values for soil organic C (SOC) were lowest for soil map units located on hilltop positions where water, wind, and tillage erosion (Schumacher et al., 2005) presumably decreased levels over time. Bulk density and microbial biomass C (MBC) measurements were made only for the 2005 samples (Tables 1 and 2). The bulk density values for surface samples were rather high except for the sites that were historically tilled with a field cultivator or located in depression areas. This resulted in scores ranging from 0.4 to 0.6 and suggests compaction may be a potential problem for many of the soils within the watershed. Bulk density may also have been high because the samples were collected after grain harvest but prior to any autumn tillage. The MBC and SOC levels followed similar patterns as expected, because MBC is one of the organic matter fractions within the total organic C pool.

RUSLE2 (Lightle, 2007) was used to generate soil loss estimates, an N leaching index, soil tillage intensity rating (STIR), and the SCI for the sites sampled in 2003/04. Field-scale information including average slope and slope length were not determined for sites sampled in 2005. The Soil Quality Index (SQI) values and soil loss showed a significant ($P<0.05$) negative relationship for all landscape and tillage groups. The STIR ratings reflect the degree of soil disturbance throughout the year. For many soil quality indicators a negative relationship with STIR ratings would be expected because more intensive tillage increases oxidation of SOM, fractures aggregates into smaller pieces, depletes soil water, and increases the potential for fugitive dust (i.e. lower air quality). Among the tillage groups, ridge-tillage had the lowest STIR rating while the highest was associated with ripping or deep tillage. The N-leaching index is a relative value ranging between 0 and 25 (D. Lightle, personal communication, 2007). It can be used to compare the potential for N leaching among various management practices. Values approaching 25 would be expected on sandy soils because they are more susceptible to leaching, but this type of soil is not found within the South Fork Watershed. This analysis showed the highest leaching potential for the hilltop and sideslope landscape groups. The SCI values were all positive and showed good agreement with the SQI values for both tillage and landscape groups.

Table 2. Effects of historical tillage practices on soil quality indicators within the Iowa River South Fork Watershed

Tillage	EC	EC score	pH	pH score	P	P score	SOC	SOC score	Soil Loss	N-Leaching Index	STIR Rating	SCI	SMAF score
2003/04 sites	ds m^{-1}				mg kg^{-1}		g kg^{-1}		Mg ha^{-1}				
Chisel plow	0.30	0.96	6.9	0.96	36	0.96	29.2	0.61	2.5	3.4	70	0.39	87
Disk tillage	0.36	0.98	6.8	0.96	43	0.98	26.6	0.58	2.7	3.3	76	0.38	87
Deep ripping	0.39	0.98	7.3	0.95	42	0.98	32.8	0.74	2.0	2.6	68	0.42	92
Ridge-tillage	0.33	0.98	7.0	0.97	30	0.98	26.5	0.59	3.1	2.9	38	0.42	88
2005 sites	EC	EC score	pH	pH score	P	P score	SOC	SOC score	MBC	MBC score	BD	BD score	SMAF score
	ds m^{-1}				mg kg^{-1}		g kg^{-1}		µg C g^{-1}		g cm^{-3}		
Chisel plow	0.37	1.00	6.5	0.99	154	0.88	57.6	0.71	541	0.76	1.33	0.57	82
Field cultivator	0.26	0.99	5.7	0.98	52	1.00	27.6	0.63	368	0.78	1.28	0.75	86
Moldboard	0.34	1.00	5.9	0.98	39	0.98	28.9	0.67	366	0.66	1.50	0.37	78
Strip-tillage	0.38	1.00	6.9	0.99	39	0.99	29.7	0.59	502	0.79	1.56	0.38	79
No-tillage	0.29	0.97	6.3	0.98	84	0.97	30.3	0.55	393	0.77	1.45	0.51	79

[1] Electrical conductivity, EC; Soil Organic Carbon, SOC; Soil Tillage Intensity Rating, STIR; Soil Conditioning Index, SCI; Soil Management Assessment Framework, SMAF; Microbial Biomass Carbon, MBC; Bulk Density, BD

As expected, the SCI and SMAF indices both show the importance of maintaining or increasing soil organic matter. A potential advantage of using the SMAF rather than the SCI is that the SMAF is designed to evaluate several soil quality indicators to assess the effects of management on the combined biological, chemical, and physical effects on soil resources. Accordingly, other types of degradation (e.g. salinity, compaction, crusting) can be identified and corrective management practices implemented. Some may consider the need for measured data as the primary input for the SMAF to be detrimental because of time and cost, especially since the SCI can be run knowing only the location, soil texture, management practices, and annual rates of wind and water erosion. We argue that use of measured data is well worth the added expense because of its greater accuracy and more site specific applications.

On-Going SMAF Developments and Applications

To date, the SMAF has been used to provide an initial overall assessment of soil quality in the Iowa River South Fork Watershed. That assessment indicated soils within the watershed were functioning at 87% of their full potential. The lowest indicator score was associated with SOM (0.60) because the average value was only 28.4 g kg^{-1} (Karlen et al., 2008). Another application of the SMAF showed that it could distinguish between cropping groups that were not differentiated by the SCI (Zobeck et al., 2008).

These research studies are promising, but due to human technical assistance constraints for programs such as the Conservation Security Program and the need for substantial amounts of measured data, the current SMAF would not be a suitable replacement for SCI in the near term. However, as part of the conservation effects assessment program (CEAP), the SMAF is being used to help interpret output from computer simulation models such as the Economic Productivity Impact Calculator (EPIC) (Potter et al., 2006). Using Natural Resources Inventory (NRI) soil and climate data, several EPIC simulations were made to evaluate 30-year effects of various conservation practices, primarily tillage types, including no-till, contour cropping, strip cropping and terracing. Recently, the SMAF has been used to interpret these simulation data with regard to predicted soil carbon changes and how those levels compare to potential or inherent soil organic carbon levels for selected Natural Resource Inventory points across the continental US.

Without the interpretation using SMAF scoring curves, soil organic carbon (SOC) at the end of the 30 year simulation showed substantial losses in the areas where SOM is inherently high, particularly in the Corn Belt (primarily in IA and MN) and the Mid-Atlantic regions (mainly coastal NC, where both wind and water erosion are prevalent). Other more moderate losses were shown in the Southern Plains and across the southeastern states, primarily due to high decomposition rates in those climate regimes. Areas of net SOC gain were predicted for the upper Great Lakes region, likely due to inherent soil texture and drainage status, and for much of Appalachia, where grazed or hayed grasses predominate (Potter et al, 2006).

When the SMAF scoring was applied to the model outcomes to better reflect level of soil function some pronounced changes were noted. First, the year-30 end point data was scored and mapped. However, this was not believed to fully reflect the change in function, so the year 1 SOC data was also scored then subtracted from the year 30 scores to show the change in soil function over the simulation period. Interpreting the simulation results with the SMAF scoring curve provides an opportunity to identify areas with high resilience, due either to inherent soil or climatic factors or the use of soil building crop rotations and management practices.

In this final analysis, using the change in SMAF-scored SOC areas with continuous cropping systems consisting of low residue crops, such as cotton in West TX, resulted in very low scores due to high carbon losses. In fact, the Southern Great Plains was the region with the greatest negative change SOC score, indicating the greatest loss in soil function over the simulation period, The Southeast and South Central regions, on average, had the next highest negative change in SOC score. Although these regions scored relatively low, their outcomes were more moderate compared with the non-scored data, because inherent soil and climate factors helped to standardize results. These soils are predicted to have moderate loss in soil function over the simulation period. Mollisols in the Midwest received intermediate scores, due to their high SOC loss rates combined with relatively high initial SOC status, indicating that although these soils are degrading their inherent depth and high SOC render them highly resilient. Areas with large quantities of pasture tended to show high positive changes in SOC scores using this method, due to the predicted carbon accrual, regardless of the beginning SOC levels, Therefore, the Northeast and Appalachian regions showed the greatest positive change in average score. All regions, however, had at least some acreage with negative changes in SOC scores.

For more information about these evaluations, please see: ftp://ftp-fc.sc.egov.usda.gov/NHQ/nri/ceap/croplandreport/Part_7_Soil_organic_carbon.pdf
and
ftp://ftp-fc.sc.egov.usda.gov/NHQ/nri/ceap/croplandreport/Part_8_Priority_Cropland.pdf.

Applying the SMAF to simulation model data enables uses to evaluate and interpret large amounts of data quickly, using site-specific scoring algorithms to do what normally what would require system or regional experts to do. While the EPIC model *per se* may be too data intensive and time consuming to be used for Farm Bill program implementation, this approach could lead to the ability to predict the environmental outcomes for conservation practices in a simple expert system (running on a database populated by model data) or operating in the background of traditional conservation business tools.

OPPORTUNITIES FOR COLLABORATION

The need for tools to assess soil quality has been established and will increase as we move forward in the 21st century. For scientists evaluating land management effects on soil quality, we envision many opportunities and needs to help improve the SMAF and other assessment tools. More than 60 potential soil quality indicators have been identified, but currently only 12 have scoring curves developed for use in the SMAF (Andrews et al., 2004). The SMAF is designed as a framework with database reference and look-up linkages. As additional indicators are developed for assessing soil management and/or restoration processes, they can be easily and efficiently added to the SMAF program. The current SMAF assessment focuses primarily on crop productivity with some indicators (e.g. NO_3-N and soil-test P) also being scored for their potential environmental contamination effects under some conditions.

Currently the SMAF can be accessed at http://soilquality.org (verified 8-14-08) or as an Excel spreadsheet from the authors. Examples of its recent use to synthesize information include that from cropping system comparisons throughout the US Great Plains (Wienhold et al., 2006) and for long-term crop rotation effects in Iowa and Wisconsin (Karlen et al., 2006). In the Great Plains study, SMAF index values were positively correlated with grain yield (an agronomic function) and total organic matter (which affects both agronomic and environmental functions). The values were negatively correlated with soil nitrate concentration at harvest (an indicator of environmental function). The crop rotation study showed higher SMAF index values for treatments that had at least three years of forage (i.e. oat (*Avena sativa* L.) followed by alfalfa (*Medicago sativa* L.) for at least two years). The lowest index values were associated with continuous corn production, because of lower soil pH, decreased macro-aggregate stability, and lower microbial biomass carbon. Without including government subsidy payments, the extended crop rotation was also more profitable when production costs were deducted from gross returns calculated using actual crop yields and National Agricultural Statistics Service crop prices for 20 years prior to the evaluation. We encourage others to examine their soil management data using the SMAF and to join in efforts to develop an even better and more meaningful soil assessment framework.

SUMMARY AND CONCLUSIONS

Soil quality/health assessment is here to stay. New and improved tools will be needed to guide sustainable land use and soil management decisions in the 21st century. Traditional tools, including the RUSLE2 and SCI, were and continue to be very useful, but they are not capable of assessing all aspects of soil quality. Tools sensitive to soil biological, chemical, and physical indicators are needed to fully evaluate the impact of decisions, such as when and where to harvest crop residues for biofuels or when and where to apply animal manures. The AEPAT, SCI, Cornell Soil Health Test, and SMAF are in various stages of development, release, refinement, or dormancy. The SCI has been incorporated into RUSLE2 software and is being used by the NRCS. The Cornell Soil Health Test was used on a trial basis in 2008 with more information available from its developer Dr. Harold van Es (Cornell University). AEPAT is operational and available on CD upon request from Dr. Mark Liebig (USDA-ARS, Mandan, ND). The SMAF is available for beta-testing from Dr. Doug Karlen (USDA-ARS, Ames, IA) or Dr. Susan Andrews (USDA-NRC, Goldsboro, NC) with 12 scored indicators. Three additional indicators (pore-filled water space, soil-test K, and β-glucosidase activity) curves have been developed and are currently being peer reviewed. The SMAF has also been evaluated at several scales and appears to be sensitive to various management scenarios. It provides integrated information and assessments for individual indicators, although substantial opportunities exist for refinement and further development. This includes developing scoring curves for additional indicators and using simulation modeling to predict some indicator values for the SMAF. Regardless of past perceptions of soil quality, we invite you to join in a concerted effort to move soil quality assessment beyond single factor analyses in a meaningful way for everyone interested in what *Science* recently referred to as “The Final Frontier.”

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