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Brian J. Wienhold
University of Nebraska-Lincoln, Brian.Wienhold@ars.usda.gov

S.S. Andrews
USDA-ARS

H. Kuykendall
USDA-ARS

D. L. Karlen
USDA-ARS, doug.karlen@ars.usda.gov

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Invited Article

Recent Advances in Soil Quality Assessment in the United States

B.J. WIENHOLD*, S.S. ANDREWS[1], H. KUYKENDALL[1], AND D.L. KARLEN[2]
USDA-ARS, 305 Entomology Hall, East Campus, UNL Lincoln, NE 68583

Abstract: Soil quality is a concept that is useful as an educational and assessment tool. A number of assessment tools have been developed including: the Soil Conditioning Index (SCI), the Soil Management Assessment Framework (SMAF), the AgroEcosystem Performance Assessment Tool (AEPAT), and the new Cornell "Soil Health Assessment". The SMAF and AEPAT were developed as malleable tools for assessing soil response to management. The Cornell Assessment builds on the SMAF approach to score laboratory tests in terms of soil function. This paper updates efforts to improve availability and utility, implementation, and future research goals associated with the SMAF. Additional scoring curves have been developed for percentage water-filled pore space (%WFPS), soil test potassium (K), and β-glucosidase activity. A web-based version of the SMAF is available. The SMAF has been implemented as part of the Conservation Effects Assessment Project (CEAP). Combining the SMAF and a CEAP survey approach appears to be a successful method for identifying soil quality risks at the watershed scale. Future plans include developing approaches for using the SMAF for model output and in spatially variable fields as well as adapting the SMAF for wide use by soil testing laboratories.

Key words: Soil management, fertility, scoring curves, soil conservation, soil indicators

Soil quality was introduced in 1977 by Warkentin and Fletcher as a concept to guide use and allocation of labor, fiscal, and other inputs to meet increasing demands being placed on agriculture. In subsequent decades, soil quality has become a useful tool for educating professionals, producers, and the public about the critical functions performed by soils and as an assessment tool for comparing among management alternatives or management effects over time. Scoring curves are one approach that can be used to standardize the relationship between a soil indicator and a soil function. Karlen and Stott (1994) proposed four general shapes for soil quality scoring curves: more is better, less is better, optimum range, and an undesirable range. Such scoring curves can be used to convert measured indicator data to relative values ranging from 0 to 1. Scoring curves have been used to convert measured indicator data into relative scores that were used to assess poultry litter management practices (Andrews and Carroll 2001) and vegetable production systems in northern California (Andrews *et al*. 2002). These efforts resulted in the development of the Soil Management Assessment Framework (SMAF) as a malleable tool that could be used to assess soil response to management within the environmental context in which it occurs (Andrews *et al*. 2004). At the 2005 International Conference on Soil, Water, and Environmental Quality - Issues and Strategies in New Delhi, India, the SMAF was described and several case studies were presented (Wienhold *et al*. 2006a).

In addition to the SMAF several other assessment tools are under development or currently in use. These include the Soil Conditioning Index (SCI) (Hubbs *et al*. 2002), the AgroEcosystem Performance Assessment Tool (AEPAT) (Leibig *et al*. 2004), and the 'Cornell Soil Health Assessment" (Gugino 2007). Wienhold *et al*. (2006b) used the SMAF and the AEPAT to assess data from a regional soil quality project. They found general agreement between the two tools using data collected over three years from conventional and alternative treatments of long-term cropping system trials at eight locations in the Great Plains. The SMAF requires soil indicator data along

*Corresponding author: Brian.Wienhold@ARS.USDA.GOV
Present addres
[1]USDA-NRCS, Greensboro, NC 27401
[2]USDA-ARS, Ames, IA 50011

with crop and soil information while the AEPAT requires the user to supply information about the shape of the curve, threshold values, and scoring weights in addition to soil indicator data. Therefore, users of the AEPAT need more knowledge of the system they are managing than users of the SMAF (Wienhold *et al*. 2006b). Zobeck *et al*. (2008) used data from irrigated cropping systems in eastern Colorado to compare the SMAF to the SCI. These two tools differ in that the SMAF uses physical, chemical, and biological indicator data in the assessment while the SCI uses a linear model to estimate qualitative changes in soil organic matter based on crop residue returned to the soil, tillage intensity, and estimates of wind and water erosion. Results were generally similar between the two assessment tools but the SMAF was better able to differentiate among management systems.

Efforts to improve and validate the SMAF continue. Improving the SMAF includes development of additional scoring curves for physical, chemical, and biological soil indicators and development of an internet accessible version of the SMAF so that the tool is more available to potential users. The SMAF is being validated by including it in the watershed-level Conservation Effects Assessment Project (CEAP) to quantify the effect investments in conservation are having on environmental outcomes. The national-level CEAP is using a modified version of the SMAF scoring to interpret model outcomes for carbon (Potter *et al*. 2006). The purpose of this paper is to present recent developments in implementation and improvement of the SMAF.

Additional Scoring Curves

When Andrews *et al.* (2004) introduced the SMAF, they included an invitation for users to validate, comment on, and modify the framework for use in assessing soil management. The Soil and Water Conservation Society (2008) recently published results from an expert consultation that identified actions needed for more comprehensive soil assessment, management, and planning tools. That panel evaluated several soil management assessment tools, including the SMAF and the SCI. One recommendation was that the number of available scoring curves for interpreting measured soil indicators in the SMAF be increased. The original version of the SMAF had scoring curves for ten soil attributes but more than 60 other attributes were identified as having potential as assessment indicators (Table 1).

The approach used to develop scoring curves for the SMAF involves a number of steps. The first step is to identify a soil indicator that responds to management and affects a soil function of interest. Data sets containing indicator values and measures of soil function, preferably over a range of environmental conditions, must be identified or collected. These data sets are used to determine the shape of the curvilinear relationship between the indicator and the soil function and then to develop an algorithm describing that relationship. Abiotic factors that cause the relationship to change or the expected range to shift are identified to allow for appropriate interpretation of the indicator within its environmental context. Coefficients or logic statement modify each algorithm to mimic these environmental factors. The algorithm is then programmed into the SMAF and validated using additional data sets.

Table 1. Soil indicators having scoring curves and soil indicators having potential for scoring curve development

Developed Scoring Curves	Potential Scoring Curves
Organic C concentration	Water-filled pore space (WFPS)
Macroaggregate stability	Mean weight diameter
Microbial biomass C	Soil test K
Potentially mineralizable N	Extractable Ca
pH	Extractable Mn
Extractable P	Extractable Zn
Microbial quotient (qCO_2)	Nitrate-N
Bulk density	Ammonium-N
Electrical conductivity	β-glucosidase
Sodium adsorption ratio	Fluorescein diacetate hydrolysis
Available water capacity	others

Recent efforts to develop additional scoring curves include Wienhold *et al*. (unpublished data) who developed curves for a physical soil attribute (water-filled pore space), a chemical soil attribute (soil test K), and a biological soil attribute (β-glucosidase activity). Stott *et al*. (unpublished data) developed scoring curves for a suite of soil enzymes using original data relating measured soil enzyme activity to management outcomes. These curves were developed and validated using the steps described above.

Percentage water-filled pore space (%WFPS) is calculated using an assumed soil particle density (ρ_p) of 2.65 Mg m^{-3} and the relatively easily measured soil properties of bulk density (ρ_b) and gravimetric water content (θ_g). The calculation for %WFPS is:

$$\%WFPS = (\theta_v/TP)\ (100)$$

where θ_v = percent volumetric water content = $(\%\theta_g)(\rho_b)$, and TP = percent total soil porosity = $(1 - \rho_b/\rho_p)$ (100). The scoring curve for %WFPS related to the production function of soils takes the form of a local optimum (Fig. 1A). At an optimum %WFPS root respiration and soil-microbially-mediated processes are

least limited by aeration or water availability. At less than optimum %WFPS water becomes more limiting and at greater than optimum %WFPS aeration becomes more limiting. Percentage WFPS affects root respiration and soil-microbially-mediated processes and is related to both the production and environmental functions of soils. Tillage, drainage, and compaction are management practices that affect %WFPS (Linn and Doran 1984).

Soil test K is a measure of the availability of an essential plant nutrient and relates to the production function of soils. As soil test K decreases there is an increased probability that yields will be reduced and an increased probability that the crop will respond to fertilizer K. Soils differ in the rate at which K is replenished and this rate is related to soil texture. The scoring curve for soil test K took the form of upper asymptotic or more-is-better with coarse textured soils requiring a higher initial soil test K level than the fine textured soils (Fig. 1B). As soil test K levels increase the probability of reduced yields and crop response to fertilizer K decreases (Tisdale *et al.* 1985). Management practices that affect soil test K include removal of K in the harvested crop and application of fertilizer K.

The enzyme β-glucosidase is involved in cellulose degradation providing glucose as an energy source for soil microorganisms. As β-glucosidase activity increases there is an increase in residue breakdown and availability of nutrients for subsequent crops. Since changes in β-glucosidase activity are easier to detect than changes in total organic C, this enzyme may serve as an indicator of soil organic matter dynamics (Bandick and Dick 1999; Ekenler and Tabatabai 2003). The scoring curve for β-glucosidase activity took the form of upper asymptotic or more-is-better (Fig. 1C). Increases in β-glucosidase activity are associated with crop residue levels (Deng and Tabatabai 1996). Management practices that affect β-glucosidase activity are those that result in reduced erosion and maintenance of soil organic matter and include tillage and cropping intensity (Acosta-Martínez *et al.* 2003).

Recently developed scoring curves represent continuing efforts to increase the utility of the SMAF. Indicator selection is the first step in using the SMAF and is dependent on the user's management goal, soil functions being assessed, additional criteria such as cropping system, tillage practice, climate, or inherent soil properties (*e.g.* organic matter class, texture, climate), and access to methods, equipment, or laboratories capable of quantifying the indictor. Over 60 soil indicators have been identified as having potential for assessing soil function and scoring curve development efforts will continue.

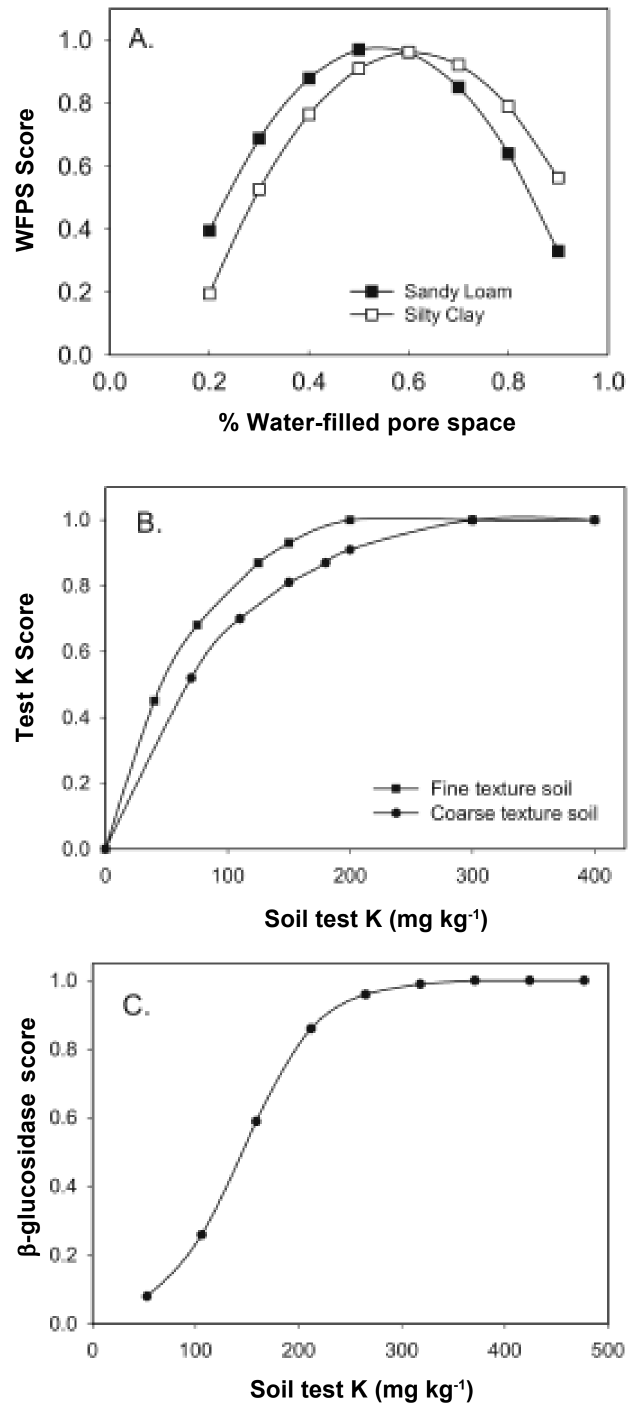

Fig. 1. Scoring curves for % water-filled pore space (A.), soil test K (B.), and β-glucosidase activity (C)

Internet Accessible Version of SMAF

Several organizations have joined together to serve soil quality information to a worldwide audi-

ence via a single web site available at www.soilquality.org. Titled *Soil Quality for Environmental Health*, the web site was launched in the autumn of 2007. Contributing partners include the USDA Natural Resources Conservation Service, University of Illinois at Urbana-Champaign, Iowa State University, USDA Agricultural Research Service, and various individuals and institutions participating in the North Central Education and Research Activity Committee. This web site provides a home for the online version of the SMAF as well as additional instructional content.

The organizational flow of soilquality.org is based on feedback obtained during focus group work sessions with farmers, educators and other practitioners. Soilquality.org offers web site visitors information on basic soil quality concepts, including discussions on how soils function, the differences between inherent and dynamic soil properties, and ecosystem stability and agricultural sustainability. It also defines common terms to advance the audience's knowledge level in preparation for further discussion of specific soil quality indicators and assessment methods.

Assessment tools are featured, including a brief discussion on the availability and use of the Soil Quality Test Kit and the web-interactive version of the SMAF. A soil problem-solving guide assists users with the identification of possible causes and improvement methods for identified soil issues, such as drainage, erosion, and organic matter content. Land management practices are linked to the soil problem-solving guide, providing why and how-to instruction to improve soil function. Management practice content follows a practical and comprehensive template to provide the most useful information to the web site audience.

The online version of the SMAF uses object oriented Java programming to dynamically generate forms and graphics based on user input about management goals, climate, and soil type. The tool can be used to suggest the most appropriate indicators to test to assess the functions necessary to meet the user's management goals. If soil has already been tested, the data can be uploaded and interpreted using site-specific scoring curves to assess the soil's level of function. Output includes tables and graphics identifying function scores for each indicator tested (up to 10). It also includes brief narratives, also generated dynamically, that offer management suggestions to improve function when indicators score poorly.

Soilquality.org is designed to be a repository for soil quality knowledge contributed by an extensive network of soil quality researchers and educators. It is a work in progress and always will be as soil quality advances are made and the web site is updated. Techniques such as collaborative writing, peer review, online publication, and institutional branding are being used to provide the latest, most pertinent information and professional recognition needed by potential contributors. Authors can work collaboratively on original content for the website or they can add information to the site to build on another contributor's work. Importantly, authors receive credit for peer-reviewed online publication, which serves as an incentive to contribute additional content. This collaborative approach to website development should serve to keep content current and provide a clearinghouse of useful information.

Use of the SMAF in the CEAP

A collaboration of various agencies within USDA and academic partners, CEAP was initiated in 2003 to provide a scientific basis for a national assessment of conservation practices. One of the CEAP objectives was an assessment of soil quality at the watershed scale to determine if linkages could be developed to show more specifically how agricultural management practices were influencing water quality in streams (NRC 1993). Recognizing that high rates of soil erosion, loss of soil organic matter, imbalanced soil fertility, and chemical or heavy metal contamination continue to be critical soil quality issues (Larson and Pierce 1991: Doran and Parkin 1994; Karlen *et al.* 2001, 2003), the SMAF (Andrews *et al.* 2004) was chosen for this assessment because of its design to use biological, chemical, and physical indicators collectively and in an organized and consistent manner.

A survey approach was chosen to identify the most limiting soil properties or processes within each of the 14 ARS benchmark watersheds (Fig. 2). An initial assessment within the South Fork Watershed of the Iowa River (Karlen *et al.* 2008) provided the foundation for the overall CEAP soil quality program. Samples were collected from five to ten locations (as replicates) under three to five conservation practices within three to five soil map units of each watershed. Each location collected samples consisting of 20 soil cores, collected using a soil probe with an inner diameter of at least 3.2 cm, from the 0 to 5 cm depth. Then depending upon the local research questions additional samples from lower depths were also collected. All sampling sites were geo-referenced and the soil map unit, landscape position, slope, and any

Fig. 2. Location of ARS Conservation Effects Assessment Project (CEAP) Benchmark Watersheds

evidence of wind, water or tillage-induced soil erosion or periodic ponding or flooding was documented. Current and past management information from the land owner/operator was collected when possible. This included conservation practices, fertilizer and/or manure management histories, crop rotations, tillage practices, yields, and other pertinent information that may have affected the soil resources.

Each composite soil sample was pushed through an 8 mm sieve. Large pieces of organic material and rocks were removed and weighed. Samples were analyzed for soil microbial biomass C (an indicator of the active soil C fraction) using the fumigation-extraction procedure of Tate *et al*. (1988). Organic C in fumigated and non-fumigated extracts was determined and biomass C was calculated using a correction factor (k = 0.33) (Sparling and West 1988). Approximately one-half of the remaining soil was air dried, ground to pass a 2-mm sieve, and analyzed for pH using a 1:2 soil-to-water ratio (Watson and Brown 1998), electrical conductivity (EC) (Whitney 1998), Mehlich III extractable P, K, Ca, and Mg (Mehlich 1984), total organic carbon (TOC) and total nitrogen (TN). Extractable P, K, Ca, and Mg concentrations were determined using an inductively coupled plasma-atomic emission spectrograph (ICP-AES). Total carbon (TC) and total nitrogen (TN) were determined by dry combustion with a Carlo-Erba NA1500 NCS elemental analyzer (Haake Buchler Instruments, Paterson, NJ). For samples with pH values exceeding 7.3, soil inorganic carbon (SIC) was determined using a modified pressure calcimeter method. Soil organic C (SOC) was calculated by subtracting SIC from the TC values.

The SMAF will be used to calculate Soil Quality Index (SQI) values for each measured indicator (Andrews *et al*. 2004) and individually for each of the watersheds. No attempt to compare watersheds will be made because of inherent differences in soils and soil forming factors within each of them (Karlen *et al*. 2003). Each soil quality indicator will be examined individually and then all will be aggregated into an overall SQI to determine how conservation practices are affecting soil quality within each of the watersheds. The SQI values will also be evaluated against water quality data to determine if meaningful relationships can be developed and described.

To date, 9 of 14 CEAP benchmark watersheds have been sampled and soil analyses have been nearly complete for five of them. A preliminary examination of the data shows that low SOM, especially on hilltops where water, wind, and tillage erosion (Schumacher *et al*. 2005) have decreased topsoil depth over time, is one of the most consistent findings. Areas receiving excess P through frequent animal manure applications often show increasing levels of soil-test P and an increased potential for surface water contamination through runoff that contains excessive levels of soluble P. This appears consistent with results from the initial Southfork watershed

study (Karlen *et al*. 2008) that showed soil-test P ratings for upland soils to be generally very high (>31 µg g^{-1}) (Mallarino *et al*. 2002) but not to the levels at which severe environmental impact (e.g. > 100 µg g^{-1}) would be expected. Lower soil-test P ratings in the depression areas were consistent with the higher pH in those soils. Soil-test K in that study was generally in an optimum range (131 to 170 µg g^{-1}) for corn and soybean production, but some areas had surprisingly low K values and this could result in early season plant K deficiencies if no-tillage practices are used (Karlen and Kovar 2005) to reduce soil erosion. Therefore, since reduced or no-tillage practices would be beneficial in order to increase soil C levels, close monitoring of K levels is recommended to prevent that essential plant nutrient from limiting crop yields.

Soil management assessment combined with water quality monitoring data have the potential to link agricultural management practices to their impact on both soil and water resources. Further assessments using the SMAF at the CEAP watershed scale are needed, but preliminary results suggest that the approach is appropriate and consistent with the goals stated in the Soil and Water Quality: An Agenda for Agriculture publication (NRC 1993).

Future Efforts

National Scale CEAP

At the national-scale, CEAP is using EPIC and APEX models to examine field scale soil, air and water quality over cropland areas throughout the entire continental US. The model is simulating conditions for geo-referenced locations across the US, which represent a subset of data points of the Natural Resources Inventory (http://www.nrcs.usda.gov/technical/NRI/). A survey conducted by the National Agricultural Statistics Service of land managers at these points provided the management practices for the simulations. The model output will be need to be interpreted within its environmental context. It is anticipated that a SMAF-like scoring approach will be needed. As a proof-of-concept, SMAF scoring was applied to the soil organic carbon and soil test P output for the precursor model runs (Potter *et al*. 2006).

Spatial Variability

Most fields exhibit spatial variability in soil properties and soil functions. An effort has been initiated to develop methods for conducting soil management assessments within spatially variable fields using the SMAF. The initial approach is to use apparent electrical conductivity (ECa) to densely sample the field, use the variability in ECa to guide soil sampling, quantify indicators at those sample sites, determine the relationship between measured indicator values and ECa, use the relationship to estimate indicator values for the rest of the field, and use these estimates to map the field.

Table 2. Coefficient of determination (r^2) between apparent electrical conductivity and select soil indicators for a Muir silty loam in southeastern Nebraska USA

Indicator	r^2	p-value
Bulk density	0.47	0.014
Electrical conductivity	0.86	0.001
pH	0.63	0.002
Bray phosphorus	0.68	0.001
Soil organic matter	0.87	0.001

A field in southeast Nebraska, USA near the town of Carleton was selected to evaluate spatial variability in soil indicators. Soil at the site is a Muir silt loam (fine-silty, mixed, superactive mesic cumulic Haplustoll). The ECa survey was conducted using a Geonics EM-38 (Geonics Limited, Mississauga, ON, Canada) mounted on a non-metallic sled pulled behind an all terrain vehicle. The ECa data was georeferenced as the survey was conducted with data logged every 5 seconds. The survey consisted of 25 transects (20 m apart) having a total of 1958 ECa measurements. Survey data was processed using the ESAP software package (Lesch *et al*. 2000). This program uses spatial statistics to select sampling locations that reflect the observed spatial variability in ECa (Corwin and Lesch 2003). A sampling design consisting of 20 locations was used. At each sampling location a soil core was collected from the 0- to 90-cm depth and sectioned into 0- to 15-cm, 15- to 30-cm, 30- to 60-cm, and 60- to 90-cm increments, air-dried and sieved. Soil bulk density, pH, electrical conductivity, organic matter content, and Bray-available P were determined. Data for Bray-available P will be presented here.

Measured soil indicator data was used to calibrate ESAP. Calibration involves calculating regression equations that best explain the relationship between measured ECa and soil indicators. Significant relationships between the selected indicators and ECa were determined (Table 2). Calibration equations were then used to estimate indicator values at the other 1938 ECa sample locations. The 1958 indicator values were then scored using the SMAF scoring curve

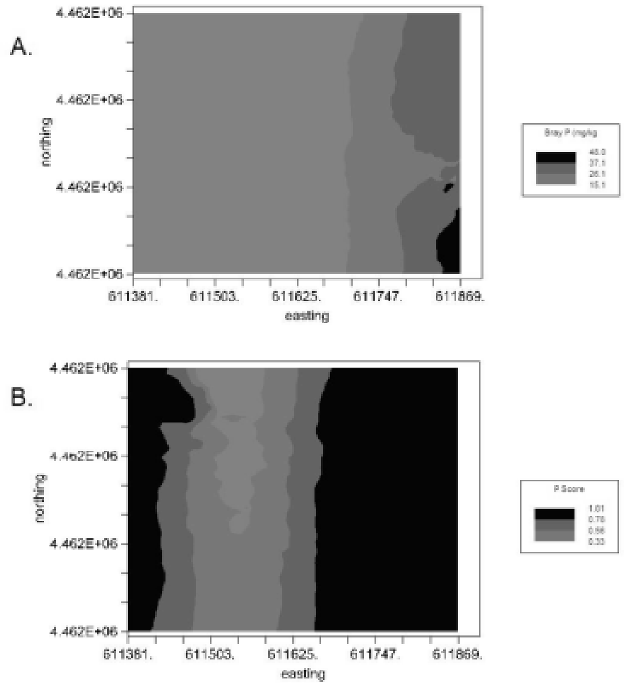

Fig. 3. Distribution of Bray available P (A.) and distribution of SMAF Bray available P scores (B.) for a Muir silt loam in southeastern Nebraska, USA

Bray available P. Maps for Bray available P were generated by kriging indicator values and scored values.

Values for ECa ranged from 12 to 62 dS m^{-1} with high values observed in the northwest and southeast portions of the field and low values observed in the middle of the field. Salinity is not an issue at this site and the variation in ECa is most likely due to variation in clay content, soil organic matter content, and depth of topsoil (Johnson *et al*. 2001; Grigera *et al*. 2006). Values for Bray available P ranged from 3.3 to 44.8 mg kg^{-1} with high values on the east and west sides of the field and low values in the middle of the field (Fig. 3A). Bray available P indicator values are below the threshold where environmental contamination is a concern so the SMAF scoring curve for the production soil function was used. Bray available P SMAF scores were high for the east and west portions of the field with lower scores in the center of the field (Fig. 3B). This figure clearly shows the area of the field where P fertilizer management practices should be applied.

Use of the SMAF in spatially variable fields requires further validation and methods refinement. Used in this way the SMAF is useful for delineating those parts of the field where management efforts should be concentrated. The approach presented above may be useful for soil test labs. Apparent electrical conductivity maps are relatively inexpensive and easy to generate. Using ECa to direct soil sampling and estimate the spatial distribution of soil indicators may be more cost efficient than grid sampling. This approach may also result in more efficient use of agronomic inputs. In the examples presented only portions of the field require fertilizer P. Applying inputs only to those parts of the field where there is a need should reduce input requirements compared to uniform application.

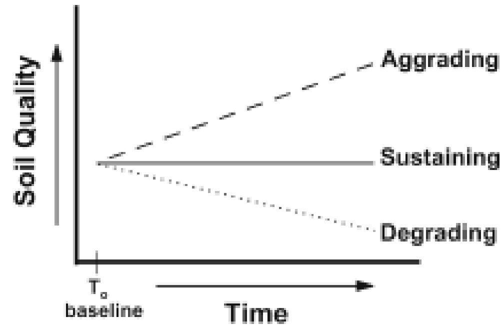

Fig. 4. Potential temporal trends identified through soil quality assessments with the SMAF (Adapted from Seybold *et al*. 1997)

Value Added Service for Soil Testing Laboratories

Soil testing laboratories typically provide soil and plant analysis results for use in nutrient management planning. More recently, analytical results have been provided for use in environmental monitoring activities such as the phosphorus (P) index or manure management plans. Scoring curves, such as those in the SMAF, can aid in interpreting soil testing laboratory data by relating the analytical results to various soil functions. The Cornell Soil Health Laboratory has adapted and simplified the SMAF scoring method as a prototypical soil quality testing lab (http://www.hort.cornell.edu/soilhealth/). Expanding soil testing results beyond the traditional soil production function to include other soil functions such as water relations, filtering and buffering, physical stability and structural support, resistance and resilience, and biodiversity and habitat represents an opportunity to provide a value added service to improve management of the soil resource (Karlen *et al*. 2007). If these assessments are conducted over time, trends in soil response to management can be determined and adjustments in management made (Fig. 4). In addition to scoring and determining trend for a soil indicator the web based version of the SMAF is being designed to include cues that suggest possible causes for a suboptimum indicator value. Once causes of

soil quality decline are identified management changes can be implemented to improve soil function affected by that indicator.

Interest in soil functions other than the production function is likely to increase. The Natural Resources Conservation Service in the U.S. is currently using soil quality impact as one factor in evaluating applications for conservation program funds. The importance of the water relations soil function will increase as demands for greater production are combined with competing demands for limited water supplies. The role of the filtering and buffering soil function will receive greater attention as our understanding of interactions between the lithosphere and the atmosphere and the effects of this interaction of air quality and global warming are better understood. The physical stability and structural support soil function is of importance because it relates to the physical environment influencing many of the other functions and processes. Well structured soils have reduced susceptibility to erosion and provide an optimum rooting environment. The resistance and resilience soil function is a measure of the stability of a soil to human or natural disturbance. The biodiversity and habitat soil function represents the resources ability to support and maintain soil biota.

Conclusions

Efforts to develop soil quality assessment tools are ongoing. This paper describes recent work associated with the SMAF. While the SMAF is primarily a research tool at this time efforts to improve its utility continue. Additional scoring curves will be developed, comparisons to other assessment tools will be made, and efforts to implement the SMAF will continue.

These activities will include federal and university researchers, commercial laboratories, consultants, and land managers. The SMAF web site, soilquality.org is listed first by Yahoo.com and second by Google.com [as of August 2008] when the search phrase is *soil quality*. Considering the extensive search results displayed, it is clear that soilquality.org has great potential to influence conservationists, consultants, agricultural and urban landowners, and others interested in *soil's capacity to function*.

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