Soil quality: Humankind's foundation for survival

D.L. Karlen, S.S. Andrews, B.J. Weinhold, and J.W. Doran

ABSTRACT: During the past decade, soil quality research and education programs have increased exponentially throughout the world. Educational and assessment approaches, ranging from simple scorecard and test-kit monitoring to comprehensive quantitative assessments and indexing using soils databases, have been pursued. The programs have emphasized that soil quality is not "an end in itself" but rather a tool for evaluating and understanding the effects of soil management on a specific soil resource. The approaches have stressed that to determine how well a soil is functioning, inherent and dynamic soil properties and processes must be evaluated using biological, chemical, and physical indicators. No soil quality researcher has ever envisioned the concept would replace modern soil survey programs or diminish the importance of scientifically based soil management strategies. Herein, we present the scientific merits of soil quality research.

Keywords: Soil health, soil management, soil ratings for plant growth (SRPG) model, soil resource assessment, soil tilth, sustainable agriculture

Many of our current soil management decisions are not sustainable and lead to environmental degradation (e.g.; salinization, compaction, erosion, contamination of ground and surface waters with nitrate, phosphorus, pesticides, or other materials). The concept of soil quality, defined 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) provides a focal point for assessing the severity of this degradation. In fact, for many soil scientists, ecologists, agronomists, and other professionals around the world, the continuing degradation of natural resources is closely associated with a loss of soil quality. Their rationale is that if soils are managed or maintained in a manner that ensures the biological, chemical, and physical properties and processes are sustained and functioning properly, much of the current degradation can be mitigated.

Many people around the world intuitively understand the concept of soil quality and are using it to improve their soil management practices. Soil quality efforts are especially important for the two billion people who are malnourished and for an equal number who live below the poverty level (Eswaran et al., 1999). Examples include Ouedraogo et al. (2001) for Africans near the Sahel Desert and Lamarca (1996) for Latin America. In New Zealand, Kiwi land managers have accepted soil quality (Shepherd et al., 2001) as a tool to help make sustainable land management decisions. For the German citizen, where the Federal Soil Protection Act (BbodSchG, 1998) recognized soil as 1) a basis for life and habitat for animals, plants, and soil organisms; 2) part of natural systems, especially water and nutrient cycles; and 3) a filter and buffer; improved soil quality is closely associated with water quality and protection. For educators and farmer-cooperators in Alberta, Canada (Cannon, 2001), soil quality provides a foundation for developing improved nutrient management practices. For farmers in the Central Valley of California, where statements such as:

> "...It is astonishing to me...that they're still only giving me a one page soil test...you need a more sophisticated tool than that,... this [soil quality index] is great...I'm sure hoping I can get more than one page now...something that I can utilize to manage my soil"

have been recorded (Andrews et al., 2003), soil quality is certainly relevant and of interest.

Most soil quality research and education efforts have been driven by the desire to use our science to help people make better decisions regarding soil management and how to make the best possible use of their finite soil, water, and energy resources (Doran et al., 1996; Herrick, 2000; Karlen et al., 2001). Why then has there been so much controversy over such laudable goals? To protect our world's soil resources, traditional research and development paradigms must now ensure the development of a more complete information base, monitoring, and indicators to establish the prevailing soil conditions. The results must be made available more quickly to more people and used to evaluate the impact of diverse policies and practices to ensure that the best management strategies for each soil resource are recommended and adopted.

We agree with the goal given by Sojka and Upchurch (1999): "Our children and grandchildren of 2030 will not care whether we crafted our definitions or diagnostics well. They will care if they are well fed, whether there are still woods to walk in and streams to splash in—in short, whether or not we helped solve their problems, especially given a thirty-year warning." Preventing the continued degradation of our world's natural resources is the first and foremost important goal. Where we differ is with regard to what tools to develop and how they should be used to improve soil management practices.

Evolution of the soil quality concept. Alexander (1971) first suggested developing soil quality criteria while discussing agriculture's role in environmental improvement. The soil quality concept per se was introduced by Warkentin and Fletcher (1977) as an

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approach to facilitate better land use planning for the multiple functions that soil resources must provide or accommodate. In Canada, the term soil health emerged as soil management research gradually shifted from controlling soil erosion and minimizing its effect on crop productivity, to broader issues including sustainable agriculture, environmental health, and prevention of further soil degradation (Karlen et al., 2003). Throughout the 1990s, research, education, and institutional changes occurred exponentially as the concept of soil quality began to be implemented worldwide (Karlen et al., 2001). Important accomplishments included the publication by Larson and Pierce (1991) that outlined a quantitative formula for assessing soil quality and relating the changes to soil management practices. As a result, soil quality was recognized and interpreted as a more sensitive and dynamic way to measure soil condition response to management changes and resilience to stresses imposed by natural forces or human uses. Many researchers participated in developing the soil quality concept by contributing to the publications entitled, "Defining Soil Quality for a Sustainable Environment" (Doran et al., 1994) and "Methods for Assessing Soil Quality" (Doran and Jones, 1996). Studies were also conducted to: 1) establish monetary land values, 2) monitor soil degradation, and 3) address challenges affecting food security. The latter is especially important in developing countries where loss of per capita land area and water resources often result in decreased soil quality (Lal, 1999).

Soil quality research and education programs have evolved even where political leaders and often scientists do not understand or agree upon the effects that land use decisions have on soil resources. The programs have grown in part because obvious linkages between soil quality, management decisions, and sustainability are often overlooked or even ignored. They have grown because questions regarding organic farming, conservation tillage, safer pesticide use, protection and maintenance of terraces, integrated crop management, management of low-intensity pasture systems, lowering stock density, use of certified compost, or urban and suburban development effects on soil quality abound and currently remain unanswered.

The soil quality concept has always been closely associated with the critical functions that soil resources perform in the biosphere (Doran et al., 1996). Therefore, we maintain that the simplest definition for the concept is "the capacity [of soil] to function" (Karlen et al., 1997) or stated another way, "how well is the soil functioning" for a specific goal or use. This closely parallels many other definitions (i.e., suitability for chosen uses or range of possible uses) that have been used (Doran et al., 1996). The close association between soil function and soil quality also helps illustrate the concept of soil services used to describe the concept of sustainability and soil resilience (Blum, 1998). Those services have been grouped in two categories. The first, focusing on agriculture, includes biomass production (food, fiber, and energy), soil as a reactor (filtering, buffering, and transforming actions), or soil as a biological habitat and genetic reserve. The second, focusing on nonagricultural uses, considers soil as a physical medium, a source of raw materials, and a repository for cultural heritage that helps preserve the history of earth and humankind (Doran et al., 1996).

Future soil quality developments. Tools for monitoring soil quality and building a knowledge base for coherent future actions are needed. The monitoring should be established using existing information systems and databases where possible. It should be designed in such a way that the data can be integrated into more comprehensive, multilayered monitoring and reporting programs. Based on systematic sampling and analysis, soil monitoring systems should aim to deliver information on changing soil parameters, important for soil functions such as nutrient and organic matter cycling, biodiversity, or resilience after contamination by pesticides, heavy metals, or other anthropogenic materials.

The focus for ongoing soil quality efforts must be on protecting or restoring critical soil functions (Höper, 2000) and using good agricultural management practices. Soil protection and prevention of further degradation requires an integrated approach based on existing and new knowledge. It also requires the development of a long-term approach through which soil protection is based on a more complete knowledge of both the direct and indirect impacts of human activities and the best practices and measures to address soil resource degradation.

As the soil quality concept continues to evolve, there are several issues that need to be resolved. Two associated with indicator selection are the spatial and temporal scale (Halvorson et al., 1997; Wander and Drinkwater, 2000). Another is the need to demonstrate causal relationships between soil quality indicators and ecosystem functions (Herrick, 2000). The accuracy, precision, and cost of identifying minimum sets of indicator variables, sometimes described as a minimum data set (MDS), are questions that have not been resolved.

We anticipate that the use of soil quality assessment will increase and will help quantify resistance [defined as the capacity of a system to continue functioning without change through a disturbance (Herrick and Wander, 1998; Pimm, 1984)] to degradation and the resilience of a soil resource to recover following degradation. Although a single minimum data set will probably never be defined because of the inherent variability among soils, a flexible suite of biological, chemical, and physical indicators will ultimately be identified and used to evaluate site-specific, temporal trends in soil quality. Whether or not the indicators are used to develop index values is not an issue. The appropriate use for soil quality assessments is to evaluate the temporal trends for a specific soil at a specific location or to determine the effects of different practices on a similar soil. Soil survey information provides a basic geographic framework and context for the assessment of soil quality for a given location and for a given point in time. Traditional soil survey documents the inherent differences among soils in the landscape and makes recommendations regarding potential uses. Thus, we suggest an important role for soil scientists is to determine appropriate indicators for various management goals or land uses. Doing so will ensure that assessments will be useful and understandable to farmers and other land managers who are, and will continue to be, the stewards of soil quality (Doran and Zeiss, 2000).

Undoubtedly, many issues need to be resolved before the soil quality concept is fully operational. However, we feel that it is important to stress in this editorial that, to our knowledge, no soil quality researcher has ever implied that the concept would replace modern soil survey programs or diminish the importance of technology and scientifically based soil management strategies. For the benefit of everyone, it is imperative that the misconceptions regarding soil quality concepts be corrected through rigorous scientific debate and dialogue.

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capacity for commodity crop production as one factor for adjusting soil rental rates. The model used inherent soil properties so that it was consistent across political boundaries and over time. In contrast, efforts to develop indices of relative soil quality (Karlen et al., 2001) have focused on dynamic soil properties. The soil ratings for plant growth was designed to use only the soil survey database because the system had to be usable for all soils and all arable land on which commodity crops were grown. Soil quality assessments utilize recent visual, on-site, or laboratory data that may or may not be interpreted using information from soil survey databases.

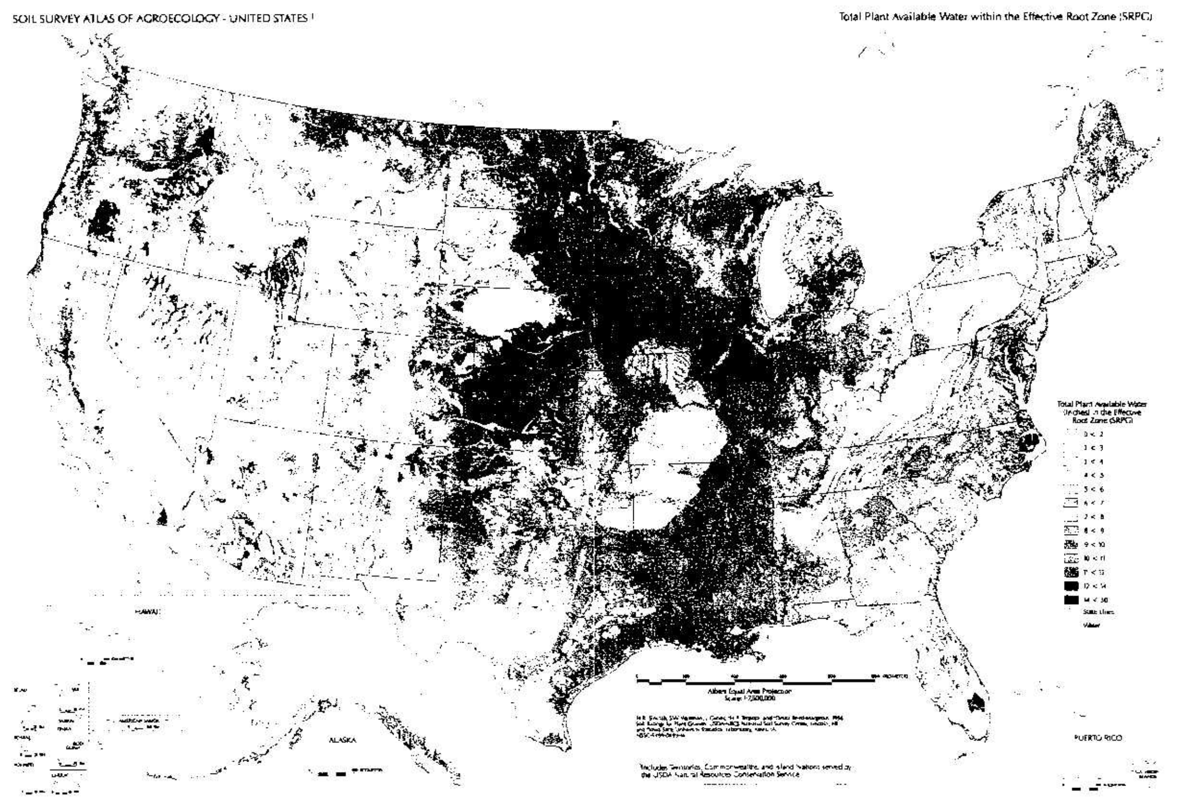
The procedures used to develop the soil ratings for plant growth model also provided information needed to develop a national map delineating root zone available water capacity. The values were computed by summing the available water capacity for each layer above an identified rooting constraint within the profile and were very influential in determining inherent productivity (Figure 1). The root zone available water map (USDA-NRCS, 1999a) displays a pattern (Figure 2) that nearly coincides with the extent of former prairie or grassland soils. Those soils, often formed in medium textured Aeolian or glacial parent material with few rooting constraints are, in soil taxonomy terminology, Mollisols. The strong positive relationship between root zone available water and soil ratings for plant growth model resulted in a close association between Figure 1 and the dominant soil orders (Figure 3) associated with United States soil taxonomy (USDA-NRCS, 1999b). This close association apparently led some (e.g.: Sojka and Upchurch, 1999; Sojka et al., 2003) to the incorrect conclusion that soil quality evaluation and indexing are taxonomically biased.

To demonstrate this error, the soil ratings for plant growth model was rerun for an irrigated condition where root zone available water (Figure 2) was not limiting plant growth (USDA-NRCS, 2002). This resulted in an irrigated soil ratings for plant growth model map (Figure 4) that closely mirrors the "market value" map presented by Sojka et al. (2003). However, with regard to long-term sustainability, it is absolutely imperative to recognize that achieving the irrigated soil ratings for plant growth levels has a real cost for water, energy, and nutrients that must be considered. Failure to account for all input costs is not acceptable.

Incomplete reviews. Sojka and Upchurch (1999) and Sojka et al. (2003) contend that the practical realities associated with interpreting indicators of the multiple functions that soils perform have not been addressed. We feel this perception is incorrect because even though Sojka et al. (2003) cite more than 340 references, they ignore Andrews and Carroll (2001), Andrews et al. (2001, 2002), Herrick et al. (2002), Karlen et al.

Figure 2

Plant available water holding capacity for soils within the United States (USDA-NRCS, 1999a).



(1998), Karlen et al. (1999) and numerous international websites where those challenges have been recognized.

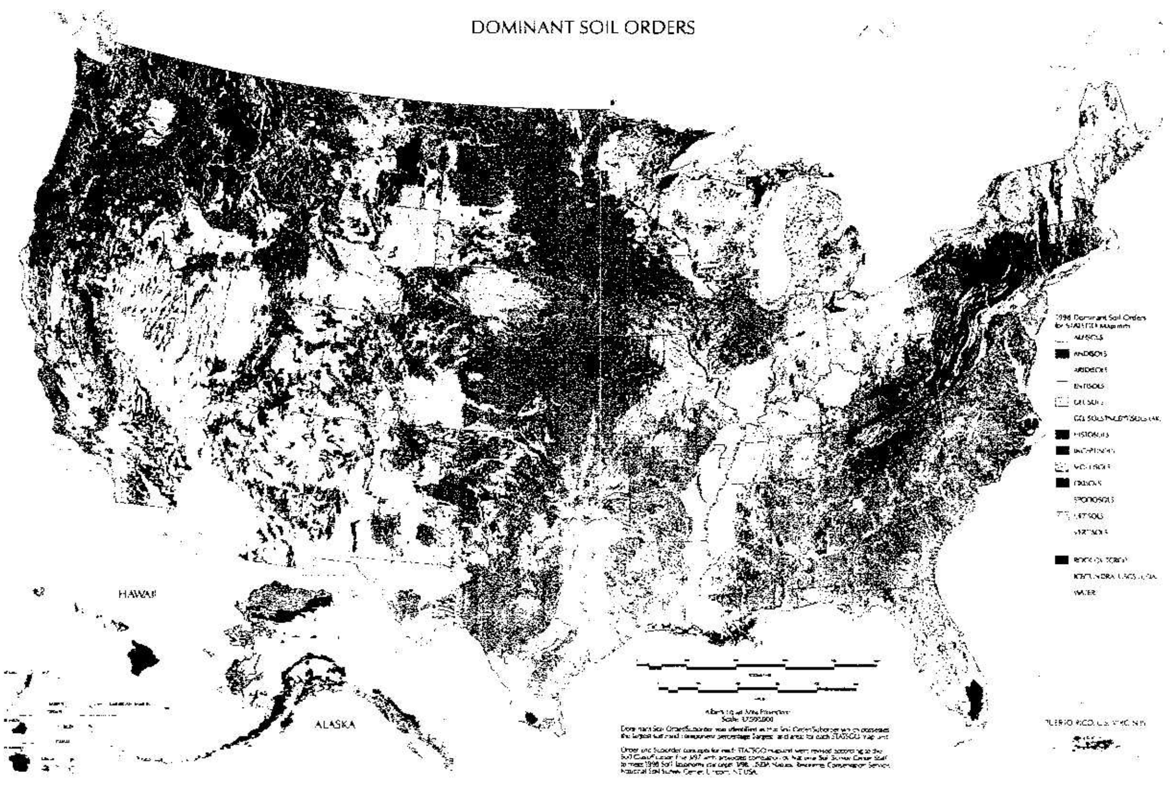
Sojka et al. (2003) also contend that no procedural approach for integrating various soil quality indicators has been offered and suggest that the complexity and conflict of values makes the process insurmountable. Other authors (e.g.; Schjonning et al., 2003) have also questioned the feasibility of assessing soil quality because of the vast inherent differences among soil resources. While we agree with Sparrow et al. (2000) that development of soil quality assessment is in its infancy, substantial progress has been made in the United States (Andrews et al., 2001, 2002; Herrick et al., 2002) and around the world (Shepherd, 2000; Beare et al., 1999). Once again, Sojka et al. (2003) chose to ignore those efforts, opting instead to return to their criticism of the nonexistent "Sinclair model of soil quality" and their position that soil quality evaluations were primarily qualitative and sensory.

Misconceptions regarding soil quality assessment. Undoubtedly, selection, interpretation, and integration of indicator data are among the more difficult and controversial issues associated with the soil quality concept. This was recognized and has been an integral part of the soil quality research and education program since our first evaluations of crop residue management and tillage treatments using a soil quality index (Karlen et al., 1994a,b). Despite assertions to the contrary (e.g.: Sojka and Upchurch, 1999; Sojka et al., 2003), substantial progress in soil quality assessment and quantification has been made during the past decade.

The selection of indicators for evaluation is most often based on expert opinion (e.g.; Doran and Parkin, 1994) but also can be accomplished with statistical procedures such as principal components or factor analysis (e.g.: Andrews and Carroll, 2001; Brejda et al., 2000). Expert opinion requires expert knowledge of the system and carries the possibility of disciplinary biases; statistical approaches require large existing data sets and are also ultimately subject to disciplinary bias as well because results depend on the number and type of indicators in the original data pool. Both approaches produced similar results in a comparison of indexing approaches using data from a vegetable production study on irrigated soils in northern California, USA (Andrews et al., 2002).

Scoring and combining the indicators into indices can be done in a variety of ways (Andrews et al., 2001). Linear scoring can be used and may be desirable for indicators that change gradually along a continuum. Step-functions (i.e.: good or bad, yes or no) may be appropriate for indicators that measure 'contaminated versus noncontaminated' situations. Nonlinear scoring accommodates

Figure 3
Dominant soil orders within the United States (USDA-NRCS, 1999b).

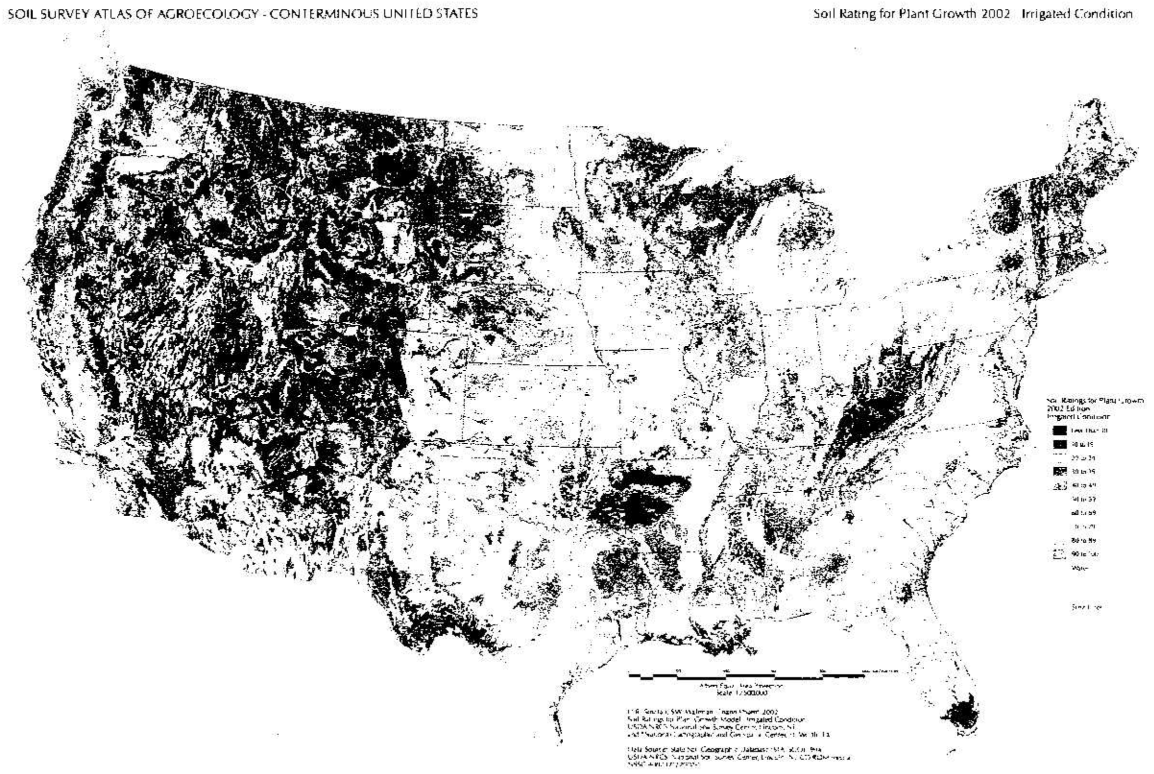


threshold and optimum values as well as transition areas where small changes in indicator values represent large changes in soil function and thus the indicators' score (Herrick et al., 2002). Andrews et al. (2002) found nonlinear scoring more accurately reflected soil function when compared to a linear method.

Development of nonlinear scoring functions requires in-depth knowledge of each indicator's behavior and relationship to functions within the system. For each indicator, baseline and threshold levels are defined based on inherent soil properties. Several methods, including the use of benchmark sites, have been suggested for establishing baseline values. Benchmarks may be most appropriate for remediation applications. For agronomic uses, thresholds should be based on studies showing the relationships between indicator values and soil function. We prefer to use measurements for a specific soil at T0 and to then determine the net change (i.e.; aggrading, degrading, or stable) at future times (TN) that are appropriate for each indicator.

A user-friendly soil management assessment framework has been proposed and tested (Andrews et al., 2001; Karlen and Stott, 1994). The framework consists of three steps: 1) indicator selection, which suggests appropriate chemical, biological and physical indicators; 2) indicator interpretation, offering site-specific interpretations of those indicators in relation to soil function; and 3) integration into an index, which provides an overall assessment of the indicator interpretations. The framework utilizes a nested hierarchy for expert opinion-based indicator selection based on management goals, soil functions, and site-specific criteria. This allows it to be flexible for various land uses across multiple scales, and for soils with different inherent characteristics. Interpretations, using nonlinear scoring, accommodate different indicator thresholds for multiple soil, climate, and crop combinations, thereby addressing important spatial and temporal issues (sensu Halvorson et al., 1997) that are based on these inherent soil and/or climatic factors. Site-specific factors that can affect indicator selection or interpretation include management goals, such as productivity or waste disposal; inherent soil properties, as in organic matter or texture; climate factors, such as annual precipitation and temperature; or crop requirements. Prototypes have been developed in Excel spreadsheet and object-oriented Java programming formats for further evaluation and refinement (Karlen et al., 2003). Several U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) scientists contributing to the Soil Resource Management National Program and other researchers around the world are currently evaluating the

Figure 4
The soil ratings for plant growth (SRPG) model for irrigated production throughout the United States (USDA-NRCS, 2002).



framework for several different soil management applications.

Misconceptions regarding individual indicators. Sojka and Upchurch (1999) and Sojka et al. (2003) objected strenuously to the importance given to soil organic matter by many soil quality researchers. One reason that soil organic matter has received so much attention is the well-documented fact that worldwide, soil organic matter levels have decreased by 50% or more during the past century. This degradation of soil quality is important because of the numerous functions that soil organic matter influences (e.g.: nutrient cycling, water retention, aggregation, surface sealing, energy substrate, etc.). The potential need for an increased rate of soil-incorporated herbicides on high organic matter soils is used as one reason why some suggest that increased soil organic matter should not be given a high priority in soil quality assessment (Sojka and Upchurch, 1999; Sojka et al., 2003). While we agree that soil organic matter levels can and do influence herbicide application rates, the relative proportion of soil-incorporated herbicide is declining. Furthermore, in the framework being developed to evaluate soil quality indicators, the scoring curves can easily be given a declining slope (and therefore lower rating) for combinations of management systems and soil organic matter levels where this might occur. A similar adjustment may be needed for forest areas where, due to litter accumulation, soil organic matter levels can become so high that runoff actually increases (personal communication, B. Hudson, USDA-NRCS (Retired), August 2003).

Sojka et al. (2003) express concern regarding the use of earthworms as a biological indicator because of their potential to increase bypass flow and rapid movement of surface-applied contaminants to groundwater. While this is possible, they fail to acknowledge that earthworm effects are species dependent, as not all create permanent vertical burrows (Berry and Karlen, 1993). As with soil organic matter, the framework being developed for assessment of soil quality indicators can be modified through the scoring curves based on available data and subsequent site-specific knowledge such as the predominant earthworm species at a given location.

Sojka et al. (2003) state that Karlen et al. (2001) failed to address how soil quality assessment could cope with the dynamic indicators such as soil respiration. This is not true if the entire body of soil quality literature is examined. Parkin et al. (1996) state that respiration is an indicator of organic matter decomposition in soil, and therefore it reflects two general processes: 1) loss of carbon (C) from the soil system, and 2) recycling of nutrients. Either process can be viewed as detrimental or beneficial depending upon the intended use of the soil, the magnitude of the respiration activity, and the temporal and spatial distributions exhibited by those processes. Parkin et al. (1996) also outline an analytical process whereby respiration, normalized to organic carbon inputs, may be a promising soil quality indicator. Specific targets or values for precise interpretation of soil respiration still need to be established, and this may have to be done on a site-by-site basis to account for the intended use of the soil, local management practices, and the climate. Other biological indicators, such as microbial biomass, seasonal, and climatic fluctuations in expected range, have been incorporated into nonlinear interpretation curves within the framework currently being evaluated.

Soil respiration is also an important soil quality indicator with regard to its educational value as evidenced by the sale of more than 500 soil quality test kits. Simple, semi-quantitative measures of carbon dioxide (CO_2) production have been used to demonstrate the living and dynamic nature of soils to many different audiences (USDA-NRCS, 1998).

Sojka et al. (2003) dispute the use of compaction, salinity, microbial biomass, microbes (e.g., *E. coli*), and almost any other potential indicator of how a soil is functioning. Repeatedly, they continue to state that "the first institutional use of a soil quality index devalued United States arid-zone soils." This occurred because they misused the soil ratings for plant growth model, an error that we have hopefully corrected (Figure 4). We fully acknowledge the difficulty associated with identifying the most critical factors affecting soil resources. Indicator evaluation and indexing have successfully demonstrated that soil management practices have multiple effects on soil function. However, viewing individual indicators from the perspective of only one discipline—chemical, physical, or biological—can result in conflicting messages to the land manager who needs to take a specific action on a particular soil resource.

Summary and Conclusion

We strongly disagree with Sojka et al. (2003), who imply that the soil quality effort is a scientific distraction that has resulted in a failure of soil scientists, agronomists, ecologists, and others to "stay on message" with regard to issues such as soil erosion. They quote Pimental (2000) who stated that soil erosion control has not received the research and mitigation support it deserves because: 1) erosion is insidious, 2) erosion occurs very slowly relative to human perception, and 3) the public has little regard for the value of soil. To the contrary, one of the underlying reasons for focusing on soil quality since the publication entitled, "Soil and Water Quality: An Agenda for Agriculture" was released (National Research Council, 1993) was the need to improve public awareness about soil resources and to help them understand how soil management decisions affect not only the soil itself but other resources (i.e., water and air) as well. Soil quality has been accepted as a concept for guiding and developing improved soil management practices throughout the world (e.g.: Beare et al., 1999; Shepherd, 2000; Shepherd et al., 2001).

Educational programs, including the use of relatively simple tools and techniques, have been used to increase awareness that soils are indeed living and dynamic. The effort has increased awareness regarding the fragile nature of many soils. This conclusion was verified through surveys in the United States (Andrews et al., 2003) and New Zealand (Shepherd et al., 2001). In the latter, 85% to 99% of the participants in visual soil assessment workshops (including 92% farmers) found visual soil assessment scorecards and field guides easy to use and technically appropriate. Educational activities sponsored by the USDA-NRCS Soil Quality Institute have also been very effective in promoting a better understanding of soil science among field staff and other natural resource personnel.

We hope that the misuse of the soil ratings for plant growth model will stop following this exchange of research editorials. The soil ratings for plant growth model is not, and never was intended to be, a model of soil quality. We have tried to set the record straight regarding why and how the maps were generated. In addition, we have attempted to refute other misconceptions about quantification of soil quality using indicators or indices.

We described a three-step framework for