The need for a soil quality index: Local and regional perspectives

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Abstract. Our knowledge of soil is based primarily on quantitative analysis of isolated physical, chemical, and biological properties. However, the interaction of these quantitative aspects determines soil quality. Integrative tools are needed by researchers, farmers, regulators, and others to evaluate changes in soil quality from human activity at a local and global level. An index needs to be adaptable to local or regional conditions. For example, the parameters needed to determine changes in soil quality may differ between a semi-arid wheat field and a rice paddy. Suitable reference points and optimum ranges are needed for soil quality attributes. The present challenge is to integrate a suite of soil tests into a meaningful index that correlates with productivity, environmental, and health goals.

Key words: soil health, soil condition, soil analysis

Introduction

Interest in soil quality dates back to ancient agriculturalists. Varro, a Roman scholar, noticed about certain crops that "when cut down and left they improve the soil." More recently, concern over the health of the soil was articulated by Albert Howard (1947) and the Rodales (Rodale, 1981). Today the term soil quality is used with increasing frequency in both the popular and scientific press, suggesting a broadening awareness about the critical importance of the soil resource and the need to monitor it more closely.

Current scientific knowledge of soil is based on analysis of various soil components. This approach often reveals little about the complex interactions of biological, chemical, and physical components that make soil a unique medium. The interest in a soil quality index represents an attempt to address this problem. Yet there is a contradiction in any attempt to quantify soil quality because of its qualitative nature. Some farmers use sensory indicators such as smell, feel, and ease of tillage to judge soil quality and the health of their fields (Beus et al., 1990), but these indicators are hard to quantify. A soil quality index needs to be sensitive to both sensory and quantitative aspects.

Four strategies can be followed in studying soil quality: quantitative analysis of soil for specific attributes (e.g., carbon and nitrogen content); study of undisturbed soil in the field (e.g., earthworms, water infiltration); bioassay with plants or animals (e.g., yield, animal weight gain); and monitoring of ecosystem processes (e.g., watershed dynamics, nutrient balances). These strategies vary from the most reductionist to the most integrative. Watershed level assessments integrate most of the important soil quality attributes, but are expensive to conduct and require evaluation over a long time.

It is unlikely that any single index will serve all cropping systems or geographic areas. A uniform process is needed for selecting specific soil quality criteria for an individual situation. At the Rodale Institute Conference on the Assessment and Monitoring of Soil Quality (Rodale Institute, 1991), three basic components of a soil quality index were proposed to help standardize soil measurements across diverse environments: 1) the ability of soil to enhance crop production (Productivity component); 2) the ability of soil to function in attenuation of environmental contaminants, pathogens, and offsite damage (Environmental component); and 3) the linkage between soil quality and plant, animal, and human health (Health component). The purpose of this paper is to describe the need and potential uses for a soil quality index and to identify barriers to be overcome in developing a valid index.

The Need for a Soil Quality Index

Numerous quantitative properties are potential indicators of changes in soil quality (Wilde, 1955; Chapman and Pratt, 1961; Black, ed., 1965; Page, ed., 1982; Smith and Mullins, eds., 1991). These include microbial biomass, diversity, and activity; carbon and nitrogen content and dynamics; fertility status and nutrient availability; soil structure; and water infiltration. Studies of changes in soil characteristics under experimental treatments or contrasting long-term management typically generate large data sets from a suite of measured parameters. But it often is difficult to judge quantitatively whether the soil as a whole has improved, deteriorated, or stayed the same, since integration of the analytical results remains subjective.

For example, soil properties of a conventionally farmed field in eastern Washington were compared to those of a field on an adjacent low-input farm after 40 years of divergent management (Table 1). Soil from the low-input farm had significantly higher enzyme levels, microbial biomass, and soil organic matter (Bolton et al., 1985). It had significantly higher available
phosphorus levels (Patten, 1982), and suffered significantly less erosion (Reganold, 1988). The low-input soils also had a higher ability to adsorb pesticides (Malawatani and Mulla, 1992). Average wheat yields on the low-input farm were 8% lower than on the conventional farm, but they were similar to yields on another neighboring conventional farm.

The cumulative properties measured in these studies likely reflect changes in soil quality, although it is difficult to assess the contributions from individual practices. Although there is scientific and popular consensus that the reduced soil erosion and increased pesticide adsorption on the low-input farm represent positive changes in soil quality, there is less agreement about the meaning of higher microbial biomass or enzyme levels. Thus, relationships need to be established between individual assays and the three soil quality components mentioned above so that judgments can be made about soil quality improvement or deterioration. Ultimately, any measure of soil quality will need to be linked to value judgments based on human-centered goals such as ample food production, improved water quality, and improved human health.

Crop yield can be an important indicator of soil quality, because it serves as a plant bioassay of the interacting soil characteristics. However, productivity alone is not a complete measure of soil quality. For example, in the Palouse region of eastern Washington, extensive soil erosion has occurred during the past century, yet average winter wheat yields have increased linearly (Soil Conservation Service, 1979). Using crop yield and soil loss as two possible indicators of soil quality would lead to conflicting conclusions about how the condition of Palouse soils has changed. Measures such as stability of yield over time or the resilience of yield to perturbations or stress are preferable to absolute productivity (Conway, 1985). Other important considerations are the efficiency of production (output per unit of input) and potential environmental impacts. Bushels of grain produced per ton of soil lost, or yield per unit of fossil fuel input can tell us more about soil quality than yield per acre or per hour of labor. The last two yield measurements address only the productivity aspect of soil quality, and ignore the environmental and health components. Soil organic carbon (or organic matter) is probably the most universal gross indicator of soil quality presently available (Rasmussen and Collins, 1991). Both farmers and researchers generally consider an increase in organic carbon to be a positive change in soil quality. But significant biological, chemical, and physical differences can exist between two soils with the same organic matter content. Australian researchers found very similar organic carbon contents in soils from plots under continuous pasture and virgin vegetation, but the virgin soils had over 70% more water stable aggregates (>2 mm) than the pasture soils (Russell and Williams, 1982). Canadian researchers (Perfect and Kay, 1990) and Ohio crop rotation studies (Table 2) also have shown that organic carbon and water stable aggregation are not necessarily correlated. Since changes in soil attributes such as organic matter can vary significantly with depth, soil quality comparisons between practices (e.g., no-till versus conventional tillage) must balance results from surface soil with those from the tillage zone and the rooting zone. A valid soil quality index would help interpret data from batteries of soil measurements and show whether management and land use are having the desired results for productivity, environmental protection, and health.

Uses of a Soil Quality Index

Farmers, researchers and policymakers are interested in an integrative soil quality index to monitor changes in soil over time. Many farmers are concerned about the long-term effects of contemporary farming practices on the soil resource (Beus et al., 1990). They are evaluating new products and practices through on-farm testing, but they lack a good indicator of changes in the soil system. Farmers who use alternative cropping practices such as green manures often report improvements in soil tilth and reduced disease problems. A growing number of products and management
recommendations carry claims regarding soil health or improved soil life that are difficult to verify or refute within our current soil analysis framework. Farmers need a soil quality index that can help them evaluate the economic potential of new options and their impact on the soil resource.

In the U.S., the 1985 Farm Bill mandated soil and water conservation compliance for commodity program participants. In developing conservation plans with farmers, the Soil Conservation Service (SCS) has relied heavily on predictive soil loss equations and easily measurable parameters, such as surface crop residue and tillage practices. Some farmers who use alternative practices such as green manure believe that their farming systems have improved soil quality and thus reduced erosion potential compared to other farming systems on the same soil type. They question the need for additional practices such as minimum tillage or strip-cropping on their farms.

A soil quality index might help the SCS resolve this issue. In the 1960s, the SCS developed a Soil Conditioning Rating Index (Soil Conservation Service, 1974) to evaluate the effect of entire cropping systems and rotations on soil quality, but it was not widely used. Researchers have shown that the K factor (soil erodibility) assigned to a given soil series can be changed substantially by management (Table 3) and perhaps should not be considered a constant in using the Universal Soil Loss Equation (Gersmehl et al., 1989). A soil quality index would help the SCS evaluate the impact of the Conservation Reserve Program and suggest future policies to optimize benefits from the 10-year public investment.

Researchers and policymakers would find a soil quality index useful in evaluating policy decisions and measuring progress. For example, considerable public and private resources have been committed nationally to the development of no-till technology. Many tests currently used to evaluate soil quality have not yet been adopted by the SCS or other agencies.

Table 3. Change in K factor (soil erodibility) of the Universal Soil Loss Equation for a Seaton silt loam soil due to past use, Wisconsin (adapted from Gersmehl et al., 1989).

<table>
<thead>
<tr>
<th>Past Use</th>
<th>Silt (%)</th>
<th>Organic Matter (%)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin forest</td>
<td>83</td>
<td>3.8</td>
<td>0.27</td>
</tr>
<tr>
<td>Crop rotation</td>
<td>86</td>
<td>1.5</td>
<td>0.39</td>
</tr>
<tr>
<td>Continuous maize</td>
<td>89</td>
<td>0.7</td>
<td>0.51</td>
</tr>
</tbody>
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Although no-till offers significant soil conservation benefits compared to many conventional tillage systems, a soil quality index would help to identify other promising approaches in need of further research and extension.

A soil quality index would improve economic assessments of agriculture. It would help assign full economic and environmental values to practices such as cover crops, conservation tillage, or green manures. Farmers could be more convincing to lenders and landlords about the need for such practices in cases where they are beneficial. Also, an index would help assign a more accurate value to agricultural land based on resource efficiency and environmental considerations such as erosion and agrichemical leaching, not just on proven yield.

Environmental and regulatory agencies need an indicator to determine whether degraded soils have been restored satisfactorily in locations such as strip mines or Superfund sites. Soil plays a role in global change that is not fully understood, acting as a source/sink for greenhouse gases (Johnson and Kern, 1991). A soil quality index would help monitor progress for these concerns.

If relationships between soil quality and human health are established, consumers might use a soil quality index in making food decisions. This could become an important market force to influence farming practices.

Reference Points for Soil Quality

Human activity has altered many ecosystems and the condition of soils around the globe. Some changes have improved the soil for agricultural use, but other changes have impaired the soil's ability to provide for human needs. A soil quality index needs reference points that reflect both the general potential for human use and the unique biophysical conditions of a specific location. What should be considered the standard: the native soil conditions at a site, or the conditions that maximize agro­nomic, environmental, and economic performance? What is more useful: absolute measures, or measures of relative change over time?

The prairie ecosystem of the Great Plains provides a logical reference point for interpreting changes in soil quality under semiarid cereal cropping. The original plant community was dominated by native perennial grasses. With the introduction of agriculture, these species were replaced with annual cereal grasses, such as maize, wheat, barley, and oats. Soils formed under the native vegetation usually are high in organic matter, tilth, and other attributes considered optimum for farming.
the cultivated crops. In this case, the native soil provides a good reference point for soil quality. Many long-term studies have used the native soil as a benchmark for comparison with differing management systems (Skidmore et al., 1975; Rasmussen et al., 1989). Native sites, cemeteries, and farm fields with contrasting long-term management all offer potential reference points for soil quality in areas where long-term research plots are not present. Often soil conditions under long-term grass sod are used as a reference point in ecosystems that were not originally grassland. Since grassland soils provide good growing conditions for many crops, this may be a reasonable approach for temperate regions.

For many agroecosystems, the reference point is not so obvious (Table 4). Soils have been changed by management to provide more suitable conditions for crop plants, and thus soil quality for agricultural purposes often has been improved. A striking example is the development of Terra Preta soils in the Amazonian basin of Brazil, where human activity led to a dramatic change in the make-up of an Oxisol (Table 5). The proper reference point is equally obscure on paddy rice soils that were not originally flooded or on desert soils that are now irrigated. Waste-water applications to desert soils can significantly increase soil organic matter while also increasing heavy metal content and salinity. A determination of net soil quality change becomes difficult in such situations.

A soil quality index must be sensitive to how the soil is used. Table 6 lists several changes in soil that are widely regarded as improvements in soil quality. Although increased infiltration and aeration and decreased bulk density may enhance maize and wheat production, they are not desirable for paddy rice soils. A field with soil conditions favorable for alfalfa will probably not be suitable for blueberries. Thus, soil quality assessments may need to vary with the intended crop.

In evaluating soil quality, it is possible to have too much of a good thing, such as organic matter or a single nutrient. Optimum ranges for soil quality parameters need to be identified for different climates and uses. Increased soil organic matter levels are generally considered a positive change in soil quality. But an increase in organic matter beyond the optimum for a crop would represent a decrease in soil quality.

**The Future**

Researchers presently select a small subset of possible analytical tests for assessing soil quality. New assays are continually developed, including those that use sophisticated technologies such as nuclear magnetic resonance, super-critical fluid extraction, and DNA probes. A major challenge in developing a soil quality index is to establish guidelines for selecting assays that reflect changes in specific agroecosystems and the productivity, environmental, and health components of soil quality. The process must integrate quantitative, reductionist results into a cost-effective and meaningful index.

Soil physical tests need to include some in situ measurements, such as infiltration, that reflect the soil condition in place without disturbance. These tests should account for macroscale variation such as distribution of earthworm tunnels or root channels, topography, and restrictive layers that are not easily determined from laboratory tests. Soil chemical tests are probably the most consistent and repeatable. Tests such as total N or pH are less influenced by short-term factors than many of the physical tests. Ratios of results from two or more tests may provide better integration and meaning than results from individual tests.

The microbial life of the soil is often considered as a key element of soil "health" or quality (Howard, 1947; Higa, 1991). Results from microbial assays are often difficult to interpret. Methods to evaluate microbial diversity are not adequately defined, although new tools such as RAPS (random amplification of polymorphic DNA) allow further study of diversity, which may be more important to soil quality than population or activity. Microbial tests need to be correlated with key physical and chemical factors for soil quality testing.

Plant or animal bioassays provide an integrated analytical approach, but the proper parameters to measure in the plant or animal need to be determined. As mentioned earlier, several kinds of yield measurements can be made to give different information about a system. A quantitative measure of plant or animal health must be defined if these concepts are to be used as
indicators of soil health. Novel testing approaches such as radionics and circular chromatography (Pfeiffer, 1984) also need to be evaluated.

Concerns about food and fiber supplies, environmental protection, and human health are broadening our interest in the soil resource. In response, the volume of research data on soil components continues to grow. A soil quality index can provide a tool to integrate these component data into practical management guidelines and wise land use policies.

References


**Federal Court Orders Pesticide Ban**

The U.S. Court of Appeals in San Francisco has ruled that the EPA must remove from the market any pesticides that have the potential to cause cancer and leave residues in processed food. The overruling of an EPA regulation, which kept the pesticides in use as long as they were deemed to have a trivial cancer risk, could ban at least 60 pesticides that show up in trace amounts in such processed food as jams, juices, and sauces. Environmental groups had argued that even "negligible" pesticide residues in processed foods can be banned under the Delaney Clause, which prohibits even trace amounts of carcinogens in processed foods.

**Two States Take Steps Toward Sustainable Agriculture**

In separate moves taken recently, Washington State has adopted organic meat and dairy standards, and California has formed a committee to help find alternative crop protection strategies to reduce the environmental problems associated with pesticide use.

Washington’s standards specify the living conditions, disease prevention and control practices, and record-keeping requirements for organic meat and dairy production. Producers who meet these standards can market their products to consumers interested in buying meat and dairy products which have been produced without the use of antibiotics or hormones and in a manner not detrimental to the environment.

The California committee’s goal is to encourage the development, testing, and dissemination of new pest management practices, with particular emphasis on the importance of the alternatives to pesticide use that are critical to IPM. It will also help identify obstacles to IPM in California’s regulatory system and in the U.S. Environmental Protection Agency.