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Critical Issue Report: Soil Quality

Assessing Soil Quality in Organic Agriculture

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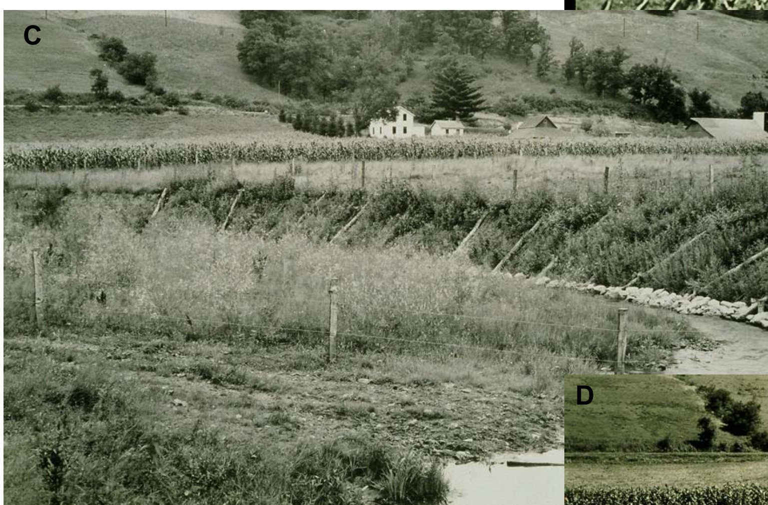
To waste, to destroy our natural resources, to skin and exhaust the land instead of using it so as to increase its usefulness, will result in undermining in the days of our children the very prosperity which we ought by right to hand down to them amplified and developed.

—Theodore Roosevelt, U.S. President, 1907.

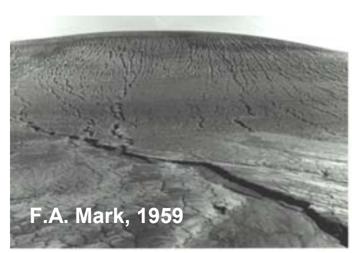


A nation that destroys its soils destroys itself.

—Franklin Roosevelt, U.S. President, 1937.

A-D: Pictorial sequence of a conservation success story initiated during the 1930s in the Coon Valley Watershed in Wisconsin.

Find out more at: http://www.nrcs.usda.gov/about/history/



Reviewing the past helps us plan for the future

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Critical Issue Report 2006.2

Executive Summary

Soil quality affects and is affected by food, feed, and fiber production practices. It is also directly linked to environmental quality (i.e. water and air quality, global warming, and energy use for production practices). Unfortunately, moderate to severe soil degradation through erosion, compaction, leaching, and loss of biodiversity, structure, and tilth continues in America and around the world due to previously unrecognized consequences of traditional soil and crop management practices (e.g., intensive tillage, excessive nutrient and pesticide applications, and over-consumption of fossil fuels). Reports on the state of our land suggest that soil (deposited off-site as sediment or dust), nutrients, and organic matter have been lost at rates far exceeding a sustainable level. The result is that traditional agricultural practices have had enormous direct and indirect consequences on productivity, profitability, and environmental quality throughout America (NRC, 1993; USDA-NRCS, 1996).

Recognizing that revitalization of the land requires social, scientific, and ethical considerations; a growing population of agriculturists across America have focused renewed attention on developing locally led, high-quality food production systems to achieve a global vision of environmental stewardship. Organic agricultural systems offer opportunities to substantially improve soil quality and agricultural sustainability. The diversity of organic agricultural systems in different ecoregions of America warrants a broad assessment of how organic management systems might affect soil quality.

Relatively limited research has been conducted on soil quality in organic agricultural systems. A more focused research effort is proposed to assess the magnitude and extent of change in soil quality that can be achieved with adoption of organic agricultural systems. This Critical Issue Report describes a scientific approach to cost-effectively monitor and compare soil quality between conventional and organic agricultural systems across a diversity of ecoregions in America. The proposed minimum-data-set approach for soil quality assessment should not be perceived as all-encompassing. It is simply an approach to highlight how soil quality in organic agricultural systems can be assessed using the current paradigm of soil testing sample submission, data evaluation, and management interpretation. The proposed minimum-data-set approach will serve as the foundation for a national survey of soil quality that *The Organic Center* plans to implement during the next two years.

> There is nothing in the whole of nature that is more important or deserves as much attention as the soil. Truly it is the soil that makes the world a friendly environment for humankind. It is the soil that nourishes and provides for the whole of nature; the whole of creation depends on the soil, which is the ultimate foundation of our existence.
>
> *—Friedrich Albert Fallon, German scientist, 1862*

What is Soil Quality?

People in cites may forget the soil for as long as a hundred years, but mother nature's memory is long and she will not let them forget indefinitely. The soil is the mother of man, and if we forget her, life eventually weakens.

—Henry A. Wallace, Secretary of Agriculture, 1936.

Scientific assessment of soil quality is essential to monitor the sustainability of agricultural systems. Soil quality is a complex subject, encompassing the many valuable services humans derive from soil and the many ways soils impact terrestrial ecosystems. Different definitions of soil quality have been proposed, each reflecting a different perspective on the use and value of soils:

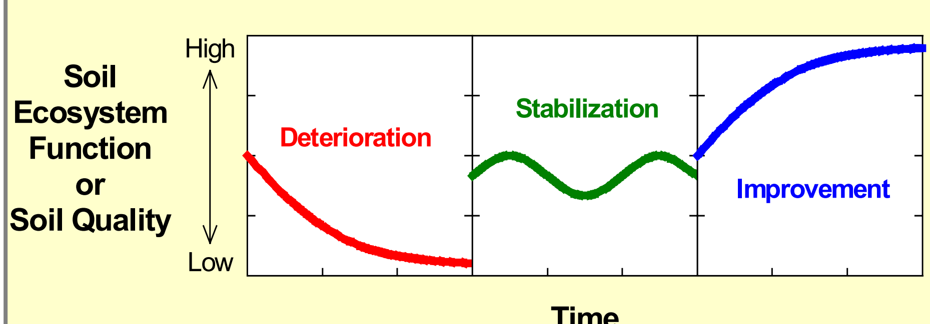
- the potential utility of soils in landscapes resulting from the natural combination of soil chemical, physical, and biological attributes (Johnson et al., 1992);
- the capability of soil to produce safe and nutritious crops in a sustained manner over the long-term, and to enhance human and animal health, without impairing the natural resource base or harming the environment (Parr et al., 1992);
- the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994);
- the capacity of soil to function (Karlen et al., 1997); and
- how well soil does what we want it to do (Schjønning et al., 2003).

Most definitions link soil quality to some defined use of soil. The use-dependent nature of soil quality definitions has created some debate among scientists about the concept of soil quality and raised provocative questions of how soil quality should be subjected to rigorous scientific investigation (Sojka and Upchurch, 1999). Notwithstanding, we see soil quality as a scientific tool for land managers that will help them adaptively manage soil resources for sustainable future use (Andrews and Moorman, 2002). Curiously, the impetus to define and assess soil quality has occurred primarily from outside the scientific community, because of societal concerns for the health of the environment (Carter, 2002). Since soil quality emphasizes maintenance or improvement in the natural resource base, it has become an integral component of sustainable agriculture (Miller and Wali, 1995; Warkentin, 1995).

Soil quality forms the basis for a sustainable agriculture.

Soil quality can be sensed...

- from the way soil feels, e.g. does it crumble into aggregates when broken in the hand or does it break into hard clods?
- from how soil smells, e.g. does it have an earthy aroma from the compounds (geosmin) produced by actinomycetes (soil bacteria), or does it smell of fermenting byproducts from a lack of oxygen?
- from how soil looks, e.g. does it have a dark color rich from organic matter and teaming with organisms or does it simply look like dirt?



Soil quality can

(1) **deteriorate** rapidly with poor management
(2) **stabilize** with time under adequate management, but undergo minor variations due to weather and crop conditions
(3) **improve** with time using best-available, adaptive techniques that restore key soil functions

How is Soil Quality Determined?

Soil quality can be determined from a variety of soil properties or processes (i.e., indicators), the selection of which may be partially dependent upon land use. Indicators of soil quality will reflect important soil functions (Magdoff and Weil, 2004), including:

- producing vigorous and healthy plants
- cycling and retaining globally important nutrients, e.g. (a) storing nitrogen in soil and releasing it to roots for efficient plant production and (b) storing carbon in soil and releasing it to the atmosphere in a dynamic balance that stabilizes atmospheric concentration of CO_2
- supplying plants with water, nutrients, and plant-growth promoting compounds
- protecting water quality (both ground water and surface water) from nutrient and pathogenic contamination
- providing physical stability and support for vegetation, buildings, and roads
- enabling animal habitat and serving as a reservoir for biodiversity (microscopic and visible)
- buffering against toxic accumulation and transport of natural and synthetic compounds
- filtering elements to protect animals, plants, and the environment from undesirable exposure

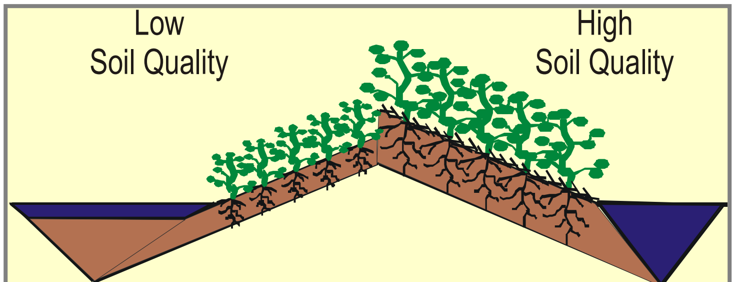
Soil quality assessments often use a small group of indicators (i.e., a minimum data set) to economically and efficiently characterize selected key soil functions. Land managers and scientists do not have unlimited time and resources to study all of the potential functions served by soil in a region, nor can they predict future needs or demands on soil resources.

A minimum data set for soil quality assessment is designed to establish a reliable estimate of the capacity of soil to perform a defined set of functions and to assess changes in soil quality over time. A well-designed minimum data set should allow us to monitor changes in soil functions brought about as a result of a particular cropping pattern, tillage system, and overall management. Specifically, a minimum data set is proposed that should reliably detect changes in soil quality as farmland shifts from conventional to organic production.

Because of the competing uses and inherent limitations for soils, the components of a minimum data set cannot be considered universal. Of vital importance to the selection of soil quality indicators that reflect key soil functions is the definition of primary management goals (Andrews et al., 2004).

In organic agriculture, management goals will often focus on

- productivity
- creating a biologically active soil food web
- avoidance of synthetic inputs
- providing a healthy food supply
- environmental protection



Low	Productivity	High
?	Healthy Food Supply	Yes
Low	Environmental Protection	High
Low	Land Stewardship	High
Low	Soil Organic Matter	High
High	Erosion / Sedimentation	Low
Low	Soil Microbial Activity	High
Low	Biological Diversity	High
Poor	Water Quality	Clean
Poor	Air Quality	Clean
?	Human Condition	Healthy

Soil quality relates directly to the functions performed by soil

High-quality soil is able to produce abundant plant materials, which feed, clothe, and provide shelter to humans. Plant residues not consumed must be returned to the soil to feed soil organisms and provide the organic nutrients for creating a biologically active food web. High-quality soil protects the environment from degradation, by reducing soil erosion and nutrient runoff (i.e. water quality protection) and by storing carbon in soil and reducing greenhouse gas emissions.

Low-quality soil lacks sufficient organic matter to sustain productivity in the long term, leads to excessive soil erosion and poor water quality, has low soil biological activity and diversity, and could lead to an unhealthy food supply and human condition.

Soil quality assessment distinguishes between static and dynamic soil properties.

Static soil properties reflect the inherent characteristics of a particular site, e.g. soil texture, mineralogy, and classification, all of which are influenced by geologic history and climatic conditions. In addition, topography, hydrology, and climate are factors that affect productivity and environmental quality of a site, somewhat independent of management. Static soil properties have been adequately characterized in North America with regional sampling approaches by the USDA's Natural Resources Conservation Service through the periodic National Resources Inventory (Brejda et al., 2000). Similar efforts have been conducted by Agriculture and Agri-Food Canada (MacDonald et al., 1995). Static soil properties provide the contextual background for how soil management practices might eventually alter dynamic soil properties.

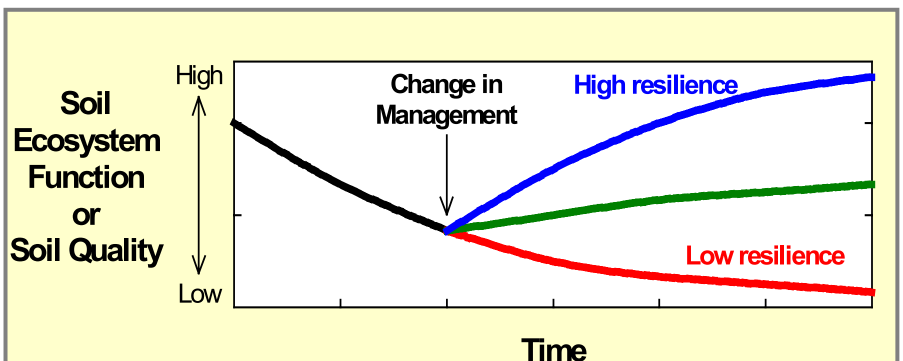
Dynamic soil properties are those properties that can change value over relatively short time periods (e.g., months, years, and decades). Dynamic soil properties are at the leading edge of soil quality assessment, because they change quickly, and oftentimes dramatically, in response to management. Dynamic soil properties can indicate whether a farm uses agronomically and ecologically sustainable practices.

Changes in soil properties with time are a key component of dynamic soil quality assessment. Sustainable cropping systems that improve soil quality indicators with time will lead to incrementally higher soil quality. Practices and strategies proven to enhance soil quality across a broad range of ecosystems include diverse crop rotations, minimal use of tillage for weed control and seedbed preparation, and addition of organic amendments like animal manures, crop residues, and compost. Management systems that cause a decline in soil quality indicators with time will lead to lower soil quality; often induced by cropping systems with low residue production, intensive tillage, and near monoculture cultivation.

Two concepts are helpful in assessing change in soil quality – the resistance of soils to degradation, and the - resiliency of soils to bounce back after a period of declining soil quality.

A soil sample rich in organic matter due to improved grassland management, despite having coarse texture and collected from the warm, humid region of the southeastern USA. Texture and climate broadly control soil organic matter content, but improved management can overcome these limitations.

Resistance of soil to degradation can be assessed by determining the extent of change in dynamic soil quality indicators, such as during a period of intensive tillage. Low resistance of a soil property to disturbance might induce a permanent and damaging change in soil functional capabilities. High resistance to disturbance is a positive attribute, reflected in strong functional capabilities that are supported by a range of management approaches. Resilience of soil is another desirable soil characteristic that can be assessed by determining how fast a dynamic soil quality indicator rebounds from a period of poor management.



How management affects soil functional capabilities creates the boundaries of soil quality assessment. Farmers making improvements to their operations will find that organic matter inputs, soil disturbance activities, and types and combinations of row cropping and sod-based management scenarios will have some of the largest effects on how soil functions.

Farmers will also find that some soils are resilient to poor management and others are not. Those soils that respond quickly to improved management practices (i.e. high resilience) will function in a sustainable manner relatively quickly and should be targeted for immediate restoration by farmers wanting to transition from conventional to organic agricultural systems. Those soils that do not respond quickly to moderate changes in management approach (i.e. low resilience) may need more intensive management inputs for an extended period of time to restore their functional capabilities within the landscape.

Soil Quality Indicators

Soil quality indicators are often divided into three main classes:

- soil chemical properties or processes
- soil physical properties or processes
- soil biological properties or processes

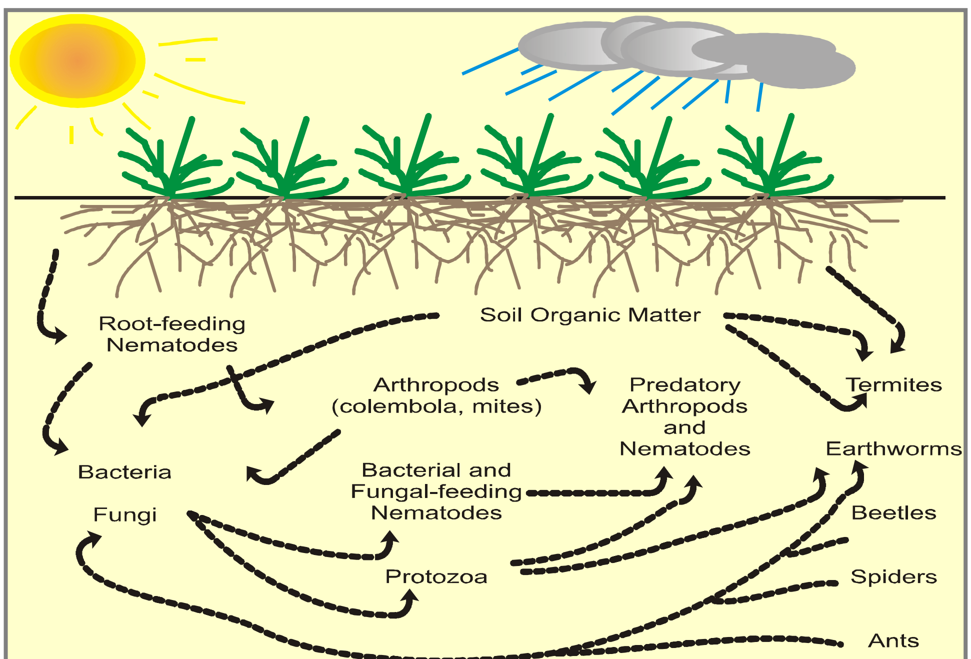
Within each of these classes, a variety of soil properties or processes can be selected to indicate soil functional capabilities.

Currently, most commercial soil testing laboratories offer a variety of soil tests to determine soil physical and chemical properties, but few have tests for rapid and reliable determination of soil biological activity and condition. In organic agriculture especially, soil biological properties and processes are of great importance, since the majority of nutrients are derived from microbial decomposition of various fractions of organic matter, instead of from fertilizers bought off the farm, as the case on most conventional farms. The structure and function of highly active soil microbial communities may also impart plant protection mechanisms to ward off diseases and create less stressful conditions for plant growth.

A minimum dataset for assessing soil quality should have the following characteristics (Doran and Parkin, 1994; Soil Quality Institute, 2006):

- easy to measure
- detect changes in soil function
- integrate soil physical, chemical, and biological properties and processes
- accessible to many users and applicable to field conditions
- sensitive to variations in management and climate
- encompass ecosystem processes and relate to process-oriented modeling
- where possible, be components of existing soil data bases

A few comparative studies have been conducted to look at soil quality under conventional and organic agricultural systems. At the Rodale Institute in Pennsylvania, organically managed soil had greater soil organic carbon and total nitrogen and lower nitrate leaching loss than conventionally managed soil (Drinkwater et al., 1998), as well as greater biological soil quality (Yakovchenko et al., 1996). At the end of 4 years of management of an apple orchard in Washington, soil bulk density, water-filled pore space, and nitrate-N were lower under organic than conventional management, while soil microbial biomass carbon was greater under organic than conventional management (Glover et al., 2000). All other soil properties measured were not different between conventional and organic management (i.e., aggregate stability, total nitrogen, extractable phosphorus, cation exchange capacity, pH, electrical conductivity, microbial biomass nitrogen, organic carbon, and earthworm population). At the end of 40-47 years of dairy farm management in Denmark, organically managed soil had greater



A strong, functioning soil food web will allow a plethora of soil organisms to decompose, incorporate, and redistribute carbon and other nutrients within the soil profile. Soil organic matter and plant roots and residues are the sources of carbon for a cascade of feeding activity by soil fauna and microorganisms. A biologically active soil food web is essential to the success of all organic agricultural systems.

fragment size, aggregate stability in water, and microbial biomass carbon than conventionally managed soil (Schjønning et al., 2002). Several other physical and biological properties were not different between management systems, but ergosterol, an indicator of soil fungi, was lower in abundance under organic than conventional management systems for some unknown reason. At the end of 21 years of crop rotation management in Switzerland, soil organic carbon and total nitrogen were greater under biodynamic management than conventional management, but organic management and integrated management (combination of manures, inorganic fertilizers, and herbicides) were intermediate (Flieβbach et al., 2006). Soil microbial biomass carbon and dehydrogenase activity were greater under organic than under conventional management, but basal soil respiration was not different between systems. Among 5 paired farms in North Dakota and Nebraska, total and microbial carbon and nitrogen, and mineralizable carbon and nitrogen were greater under organic than under conventional management (Liebig and Doran, 1999). The authors stated that the capacity of organic production practices to improve soil quality was mainly due to use of more diverse crop sequences, application of organic amendments, and less frequent tillage.

The aforementioned comparative studies had consistently greater soil microbial biomass carbon under organic than under conventional management. Depending upon the suite of soil properties measured, various other soil microbial activity assays (dehydrogenase activity, mineralizable carbon, and mineralizable nitrogen) were also greater under organic than conventional management. Total organic carbon and nitrogen were sometimes greater under organic management, but not always. Various soil physical properties, when measured, were often greater under organic than under conventional management, but this effect was not consistent. From the relatively few studies available, we conclude that total and biologically active fractions of soil organic matter will be important response variables characteristic of organic management systems. In addition, there is a great need to quantitatively assess the difference between conventional and organic agricultural systems across a wide range of ecological conditions using a consistent suite of soil biological, physical, and chemical indicators. Inherent conditions within a particular ecoregion may be strikingly different, resulting in significant variation in how soil responds to organic management.

Key Soil Terms

Soil organic carbon – The amount of organic material in soil, usually determined by the difference between total carbon (determined by dry combustion or wet chemistry) and inorganic carbon (determined by acid dissolution). Carbon atoms in an organic compound that are linked to other carbon atoms by covalent bond.

Soil organic nitrogen – Nitrogen that is bound to carbon-containing compounds.

Soil organic matter – The organic fraction of soil; includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

Soil tilth – The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration.

Soil aggregation – The process whereby primary soil particles (sand, silt, clay) are bonded together to form aggregates, usually by natural forces and substances derived from root exudates and microbial activity.

Soil aggregate stability – The ability of soil aggregates to resist rearrangement and breakdown into primary particles by various disruptive forces, especially the effects of water. The stability of aggregates to disruptive processes is related to soil particle size distribution, type of clay mineral, specific ions associated with the clay fraction of soil, the kind and amount of organic matter present, and nature of the microbial population.

Soil microbial biomass – The total mass of living microorganisms in a given volume or mass of soil.

Soil microbial community structure – The taxonomical and/or physical arrangement of microorganisms in soil.

Soil humus – All the dead organic material on and in the soil that undergoes continuous breakdown, change, and synthesis. The fraction of soil organic matter that remains after removal of macroorganic matter and dissolved organic matter. It is usually dark colored.

Soil function – The various roles that soil performs, or the tasks that are placed upon soil, underpinning the concept of soil quality. Soil functions in three main ways: as a medium for plant growth, a regulator or partitioner of water and energy, and an environmental buffer or filter.

Soil quality – The value placed on a soil with respect to its fitness for a specific use; categorization of the fitness of a soil for a certain use based on ecological aspects, such as soil functions, that involve evaluating the capacity of a soil to function within specific ecosystem boundaries.

Soil health – An approach to soil condition analogous to human or community health, by which the condition of a soil's properties and morphology are assessed against some optimum condition (i.e., soil as an organism), or a soil's functions assessed against the goals placed upon them (i.e., soil as a community), or against an optimum functional state. Often soil health is used synonymously with soil quality, except that a soil may have poor inherent soil quality but still have good health.

Potential soil quality indicators are listed in Appendix 1. For many soil properties and processes, there are several approaches that can be used by soil scientists and testing laboratories. Several specialized tests have been developed, or adapted for application in unique circumstances. All of these methods can produce valid information when properly applied, but none are perfect for all applications. The challenge in selecting and applying a minimum data set for soil quality assessment is to gain the most in-depth and reliable quantitative measure of soil quality with the minimum number of indicators. In addition, indicators should be selected mindful of the time and expense required for accurate and reliable determination.

We propose a selection of the indicators listed in Appendix 1. Measurement of these indicators with time will produce a minimum data set that can be used to quantitatively assess the changes in soil quality:

- prior to the adoption of organic agriculture
- during the transition to organic farming practices
- following successful implementation of organic farming for an extended period of time

The proposed minimum data set combines the need to describe critical soil functions with the need for indicators that are relatively simple, rapid, and reliable. *The proposed minimum data set is based solely on laboratory techniques from soil samples collected from the field.* In-field measurements of plant productivity (indicated by crop yield and total plant biomass), rooting conditions (indicated by rooting depth, soil compaction, or water infiltration), environmental threats (indicated by nitrous oxide emission, nutrient and sediment runoff, or airborne particulate matter), and soil biodiversity (indicated by earthworms, nematodes, and soil microarthropods) should also be considered for a more thorough evaluation of how management systems might be affecting soil quality at a particular site.

The minimum data set for soil quality assessment in organic agriculture builds upon previous knowledge of soil quality assessment in more traditional and conventional agricultural systems. However, soil quality assessment in organic agricultural systems relies more heavily on soil biological indicators, because of the inherent reliance on microbial processes that control organic matter decomposition for efficient nutrient cycling and biological-environmental interactions that suppress diseases and promote plant health.

The proposed minimum data set for soil quality assessment in organic agriculture includes:

Soil organic carbon and total nitrogen – reflecting the functional capability of soil to supply nutrients to plants, serve as an organic nutrient reserve, mitigate greenhouse gas accumulation, and provide organic resources for stabilizing the soil surface against erosion, for filtering of water, for buffering against nutrient extremes, and for promoting a biologically diverse and healthy microbial population. Soil organic matter can be related to most other indicators of soil quality, but by itself does not adequately reflect the breadth of ecological processes occurring in soil. Soil organic matter is a key component of productivity, avoidance of synthetic inputs, healthy food supply, and environmental protection goals.

Water-stable aggregation and stability – reflecting the functional capability of soil to provide physical stability and resistance against water erosion. Soil aggregate stability reduces runoff of sediments and pathogens, as well as nutrients and pesticides bound to soil particles. Soil aggregation is an important component in all conservation systems designed to protect water quality.

Flush of CO_2 following rewetting of dried soil – reflecting the functional capability of soil to cycle nutrients, decompose organic amendments, and catalyze and stabilize ecosystem processes through the interactions among a diversity of organisms. The flush of CO_2 following rewetting of dried soil is highly related to soil microbial biomass, potential microbial activity, and potentially mineralizable nitrogen. The flush of CO_2 following rewetting of dried soil is an important component of soil productivity, limiting reliance on synthetic inputs, progress toward safer and more nutritious food, and achieving environmental protection goals.

Microbial substrate utilization – reflecting the functional capability of soil to provide biodiversity and habitat, cycle nutrients, decompose organic amendments, filter water passing through soil, and provide biological resilience to soil disturbance. Microbial substrate utilization is a measure of the functional diversity of soil microbial communities, deserving closer attention in both conventional and organic farm management systems.

Inorganic nitrogen, extractable phosphorus, and soil pH – reflecting the functional capability of soil to supply readily available nutrients. Inorganic nutrients are important for meeting the goal of crop productivity, but excessive accumulation can be a threat to a healthy food supply and environmental protection. Inorganic nutrients are some of the most commonly determined soil properties in the world and a large database exists for comparison.

Outlook

The proposed minimum data set will be used to develop a widespread, scientifically defendable database to identify and support agricultural management practices that contribute to high soil quality and sustainable land management. A similar approach was recently undertaken to evaluate soil quality under alternative compared with conventional management systems in the Great Plains region of the USA (e.g., conservation tillage rather than inversion tillage, intensive cropping sequences rather than bare fallow rotations, and sod-based rotations rather than continuous row-cropping) (Varvel et al., 2006). Sensitive soil indicators to management included total organic carbon, microbial biomass carbon, and aggregate stability (Wienhold et al., 2006). We propose to use these and additional indicators in our minimum data set.

Our proposed soil quality assessment with a minimum-data-set approach should reveal clues as to how and when soil quality is affected when land is converted from conventional to organic agriculture, as well as why soil quality changes, if evaluated on farms in different ecoregions and with different management strategies. Evaluated across a variety of soils throughout America, we will be able to estimate the potential agronomic, water quality, and global warming benefits of conversion to organic agriculture.

A detailed protocol for collecting soil samples and for their analysis can be found in Appendix 2.

Reasons for selecting the relatively few number of soil tests were cost of analysis (total cost of $\leq$\$100/sample), time required to complete analyses, minimizing overlapping information obtained, and relevance to important soil functions.

The development of quantitative relationships among soil quality, environmental protection, and human health will provide farmers, consumers, and policy analysts critical new information to make decisions about the relative merits of different food-production systems and technologies. Ultimately this information, and new insights derived from it, will empower society to promote and reward progress toward more sustainable and healthy food and fiber production systems.

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Earthworm casts are visible evidence of soil biological activity

Appendix 1. *List of commonly used soil quality indicators*

Indicator	Measurement Method	Applications, Strengths, and Weaknesses	References
Soil physical properties and processes			
Aggregate stability	Exposure to energy and sieving	Indicates resistance to erosion; relatively minor equipment needed; values depend on water content at time of sampling	Arshad et al. (1996)
Aggregate distribution	Dry or wet sieving	Indicates soil structure and resistance to erosion; relatively minor equipment needed; varies moderately with management	Arshad et al. (1996)
Texture	Hydrometer; feel	Indicates water-holding capacity and susceptibility to erosion; relatively minor equipment needed; time consuming; varies little with management	Arshad et al. (1996)
Depth available for rooting (topsoil depth)	Excavation; coring	Indicates compaction and previous soil erosion; labor intensive; spatially variable	Arshad et al. (1996)
Bulk density	Coring; drying	Indicates compaction and porosity; simple; needed to convert most soil properties to volumetric basis	Arshad et al. (1996)
Penetration resistance	Pocket penetrometer	Simple; spatially variable; dependent upon soil water content; related to compaction	Arshad et al. (1996)
Water retention	Water content between field capacity and wilting	Indicates compaction and soil structure; specialized equipment needed; time consuming; varies little with management	Klute (1986)
Water content	Volumetric; drying	Indicates water availability; highly variable during season; controls biological processes	Lowery et al. (1996)
Total porosity	Volumetric; drying	Indicates compaction and balance of air and water in soil; simple; controls biological processes	Lowery et al. (1996)
Air-filled porosity	Volumetric; drying	Indicates potential for anaerobic conditions and compaction; simple; controls biological processes	Lowery et al. (1996)
Temperature	Hand probe	Indicates heat transmission; simple; variable with depth, time of day, and season; controls biological processes	
Hydraulic conductivity	Permeameter	Indicates potential for water movement in soil; relatively minor equipment needed; time consuming; spatially variable; varies moderately with management	Lowery et al. (1996)
Mineralogy	X-ray diffraction	Indicates inherent physical and chemical properties; specialized equipment; does not vary with management	Dixon and Weed (1989)
Water infiltration	Single ring in field	Indicates water movement into soil and potential for soil erosion; simple; spatially variable; depends upon soil water content at time of sampling; field measurement	Lowery et al. (1996)
Water-holding capacity	Wetting of soil in lab or field	Indicates water storage in soil and compaction; simple; variable with depth; varies moderately with management	Lowery et al. (1996)
Soil chemical properties and processes			
Total organic carbon	Wet or dry combustion; color; reflectance	Indicates nutrient reserve and potential nutrient cycling; determined by soil testing facility with specialized equipment; variable with depth; controls many physical, chemical, and microbial processes	Sikora and Stott (1996)
Total nitrogen	Wet or dry combustion	Indicates nitrogen reserve and potential nutrient cycling; determined by soil testing facility with specialized equipment; variable with depth	Sikora and Stott (1996)
pH	pH meter	Indicates potential for macro- and micro-nutrient availability; relatively simple equipment; controls nutrient availability and microbial processes	Smith and Doran (1996)
Inorganic nitrogen	KCl extraction	Indicates available nitrogen for plant growth; determined by soil testing facility with specialized equipment; spatially variable; when excessive, contributes to poor water quality	Allan and Killorn (1996)

Indicator	Measurement Method	Applications, Strengths, and Weaknesses	References
Inorganic phosphorus	Acid or bicarbonate extraction	Indicates available phosphorus for plant growth; determined by soil testing facility with specialized equipment; variable with depth; when excessive, contributes to poor water quality	Allan and Killorn (1996)
Available potassium	Acid or ammonium acetate extraction	Indicates available potassium for vigorous plant growth; determined by soil testing facility with specialized equipment	Allan and Killorn (1996)
Electrical conductivity	Conductivity meter	Indicates soluble salt accumulation; simple equipment; when excessive, limits chemical and microbial processes	Smith and Doran (1996)
Cation exchange capacity	Ammonium acetate extraction	Indicates potential supply of cationic nutrients; determined by soil testing facility with specialized equipment	Sumner and Miller (1996)
Organic chemical contaminants	Extraction; chromatography; bioassay	Indicates soil pollution; highly specialized equipment needed; determined only if pollution expected	Moorman (1996)
Soil biological properties and processes			
Microbial biomass carbon	Chloroform fumigation-incubation	Indicates soil microbial population; various methodologies; controls nutrient cycling and biological transformation necessary for soil aggregation; dependent upon organic inputs	Rice et al. (1996)
Microbial biomass nitrogen	Chloroform fumigation-extraction	Indicates biologically active fraction of soil nitrogen; various methodologies; controls nutrient cycling; dependent upon organic inputs	Rice et al. (1996)
Potentially mineralizable nitrogen	Aerobic incubation for >2 weeks; 1-week anaerobic incubation	Indicates nitrogen cycling potential; determined by soil testing facility with specialized equipment following incubation in a nonstandard laboratory; relatively time consuming; dependent upon high quality organic nutrients	Drinkwater et al. (1996)
Soil respiration (flush of CO_2)	Field chamber; Aerobic incubation for >1 week in lab	Indicates soil microbial activity; relatively simple equipment conducted in a nonstandard laboratory; can be determined in field or in laboratory; relatively time consuming; dependent upon organic inputs	Parkin et al. (1996)
Ratio of microbial biomass to total organic carbon	Calculation from individual measures	Indicates enrichment of microbial biomass relative to total organic carbon; determined in nonstandard laboratory with specialized equipment;	Rice et al. (1996)
Respiratory quotient (qCO_2)	Calculation from soil respiration divided microbial biomass carbon	Indicates activity of microbial biomass; determined in nonstandard laboratory with specialized equipment; when high, considered an indication of stress on microbial biomass	Rice et al. (1996)
Enzyme activity (urease, amidase, dehydrogenase, β-glucosidase, phospatase, arylsulfatase, fluorescein diacetate hydrolysis)	Laboratory incubation	Indicates potential microbial activity and nutrient cycling reactions; determined in nonstandard laboratory with specialized equipment; highly spatially and temporally variable; dependent upon organic inputs	Dick et al. (1996)
Phospholipid fatty acid (PLFA)	Methanol-KOH extraction	Indicates bacterial population structure; time consuming; determined in nonstandard laboratory with specialized equipment; expensive equipment	Dick et al. (1996)
DNA	Extraction and quantification	Indicates total biological structure; time consuming; expensive equipment; determined in nonstandard laboratory with specialized equipment; difficult for complete extraction	Sadowsky (1994)
Carbon substrate utilization (BIOLOG)	Incubation of soil with substrates; color development	Indicates functional microbial diversity; determined in nonstandard laboratory with specialized equipment; produces large quantities of data; complex interpretation	Dick et al. (1996)
Nematode population	Various extraction techniques	Indicates soil food web functioning, species richness, and abundance; spatially variable; time consuming	Blair et al. (1996)
Earthworm population	Handsorting; expulsion	Indicates soil food web functioning; spatially and seasonally variable; time consuming	Blair et al. (1996)
Pathogen risk assessment	Soil inoculum; bioassay	Indicates potential disease abundance; determined in nonstandard laboratory with specialized equipment; host specific; time consuming	Van Bruggen and Grünwald (1996)

Appendix 2. Protocol for soil sampling and laboratory analyses.

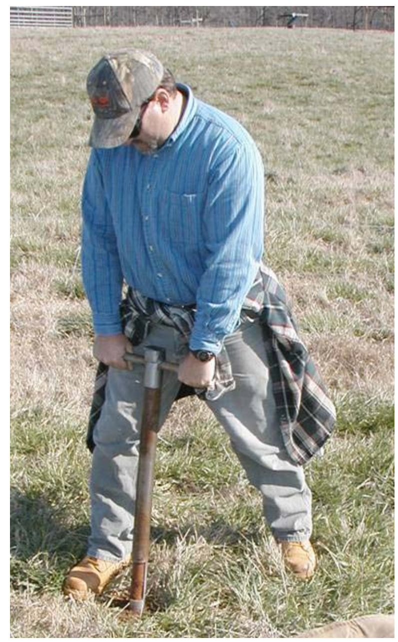
Question

Can a difference in soil quality be detected between two approaches to agricultural management (e.g., between conventional and organic agriculture)? Many other similar questions will arise in assessing different management systems.

Selection of Fields

Paired farms using conventional and organic agricultural practices should be selected with similar environmental characteristics (i.e., agro-climatic region, hydrologic unit, landscape position, soil type, etc.). Depending upon the scope of inference, replicate farms or fields should be selected to avoid bias due to limited sampling.

Soil Sampling



Within an experimental unit (crop, field, or farm), soil should be sampled to a depth of 0-2" (0-5 cm), 2-6" (5-15 cm), and 6-12" (15-30 cm), if possible. The experimental unit should be representatively sampled by compositing 20 cores (1"; 2.5-cm diameter) from across the field. With quantitative extraction of soil from the known volume of cores, an estimate of bulk density (compaction) could be obtained. Sampling time should be either in springtime, whenever soil is not too wet and not too dry, or in autumn prior to subsequent tillage operations. Soil cores should be divided into the three depth increments and placed into separate sampling bags (1-gallon zip locks) that are marked with the location, date, and type of management. Samples should be kept in a refrigerator until ready for shipment to the designated receiving laboratory. Samples should be shipped as soon as possible after sampling.

Laboratory Analyses

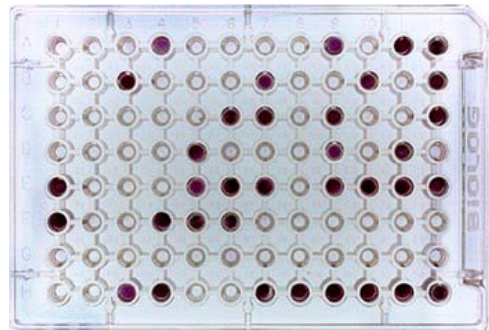
Samples will receive documentation at the receiving laboratory to create metadata describing the environmental, field, long-term history, and recent management conditions. Geographic coordinates (degrees and minutes) should be supplied. Samples will be split into (a) field-moist and (b) dried (50 °C) subsamples and divided further for shipment to cooperating laboratories. Samples will be ground to pass a 4.75-mm screen prior to analyses.

Soil organic C and total N will be determined from a dried sample that will be further ground into a fine powder prior to analysis with dry combustion (Franzluebbers et al., 2000a).

Water-stable aggregation and stability will be determined from a 100-g dried sample placed on a nest of sieves (Franzluebbers et al., 2000b). The top-most sieve will have openings of 1.0 mm and other sieves will have openings of 0.25-mm and 0.053-mm. The nest of sieves will be oscillated in water for 10 minutes at a stroke length of 2 cm and a stroke cycle of 31 cycles min^{-1}. At the end of 10 minutes, sieves will be placed in an oven (50 °C, 24 hours) to determine the amount of soil retained on each sieve. The mean-weight diameter of water-stable aggregates will be computed by summing the products of aggregate fraction weight and mean diameter of aggregate classes. Stability of aggregates will be calculated from the ratio of water-stable aggregates to dry-stable aggregates. Dry-stable aggregates will be determined following a similar procedure, except not immersed in water.

The flush of CO_2 following rewetting of dried soil will be determined from a 20-65 g dried sample (weight dependent upon expected soil organic C) placed in 50-mL containers, wetted to 50% water-filled pore space, and incubated at 25 ± 1 °C for 3 days (Franzluebbers et al., 2000a). The container of soil will be placed in a 1-L canning jar along with a vial of 1.0 *M* NaOH to absorb CO_2 and a vial of water to maintain humidity. The amount of CO_2 evolved will be determined by titration of the NaOH with 1.0 *M* HCl in the presence of excess $BaCl_2$ to a phenolphthalein endpoint.

Microbial substrate utilization will be determined from a multi-well incubation assay using commercially available Biolog GN plates (Buyer et al., 1999). Soil will be diluted in sterile saline solution and dispensed into each of the 95 different wells containing different carbon sources (e.g., polymers, carbohydrates, carboxylic acids, amines and amides, amino acids, and miscellaneous sources). Plates will be incubated at 22 °C for 3 days and positive reaction determined by colorimetric detection.



Inorganic nitrogen, extractable phosphorus, and soil pH will be determined using standardized protocols conducted at most commercial soil testing facilities. Inorganic NH_4-N + NO_3-N will be determined from KCl extraction and colorimetric detection following salicylate-nitroprusside and Cd-reduction reactions, respectively, on an automated, segmented-flow analyzer. Extractable PO_4-P will be determined from a dilute acid extract and colorimetric detection following molybdate reaction on an automated, segmented-flow analyzer. Soil pH will be determined from a 1:2 soil:water slurry using a glass electrode.

Photo by Scott Bauer, USDA-ARS

Photo by Bruce Fitz, USDA-ARS

Photo by Bob Nichols, USDA-ARS

If possible, plant production characteristics should be sampled yearly at as many sites as possible to make direct comparisons with soil quality measures. In addition, water quality analyses, greenhouse gas emissions, and economic estimates would enhance the value of management comparisons.

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