# ASSESSING THE SOIL SYSTEM

## A SOIL QUALITY LITERATURE REVIEW

ENERGY AND SUSTAINABLE AGRICULTURE PROGRAM
MINNESOTA DEPARTMENT OF AGRICULTURE

**Minnesota Department of Agriculture**
**Energy and Sustainable Agriculture Program**

# ASSESSING THE SOIL SYSTEM

## A REVIEW OF SOIL QUALITY LITERATURE

by Ann Lewandowski
with Mark Zumwinkle
edited by Alison Fish

**PURPOSE**
This publication is an introduction for non-soil scientists to the issues and terminology found in soil quality research. For the reader who wants to learn more, the "Suggested Topic Reading" section provides suggestions for entry points into the literature.

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MDA Website: www.mda.state.mn.us
For additional copies of this publication please write to:
Minnesota Department of Agriculture
Energy and Sustainable Agriculture Program
90 West Plato Boulevard
St. Paul, MN 55107
Phone: 651-296-7673
Fax: 651-297-7678
E-mail: Mark.Zumwinkle@state.mn.us

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### *How to use this review:*

*Soil quality is about interactions among soil processes and between soil management processes.*

*Scanning this document to get a broad picture may be beneficial before focusing on individual pieces.*

*We suggest looking at the following several tables that integrate large amounts of information:*

*Figure 1.1 on page 10*

*Table 3.1 on page 15*

*Table 3.5 on page 18*

*Table 4.1 on page 33*

*Table 4.2 on page 35*

*An extensive glossary of soil quality terminology is provided at the end of this review on page 48.*

# SUMMARY

## Defining Soil Quality

Soil quality is "the capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Parkin, 1994).

*The concepts of soil quality and health imply an assessment of how well soil performs the following multiple functions:*

- a medium for plant growth
- a regulator of water flow in the environment
- an environmental filter
- maintenance of human and animal health
- as part of the global storage and cycling of nutrients (Larson and Pierce (1991), Papendick, and Karlen et al. (1996), Lal et al.)

## What is in the Literature?

The soil quality discussion that has developed since the late 1980's has raised important issues about soil assessment and management. At the same time, it is often frustrating due to the lack of direct testing of the proposed concepts.

The current discussion of soil quality is distinguished from previous soil assessment efforts by its attention to the dynamic soil characteristics that are affected by management choices. It is distinguished by focusing not just on characteristics such as nitrogen, phosphorous, potassium, and total organic matter levels, but also focuses on overall soil biological activity, organic matter fractions, water infiltration, and structural aggregation. In addition to crop production, the current soil quality discussion has considered soil functions such as management of water flow and the filtering and buffering of environmentally active substances. This discussion does not define soil quality only by the absence of degradation such as erosion, but by its fitness or ability to perform desired functions.

The characteristics that define a high quality soil depend on the inherent features of the soil, landscape, climate, and land use. But there are some general features that most authors imply are necessary for a soil to be described as healthy or of high quality. Quality soil is thought to be:

- high in organic matter and biological activity,
- friable with stable aggregates,
- easily penetrated by plant roots,

- easily infiltrated by water rather than running over the surface, and
- low in weed and disease pressure.

Quality soil will produce healthy crops over the long-term without increasing levels of inputs. It will control water flow and will filter and degrade potential environmental contaminants. Healthy soil is buffered against wide swings in temperature, moisture and other environmental conditions. This buffering capacity will be reflected in low levels of pest outbreaks and relatively stable production levels.

Generally, the literature implies that quality soil is achieved by:

- supplying generous amounts of organic matter,
- avoiding excessive tillage and traffic,
- keeping soil covered with residue or living plants, and
- increasing ecological diversity through the use of crop rotations, mixed cropping, and vegetative buffer zones.

The intent behind much soil quality research is to give soil the same research and policy attention that has been given to water and air quality. Soil is a dynamic, and interacting component of our ecosystem, not just an inert medium to hold roots and nutrients for plants. Unlike the fluids air and water, soil mixes little and varies greatly and abruptly from place to place.

The resurfacing of the soil quality discussion in recent years has helped to refine the meaning of the term. However, the lack of success in quantifying soil quality through minimum data sets and indexes has only served to highlight the local and long-term nature of trends in soil health. Monitoring farm system performance may prove to be more fruitful than attempts to develop regional soil quality guidelines.

Preserving and improving soil quality is about sustainability. It is about maintaining the long-term function of our soils.

Understanding and building soil quality requires a holistic and complex view. This requires the involvement of farmers in research. Rather than recommendations for specific, isolated practices or soil characteristics, farmers need access to options and information that help them modify (or build) new systems that fit their unique situation.

***Using the soil quality literature***

Much work has been done to identify indicators of soil quality. More work is needed to understand how these indicators link to management practices and to soil performance, so they can be used to improve the quality of Minnesota soils.

The first rule in interpreting the measurements of soil quality is to recognize the complexity of the soil system. This means that no single

*Preserving and improving soil quality is about sustainability. It is about maintaining the long-term function of our soils.*

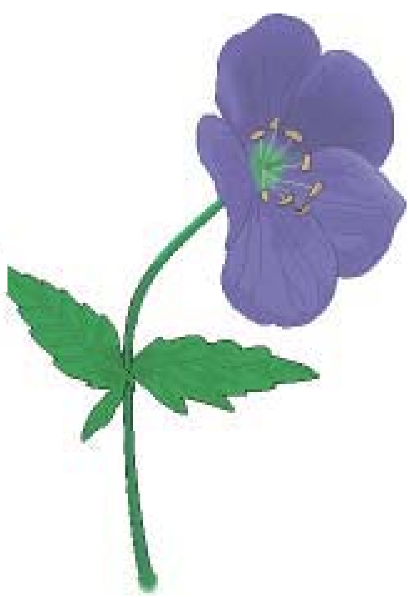
characteristic of soil tells its story. Understanding the quality of soil requires several kinds of observations, at several places, at several points in time. Which particular observations, places, and times depends on the type of soil.

The second rule in interpreting soil observations is to recognize the scale of the measurement, the scale of the process related to that soil characteristic, and the scale at which solutions should be attempted. For example, a regional monitoring program needs to track long-term trends in overall soil function, while a farmer needs guidance for this season's production decisions. The kind of measurements that give a picture of the region's soil resources, do not necessarily inform local management.

### Systems Research

Systems research compares whole systems, often using several approaches, so the effect of unanticipated or poorly understood interactions can be observed. This is in contrast to reductionistic research which aims to minimize the effect of all but one or a very few variables to determine cause and effect.

With tightly controlled plot or laboratory experiments, the effects of single changes in management practices can be observed. Specific management practices are rarely adopted alone, so highly controlled experiments are most useful if the results are interpreted alongside systems research which may show whether the results are meaningful in real farm situations.



Systems research is often done as "across-the-fence" studies. Soil characteristics and soil function are compared on neighboring farms that share the same landscape but use different management systems. If only one pair of farms is used, this is not true replication, regardless of the number of samples taken on each farm. Comparative research such as this is valuable in identifying significant indicators, but it is of limited use in identifying the processes and components of the system that are causing the difference in soil characteristic. For this reason, systems research is best interpreted alongside reductionistic research.

The National Research Council committee (1993, p. 110) describes how a systems approach:

- has the flexibility to address varied enterprises and changing resource or market conditions,
- allows targeting of programs to problem areas, and
- makes it possible to coordinate multiple government programs that have sometimes conflicting objectives. (Chapter Three of the above reference provides an explicit explanation of what it means to apply a systems approach at different scales.)

One component of systems thinking is to study soils at the landscape scale. Point measurements can then be placed into a context of where soil types change, how water moves, or where management practices change. It is necessary to view soil processes at this broader scale to analyze and understand how to use off-field techniques such as buffer strips.

Policy aimed at improving soil quality should not only focus on setting soil quality standards. Improving soil quality is a site-specific process. Land management will be most improved if it is guided by farmers working with local advisors that are trusted and knowledgeable about the character of the local area.

The site-specific nature of soil quality is troubling to agricultural support institutions that are designed to handle generalizable recommendations. Managing the state's soil resources requires tools and institutions that help farmers interpret the signals on their land, and apply general conclusions to specific situations. This means involving more farmers with research, so they can learn to interpret research, design informal studies for their own purposes, and help direct the goals of formal researchers. There may need to be less emphasis on writing formulas for soil management, and more emphasis on giving farmers the information they need to make judgment calls when applying formulas.

Managing for soil quality means constantly changing, adapting, and responding to conditions. Process and monitoring are as important as specific practices and standards.

## Future Directions

In summary, here are several directions that researchers, policy makers, and administrators could work towards to promote the quality of Minnesota soils.

### *Recognize more soil components*

Soil is not simply mineral matter through which water flows and roots grow. Soil *is* minerals, microbes, root exudates, water movement, living, non-living, and dynamic processes. Promoting soil quality means broadening the study of interactions among soil components.

- Study rooting dynamics in response to manure and other practices.
- Examine the water use efficiency of different systems.
- Provide easier access to soil tests beyond NPK and total organic matter.
- Use spatial and temporal variability as an indicator of soil quality.

***Recognize time***

- Account for the dynamic nature of soil processes when testing and interpreting soil characteristics.
- Use the temporal pattern of soil characteristics to describe soil quality.
- Examine and account for the transition time after a farmer changes practices.  Soil characteristics may take several years to become relatively stable after a change.

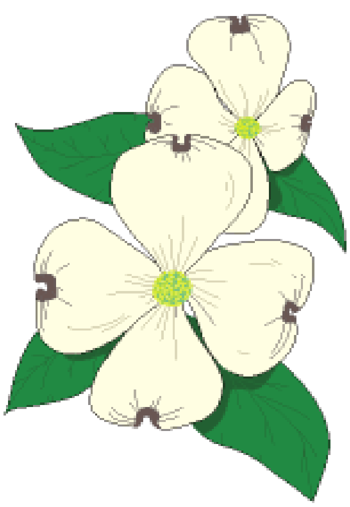
***Recognize different users of soil quality information***

Researchers studying soil dynamics, farmers making daily agricultural production decisions, and policy makers monitoring regional soil and water resources are each asking different questions about soil.  They see problems at different scales, need to measure different characteristics, and use different techniques.  Point-level indicators have been valuable to researchers trying to understand soil processes, but have been less useful to other people interested in assessing soil.

- Develop field-scale indicators that provide timely information for farmers.
- Develop regional-scale indicators that give a meaningful, but broad picture of the quality of the soil resource.

***Experiment with different ways of learning***

- Create stronger linkages between on-farm, systems research and reductionistic research.
- Develop institutions that go beyond the generation of general, regional recommendations, to helping farmers with site-specific decision-making.



# Chapter I
# WHAT IS SOIL QUALITY?

Soil quality is the fitness of soil for use (Pierce and Larson, p. 8). It is assessed in the context of the soil's inherent capabilities, the desired uses of the soil, and the scale of assessment.

The goal of soil quality research is to learn to manage soil for long-term productivity and environmental integrity. Soil scientists have extensively examined characteristics such as organic matter, erosion rates, and nutrient availability. Focusing on soil quality has added a focus on the dynamic and biological character of soil. This means assessing soil processes such as nutrient and water cycling for clues about short- and long-term soil function.

Studying soil quality is about site-specific land management decision-making, rather than general land use assessment. The result of soil quality research is not a map of optimal land uses and a prescription for optimal land management. Instead the result of soil quality research should be many maps of soil conditions over time, an understanding of the processes that tie management to soil performance so that managers can make better site-specific decisions, and more direct linkages between the work of farmers and researchers.

Soil quality is inextricably linked to sustainability (Doran et al. 1996). Understanding soil quality means reading and managing the soil so that it functions optimally now and is not degraded for future use.

*Understanding soil quality means reading and managing the soil so that it functions optimally now and is not degraded for future use.*

### Definitions of the Term "Soil Quality"

As the field of soil quality research expands, several good specific definitions have emerged.

> "The capacity of a soil to function within its ecosystem boundaries and interact positively with the environment external to that ecosystem." *Larson and Pierce 1991, p. 176*.
>
> "The state of existence of soil relative to a standard, or in terms of a degree of excellence." (This definition was used for monitoring soil quality using statistical quality control methods.) *Larson and Pierce 1991, p. 179*.
>
> "The capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health." *Doran and Parkin, p. 7.*
>
> "The continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, maintain the quality of air and water environments, and promote plant, animal, and human health." *Doran et al. 1996, p. 11.*

"Net Soil Degradation = (natural degradation + anthropogenic degradation) - (soil formation + restoration management)" *Blaikie and Brookfield 1987*.

"its fitness as a nutrient-rich medium for optimal growth of healthy crops and beneficial organisms, and its capacity to reduce erosion, pollution and loss of nutrients, and minimize environmental stresses on plants." *Papendick, p. 3.*

Soil quality and soil health are often used interchangeably. *"Health" is most often used to emphasize the linkage between soil and human or animal health, and the idea that soil works as an organism or system. "Quality" is used as the more technical term.*

## Major Themes of the Literature

The current soil quality literature focuses on:

- dynamic rather than inherent characteristics of soil,
- promoting soil fitness rather than just preventing degradation, and
- interactions among soil processes rather than soil components.

*Focusing on soil quality means focusing on biological activity, dynamic structural features and water and nutrient movement.*

### *Dynamic vs. inherent soil characteristics*

*The soil quality discussion focuses on dynamic soil characteristics that are affected by management practices. Dynamic characteristics* are those that change on human time scales—biological activity, some structural features, and water and nutrient movements. Practically speaking, *inherent characteristics* are those that change over geologic time scales—texture, slope, mineralogy, and depth. Previous assessments of soil have focused on inherent features and how they relate to potential productivity, erodability, and determinations of appropriate land use. Soil is changing continually, so, strictly speaking, there are no permanent or inherent features.

### *Soil fitness vs. lack of degradation*

A doctor may call a person "healthy" if there are no signs of illness. But the word "healthy" also implies a certain level of fitness—an ability to perform desired activities and cope with stresses. Similarly, soil might be described as healthy if it does not show signs of degradation such as erosion, compaction, or salinization. But healthy soil also refers to its fitness, or effectiveness, for supporting plant growth, managing water, and responding to environmental stresses.

**Table 1.2: Soil Functions**

(based on Larson and Pierce (1991), Papendick, and Karlen et al. (1996)

- ⇑ a medium for plant growth
- ⇑ a regulator of water flow in the environment
- ⇑ an environmental filter
- ⇑ maintenance of human and animal health
- ⇑ as part of the global storage and cycling of nutrients (see Lal et al. 1995a and b)
- ⇑ support for construction
- ⇑ protection of archeological artifacts

Health, or fitness, is not an absolute concept. “Fitness” is only meaningful when defined in terms of how the soil is used (Table 1.2). This review focuses on three of the functions or uses of soil identified by Larson and Pierce (1991): 1) a medium for plant growth, 2) a regulator of water flow in the environment, and 3) an environmental filter. The third function might be stated more broadly as a buffer for managing environmentally active compounds such as plant nutrients and pesticides. In all cases, the functioning of a soil is relevant to the immediate ecosystem as well as to neighboring and distant systems.

### *Interactions among soil processes*

*The concepts of soil quality and health imply an assessment of how well soil performs its multiple functions. Lack of degradation is only one piece of this assessment.*

One metaphor for ecological systems, and soil specifically, is as an organism. DeLuca, for example, describes sand and silt as analogous to a skeleton, water and solutes as blood, clay and organic matter as the skin and connective tissue, and microbes as the respiratory and digestive system.

Soil can also be viewed as a community (Doran et al. 1996, p. 23). In a community, the output and wastes of one group of individuals becomes the resources for another. The functions of different individuals can complement one another and there is a need for both generalists and specialists. A healthy community has a level of resilience and stability achieved by diverse members performing overlapping functions that allows for adaptation under changing environmental conditions.

Larson and Pierce (1994), compared soil processes to industrial processes by applying statistical quality control procedures to soil monitoring. Statistical quality control is a systematic way of monitoring variations in manufacturing processes.

*The concepts of soil quality and health imply an assessment of how well soil performs its multiple functions.*

All of these metaphors share a systems view of soil. Soil is not a bucket with matter being put in and taken out. It is a complex set of interacting processes and transformations. *The study of soil quality focuses on the interactions among soil processes rather than on soil components in isolation.*

## Goals of Soil Quality Research

Current soil quality research has several motivations. The most important is the desire to improve environmental quality and productivity through better site-specific (and soil-specific) management decisions. A less common motivation is to develop a means to monitor the value of soil as a natural resource at the national and regional scale.

Most researchers attempt to reconcile the goals of farmers with the needs of future generations, and with the off-site environmental goals of individuals and society.

Because site-specific assessment is important to this work, the relationship between researchers and farmers is a critical component of the study of soil quality.

## Soil Quality Research Framework

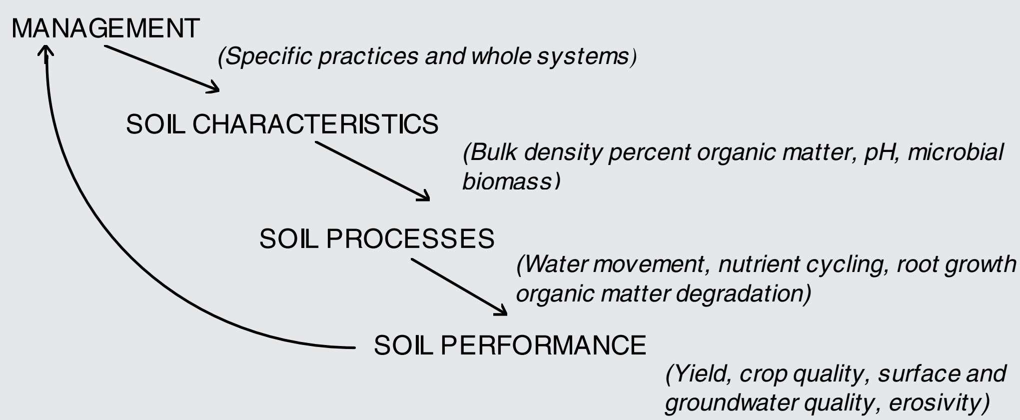
The general approach to soil quality research is illustrated in Figure 1.1. The most distinctive contribution of soil quality research is the study of the linkages among four components of the soil system:

1) management practices and systems,
2) observable soil characteristics,
3) soil processes, and
4) the performance of soil functions.

Soil quality researchers are asking how the whole production system (e.g., tillage, planting, harvest, and crop rotation) changes the pest, water, and nutrient cyles which change farm productivity and water quality over the long term. In addition to studying linkages, soil quality research has also expanded the understanding of the individual components shown in Figure 1.1. For example, it has promoted development of new measures of biological characteristics.

**Figure 1.1: The Soil Quality Research Framework**

Management practices and systems cause changes in soil characteristics and processes which affect soil performance. Soil performance provides the motivation to change management systems.



# Chapter II
# BACKGROUND

*Both organic and systems thinking have roots in holism, in designing systems that promote healthy relationships.*

## Historical Origins

The current soil quality discussion is a response to three developments this century: 1) the evolution of agricultural technologies, 2) methods of land evaluation, and 3) organic and systems thinking about agricultural problems.

### *The evolution of ag technologies*

When tractors entered the agricultural scene in the early part of the 20th century, fields got larger, and fewer farms kept animals and spread manure on fields. The Dust Bowl was the most dramatic result of this mechanization, and brought renewed interest in managing the tilth and organic matter of soil. After World War II, the use of pesticides and “artificial manure” exploded, and the living characteristic of soil was again neglected. In the 80’s, the cost of chemical inputs began rising significantly. Interest in better management of on-farm resources, and an appreciation for the variability of soils and the potential of soil-specific farming technology increased.

### *Methods of land evaluation*

Researchers have been developing land evaluation systems such as the Land Capability Classification system, the Soil Survey tables, and others, since the first half of the century. These systems focus on the inherent qualities of land. In the 70’s and 80’s, criticism of the T concept (tolerable soil loss) and other limited assessments of soil and management practices grew. Interest in understanding and monitoring the dynamic, especially biological, properties of soil developed.

### *Organic and systems thinking*

Early this century, Sir Albert Howard, William Albrecht, and the Rodales (among others), studied and promoted systems thinking in agriculture. (At that time, “organic” meant adopting a systems approach toward understanding and managing a farm.) This tradition pervades modern soil quality discussions. Feeding plants through soil is not a check-book process of adding nutrients, but one of managing soil biological processes so that soil structure and nutrient cycling systems are maintained to feed plants and keep soil and nutrients from moving to undesired parts of the landscape. Systems thinking applies not only to how one manages soil, but to how it is studied.

**Major Publications**

The soil quality discussion that is summarized in this publication began in the late 1980's.  This new discussion is focusing on:

- soil fitness and performance of multiple functions
- the biological component of soil
- how management affects soil characteristics
- the interaction of soil processes, and
- the development of indicators.

This discussion is distinctive in that it is not limited to severe soil degradation (e.g. erosion), to crop yield as the measure of soil performance, nor to the inherent soil characteristics as indicators.

The four major publications listed below established the framework of the discussion summarized in this review.  These publications identified soil characteristics that could be used as indicators of soil quality, and began to propose standards and indexes that could be used to define quality soil.

1. *Conservation and Enhancement of Soil Quality.*  The tone of the discussions of the late 1980's are perhaps best captured in a 1991 paper by Larson and Pierce.  They established a definition of soil quality based on how well it functions in the context of its ecosystem.  Soil functions included productivity, the regulation of water flow, and environmental filtering.  Larson and Pierce encouraged researchers to focus on developing a "minimum data set" of soil quality indicators, and on the development of indexes to interpret the measurements.

2. *Proceedings of the Soil Quality Standards Symposium San Antonio October 23, 1990.*  Sponsored in 1990, by the U.S. Forest Service and the Soil Science Society of America.  The resulting papers focused on establishing numerical standards for physical and chemical soil characteristics.  These were more easily established for forest management than for production agriculture.

3. In 1991 the Rodale Institute sponsored the *International Conference on the Assessment and Monitoring of Soil Quality.*  The purpose of the conference was to develop a worldwide system for monitoring soil changes.  This large-scale monitoring goal has received less attention than the goal of improving farm management.  It is not clear how work at these two scales relate and to what extent they can use the same research to support their goals.  Two other unique contributions of the Rodale conference are their call for development of easy visual indicators of soil quality, and for examining the connection between soil quality and food and feed quality.

*Soil quality is a focus on the ability of soil to perform multiple functions.*

4. *Soil and Water Quality: An Agenda for Agriculture* (National Research Council). Discusses soil quality indicators, and also examines how to use a farm systems approach to implement policy and apply the use of indicators. The book is an excellent resource on the status of soil and water quality and policy, and as an introduction to the technical information available on the topics of nitrogen, phosphorous, pesticides, sediments, salts and trace elements, and manure. The committee recommended four areas for research and policy (Table 2.1).

**Table 2.1: Research and Policy**

***Recommendations of the Committee on Long-Range Soil and Water Conservation***

(National Research Council 1993)

1) Conserve and enhance soil quality by giving it the research and political status of air and water quality.
2) Increase the use efficiency of nutrients, pesticides, and irrigation in farming systems.
3) Increase the resistance of farming systems to erosion and runoff.
4) Make greater use of field and landscape buffer zones.

# Chapter III
# INDICATORS OF SOIL QUALITY

This chapter first describes what constitutes a good soil quality indicator. Second, commonly used indicators are listed. Third, specific indicators are reviewed for each characteristic, there is an explanation of what is being measured and how it relates to soil performance. The final portion of the chapter describes methods for dealing with soil's inherent variability.

## Section 1
## WHAT IS A GOOD INDICATOR?

Soil quality can be assessed at three points of the soil system shown in Figure 1.1. Each of these types of indicators have different advantages and disadvantages.

- Measures of *management* quantify the *pressures* being placed on the soil system. These include levels of pesticide use, tillage methods, grazing pressure, or crop rotations. For example, the National Research Council has done state-by-state estimates of the amount of nitrogen and phosphorus added to and removed from the soil system.
- Most research has measured the *characteristics*, or the *state*, of the soil. Using these measurements requires an understanding of how soil characteristics are linked to soil performance and to management practices.
- *Soil performance*, or *response*, measurements include yield per unit input, erosion rates, stream flow rates and sediment levels, and levels of water contaminants. These are direct measures of the benefits we receive from soil. Performance measures are poor indicators of the cause of problems, and they may not indicate whether management changes are having a positive or negative effect until after damage is done.

*Useful indicators are sensitive to management changes, but somewhat stable in response to non-management changes such as weather.*

The management-characteristics-performance categories of indicators are analogous to the pressure-state-response framework of indicators described by Hammond et al.

The features of useful indicators include:

- sensitive to management changes, but somewhat stable in response to non-management changes such as weather,
- reflects some aspect of the functioning of the system,

- always exists throughout a field or region but respond to temporal and spatial variation in ecosystem function, and
- readily and economically accessible (after Turco et al., p. 75; Kennedy and Papendick, p. 244).

There is no single ideal indicator or suite of indicators of soil function. They are interrelated, and each provides different clues about the processes occurring in soil.

## Section 2
## COMMONLY USED INDICATORS

The indicators that have received the most attention are listed in Table 3.1. All of these measure the status of soil at a point in time and space. When using point measurements, it is critical to sample carefully and understand how each characteristic varies over the area that the sample is meant to represent.

Non-point measurements summarize characteristics over a larger area. For example, water infiltration is measured at a point, but infiltration for a whole watershed can be inferred by measuring the amount of increased stream flow after a storm. A large increase in stream flow means high runoff and low total infiltration over the whole area.

Other measurements summarize characteristics over time. Microbial activity can be measured at one point in time, or the amount of degradation of a buried cotton strip can be measured to represent microbial activity over several weeks.

**Table 3.1: Commonly Studied Soil Quality Indicators**

(The terms below are defined in the Glossary and further explained in this chapter.)

| ***Chemical measurements:*** | ***Physical measurements:*** | ***Biological measurements:*** |
|---|---|---|
| Organic carbon and nitrogen | *Water infiltration | Potentially mineralizable nitrogen |
| Cation exchange capacity | Rooting depth | *Microbial biomass |
| Extractable bases | Penetration resistance | Basal respiration |
| pH | *Aggregate stability | Earthworms |
| Electrical conductivity | Water holding capacity | |
| Sodium adsorption ratio | Bulk density | |
| *Particulate organic matter | | |

*These measures look especially promising as indicators of changes caused by management. They have been identified in studies that compare soil characteristics under different management systems.

Karlen, et al. (1996a) lists potential indicators of soil quality at the field- to the international-scale (Tables 3.2, 3.3). Many of the non-point measurements in these lists have received little attention in the soil quality literature.

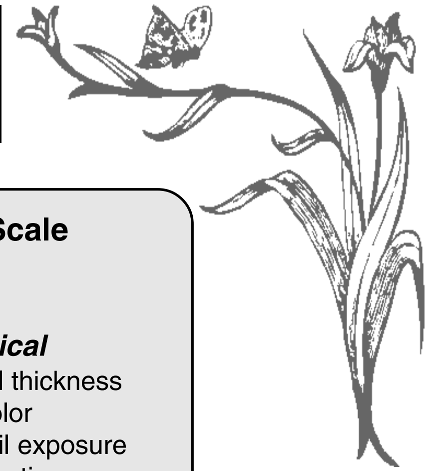


**Table 3.2: Potential Field-, Farm-, or Watershed-Scale Indicators of Soil Quality** (Karlen et al., 1996a)

| ***Biological*** | ***Chemical*** | ***Physical*** |
|---|---|---|
| crop | organic matter changes | topsoil thickness |
| crop appearance | pH changes | soil color |
| weed pressure | available phosphorous & potassium | subsoil exposure |
| disease pressure | cation levels | compaction |
| nutrient deficiencies | nitrogen availability | crusting |
| earthworms | heavy metals | ponding (infiltration) |
| decomposition rates | salinity | runoff |
| root growth | nutrient loss in streams | rill and gully erosion |
| poor plant emergence | nutrient loss to groundwater | ease of tillage |
| | | soil structure |

**Table 3.3: Potential Regional-, National-, or International-Scale Indicators of Soil Quality** (Karlen et al., 1996a)

| ***Biological*** | ***Chemical*** | ***Physical*** |
|---|---|---|
| productivity (yield stability) | organic matter trends | desertification |
| taxonomic diversity at the Group level | acidification | loss of vegetative cover |
| species richness, diversity | salinization | water erosion |
| keystone species & ecosystem engineers | water quality | wind erosion |
| biomass, density & abundance | air quality | siltation of rivers and lakes |

### "The Soil Quality Test Kit"

John Doran (1996) attempted to increase the accessibility of common soil quality tests by creating a compact kit of simplified versions of soil measurements (Table 3.4). These tests are informative for some management and education purposes, but they are less precise than is required for most research applications, and still too time consuming for most farmers.

**Table 3.4: Tests Included in the Soil Quality Test Kit**

| | |
|---|---|
| bulk density | soil respiration |
| soil water content | nitrate-nitrogen levels |
| % water-filled pore space | pH |
| infiltration | electrical conductivity |
| water holding capacity | |

One educational benefit of the Soil Quality Test Kit is the demonstration of the effect of soil moisture, temperature, and oxygen on soil respiration. The test kit user is provided with equations to normalize respiration to a "non water-limited respiration rate." This not only gives more credence to the numbers but has the added benefit of reminding the user how diverse soil processes are intertwined.

A major criticism of the Soil Quality Test Kit (and this reflects a much broader dilemma in soil quality research) is that there is little guidance in how to interpret test results. The Soil Quality Test Kit has succeeded at expanding the number of field workers that have access to soil quality tests, and at demonstrating the potential for simplifying soil monitoring. Far more work is needed to develop ways to easily and systematically monitor soil quality in the field.

## SECTION 3: BIOLOGICAL INDICATORS

### Microbes, Fauna, and Soil Quality

*The tons of organisms in each acre of soil play essential roles in nutrient cycling and the development of soil structure.*

A major contribution of the soil quality literature has been its emphasis on the importance of microorganisms to understanding the soil system. The tons of organisms in each acre of soil play essential roles in nutrient cycling and the development of soil structure. Soil organisms are continually adapting to changes in their environment, and therefore are rapid and sensitive indicators of soil quality changes. Unfortunately, measurements of soil organisms are difficult to make and interpret because of their responsiveness to environmental changes, and because microbial environments can change over short distances and short periods of time.

Microorganisms are necessary for the decomposition of plant residue into humus and into nutrients that plants can use for growth. Minerals and ions are immobilized by the microbial community then released when organisms die. Microorganisms play numerous critical roles in:

- nitrogen cycling,
- promoting plant growth,
- degrading synthetic soil contaminants and other potential pollutants,
- improving the drought tolerance of plants,
- improving soil aggregation, and
- controlling diseases and insect pests (Table 3.5).

Soil fauna are often categorized by their feeding habits: bacterivores, fungivores, omnivores, and detritivores (feed on plant residues). The feeding intensity of soil fauna will affect microbial populations, change the rate of turnover of microbial biomass, and thus change nutrient availability. Medium-sized fauna increase the surface area of organic substrates and thus speed decomposition. Larger fauna such as ants and earthworms redistribute organic matter and, through burrowing, have important effects on soil structure that influence infiltration, hydraulic conductivity, and root penetration.

**Table 3.5: Influences of Soil Biota on Soil Processes**
(Linden et al. p. 93)

| | Nutrient Cycling | Soil Structure |
|---|---|---|
| **Microflora** (i.e. bacteria, fungi, algae) | Catabolize organic matter<br>Mineralize and immobilize nutrients | Produce organic compounds that bind aggregates<br>Hyphae entangle particles onto aggregates |
| **Microfauna** (i.e. nematodes, protozoa, rotifers) | Regulate bacterial and fungal populations<br>Alter nutrient turnover | May affect aggregate structure through interactions with microflora |
| **Mesofauna** (i.e. mites, small worms, collembola) | Regulate fungal and microfaunal populations<br>Alter nutrient turnover<br>Fragment plant residues | Produce fecal pellets<br>Create biopores<br>Promote humification |
| **Macrofauna** (i.e. ants, earthworms, termites, millipedes) | Fragment plant residues<br>Stimulate microbial activity | Mix organic and mineral particles<br>Redistribure organic matter and microorganisms<br>Create biopores<br>Promote humification<br>Produce fecal pellets |

## Microbial and Faunal Indicators

A number of analyses have been developed to describe soil microbial activity, but interpretation of those values has not developed enough to suggest general guidelines.

**Microbial Indicators** (Kennedy and Papendick)

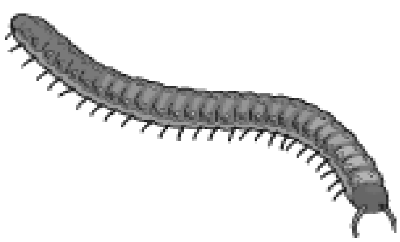
- Organic carbon
- Microbial biomass
- Potentially mineralizable Nitrogen
- Soil respiration
- Enzymes
- Ratio of biomass carbon to total organic carbon
- Ratio of soil respiration to microbial biomass
- Microbial community fingerprinting
  - -substrate utilization
  - -fatty acid analysis
  - -nucleic acid analysis

The significance of absolute values change from one place to another. Even a change in value does not necessarily imply a significant difference in the functioning of the system. For example, Kennedy and Smith show that there is not a simple relationship between higher soil microbial diversity and higher soil quality.

Visser and Parkinson, and Linden et al. divide microbiological and faunal studies into three levels of study:

1) **Population studies** that measure the dynamics of specific key species. These might measure the numbers or biomass of a species, rates of growth, or age distributions.
2) **Community studies** that assess the mix of microorganisms. These might estimate biodiversity or count the organisms in different functional or trophic groups. Microbes also can be categorized based on the substrates they will grow in, profiles of their proteins or other metabolites, or antibiotic resistance (Turco, p. 81).
3) **Ecosystem studies** that measure biological processes. These include *biomass* measurements such as direct microscopic counts, measures of microbial products including enzymes, or measures of substrate induced respiration. Also included are measures of *biological activity* such as nutrient cycling, soil respiration, bioaccumulation of heavy metals or pollutants, decomposition and mineralization rates, or observations of soil modifications such as burrowing, feces, soil aggregation, and mixing.

Visser and Parkinson argued that ecosystem-level studies are the most promising because they assess soil functions more directly, and because they are less susceptible to problems of temporal and spatial variation. They are especially important in identifying the most useful population- and community-level research to pursue.



Kennedy and Smith pointed out that ecosystem or process level studies treat the microbial community like a black box. We need a better understanding of what is in that black box: how diverse is it, what are the functional roles played by different microbes, and, perhaps most importantly, how resilient is the community to stresses? They imply that examining the diversity and resilience of functional groups is more useful than creating indicators based on keystone species because the response of a single species to a stress cannot capture the effect of a stress on the interactions that occur in a community.

***Microbial measurements***

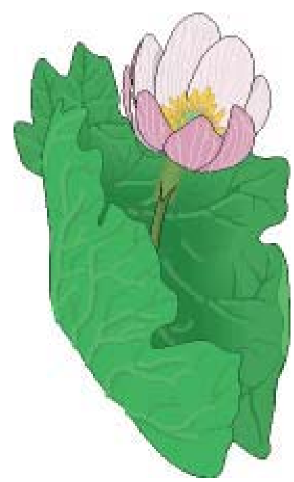
<u>Biomass and respiration</u>. Carbon dioxide evolution can be measured directly from soil that is held under controlled conditions. This is called *basal respiration*. It provides a measure of biological activity, but does not indicate how many or what kind of organisms are present. *Substrate-induced respiration* is a measure of the $CO_2$ evolved from a soil sample after adding sugar. Because the sugar increases biological activity, this is not a measure of normal activity but of the size of the

microbial community. The ratio of these two numbers is called the *metabolic quotient,* and is often more informative than either measure alone. The metabolic quotient is the amount of biological activity divided by the microbial biomass.

The ratio of microbial carbon to total organic carbon is another common measure of biomass.

The *cotton strip test* is an indicator of biological activity. Strips of a standardized cotton cloth are buried in the soil for a few weeks and then tested for tensile strength (pulled apart) or weighed to determine how much decomposed. This method summarizes biological activity over time, reducing the problem of interpreting a measurement taken at a single point in time.

<u>*Potentially mineralizable nitrogen*</u>. This test is an estimate of the amount of nitrogen that is immobilized in organic forms and potentially could be decomposed by microorganisms into a plant-available form. The amount of potentially mineralizable nitrogen depends on the amount and form of nitrogen in the soil, the microbes available to degrade nitrogen-containing compounds, and a carbon source to feed the microbes. Potentially mineralizable nitrogen appears to be less temporally variable than measuring microbial biomass nitrogen (which is only a portion of potentially mineralizable nitrogen).



***Measurements of soil fauna***

<u>*Nematodes*</u> are especially promising as ecological indicators. They are ubiquitous, easily separated into functional or trophic groups, respond quickly to changes in food supply, but are stable (relative to microbes) in response to weather changes. Proportions of fungus feeding vs. bacteria feeding nematodes may indicate the size of fungal and bacterial populations more accurately than attempting to measure fungi and bacteria directly (e.g. Christensen et al.). Nematodes promote nutrient mineralization by eating microbes (Bohlen and Edwards). Measurement techniques involve counting the size of populations, and determining the proportion in various trophic groups.

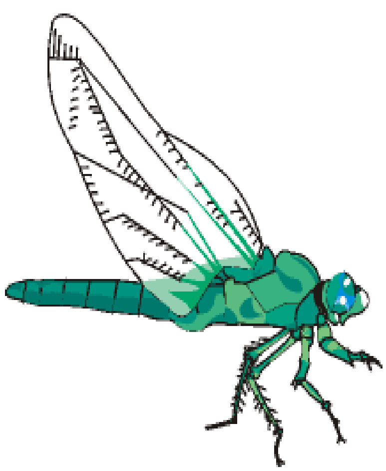
The conspicuous <u>*earthworm*</u> may also be valuable in assessing soil. Tillage, pH, chemical additives, and especially crop residues affect earthworm numbers. Earthworms play important roles in air, nutrient, and water cycling and so are indicators of these soil processes. Tunnels increase air space which improves infiltration rates and provides habitats for springtails and other non-burrowing invertebrates. During the process of eating and producing wormcasts, earthworms improve aggregate stability, promote soil mixing, increase the surface area of residue so it can be decomposed, and enhance microbial activity in the casts. Different species of worms have different tunneling and eating habits, and have different effects on soil structure and biological activity.

Earthworms differ from other fauna in that they are not ubiquitous. They are important to soil processes, but may not be critical. This means that their absence may not indicate poor soil quality. Their presence may be either a cause or result of high productivity and good soil quality. This may not make them less valuable as indicators, but it does point to the importance of recognizing the site specificity of soil quality measurements and interpretations. It also illustrates the importance of separating the use of a measurement as an indicator from its use to prescribe management changes. For example, while the presence of worms on one farm may indicate good soil quality and management, the absence of worms in another region does not mean that management is necessarily poor or that a problem should be solved by importing worms.

### Plant Assays

Plants have received only a small amount of attention as soil quality indicators. Characteristics that could be used as indicators are crop yield patterns, root structure, plant tissue characteristics, diversity of forage species, and dominant weed species.

Yield data is most informative when it is combined with some indication of the sustainability of the yield level. For example, yield might be compared to inputs or to changes in soil characteristics. Resilience of yield to weather extremes could be an important component of soil quality assessments.



Much about the condition of soil can be read from *root structure*. The direction of root growth and amount of branching respond to dense layers in the soil, availability of nutrients, water, and air, and to high concentrations of salts or other soil amendments.

Like all plants, each weed and forage species thrives under different conditions, and are indicators of those conditions.

## Section 4:
## CHEMICAL INDICATORS

### Chemistry and Soil Quality

Microorganisms and plants acquire nutrients via chemical processes. The growth of organisms is greatly affected by the chemical environment of soil including the pH, the chemical structure of minerals and organic compounds, and the composition of the soil solution.

### Chemical Measurements

#### *Standard tests*

Several well-established soil tests are included in most soil quality minimum data sets. Further descriptions of these tests can be found in Klute and in Weaver (*Methods of Soil Analysis Part I* and *Part II*).

*Cation exchange capacity, pH, and base saturation*. Cation exchange capacity, or nutrient retention capacity, is a measure of the amount of positively charged nutrients that the soil could hold onto electrochemically and release for plant use. It depends on the soil texture, type of clay minerals, the amount of organic matter, and the pH.

Soil pH is an important control on the chemical reactions that take place in soil. Different nutrients have different pH ranges at which the highest proportion is in a plant-available form. Each crop and microorganism has its own optimal pH range. pH depends on parent material and climate, and is strongly affected by the use of fertilizers. The pH of a mixed soil sample is fundamental to any soil assessment, but does not tell the whole story. Chemical reactions occur (and microorganisms live) in soil microenvironments, where the pH and other conditions may differ greatly from that of the average soil environment.

The base saturation is the percentage of the total cation exchange capacity occupied by the basic cations, calcium, magnesium, potassium, and sodium. Base saturation is related to pH—as the amount of basic cations increases, the pH increases.

*Electrical conductivity (EC)* of soil is a measure of the concentration of ions in solution. It is generally used as an indicator of salinity, but where nitrate levels are high and depending on the time of year and the climatic zone, EC can be an indicator of soil nitrate status. *Exchangeable sodium percentage* measures exchangeable sodium ions as a percentage of other exchangeable cations. *Sodium adsorption ratio* is the ratio of sodium concentration to calcium and magnesium concentrations. These three measurements are most useful in arid soils.

*Organic matter analysis* is part of a standard soil test. Please refer to the following sections for a detailed description of new ways to monitor changes in the character of organic matter.

### ***Organic matter analysis***

The amount, type, and location of organic matter may be one of the best integrating indicators of many physical, chemical and biological processes. Measurements of organic matter fractions indicate more about soil quality than the measurement of total organic matter. Total organic matter is strongly affected by soil texture and climate, and requires decades to change significantly in response to most management changes. The active fractions of organic matter respond much more quickly to management changes.

As with many soil characteristics, what is being measured is not the same as what is being indicated about soil health. This is especially true with regard to organic matter. Analyzing organic matter requires chemical tests, but the results are strongly linked to the physical structure and biological activity of the soil.

Soil organic matter is critical for its nutrient and water holding capacity, as a substrate for microorganisms, and in the formation of soil structure. Organic residue on the surface mitigates the impact of rainfall and the movement of water.

**Types of organic matter:** Soil organic matter includes all the carbon-based materials left behind by plants and animals and produced by microorganisms. It ranges from stems and roots from last year's crop, to highly decomposed residue, to recombinations of organic molecules into unique humic compounds. Some is protected from degradation and persists for centuries. Some is dynamic and repeatedly reformed through the work of microorganisms and larger flora and fauna.

Each of these materials has a different effect on the soil environment depending on its size, location, age, and composition. For example, some earthworms only eat surface residues; others eat organic matter in the soil. Large residue provides habitat for some organisms and slows surface water flow. Old humic compounds resist decomposition and are important in binding particles into microaggregates, and increasing the cation exchange capacity and water holding capacity of soil. Highly labile compounds are sources of nutrients for microorganisms and plants.

**Measures of soil organic matter as soil quality indicators.** *Total organic matter* has long been recognized as an important determinant of soil performance. It depends on how much organic matter is added to the soil, how quickly it decomposes, and how much can be held by the soil. Climate and aeration (drainage and tillage) determine the rate of organic matter degradation. Climate and farming practices determine the amount of organic residue that is returned to the soil. Soil texture determines how much organic matter the soil can hold. Sandy soils are often no more than 2% organic matter; a clay soil could have 4% or more. Non-farmed prairie soils can have over 8% organic matter.

Levels of *organic carbon and nitrogen* reflect levels of total organic matter. These can be expressed as a ratio with microbial carbon and nitrogen levels.

Despite its importance, the level of total organic matter is only a good long-term indicator because it changes only slowly in response to management. Recent soil quality research has focused on identifying and understanding components of organic matter that would signal the effects of management long before total organic matter levels change. Interest has focused on the active portion, which is involved with the formation of meso- and macro-aggregates, and acts as a nutrient pool for plants and soil organisms.

*Recent soil quality research has focused on identifying and understanding components of organic matter that would signal the effects of management long before total organic matter levels change.*

The challenge of this research is that the pools of organic matter that can be isolated using laboratory methods are not the same as the pools that researchers want to study (Parton et al., Molina et al.). For example, researchers would like to isolate the organic matter that is active in microbial processes from that which is highly resistant to degradation. Unfortunately, chemists can only divide soil organic matter into physical categories of light and heavy fractions, or chemical categories such as fulvic or humic acids, or polyphenols, but none of these categories match neatly with the active vs. highly-resistant pools that researchers want to study. The best proxy measures for the biologically active portion of soil organic matter seem to be <u>*particulate organic matter*</u> and <u>*light-fraction organic matter*</u>.

Particulate organic matter are the larger particles of free organic matter, in contrast to the smaller particles that are associated with mineral matter. Particulate organic matter has been isolated based on size by sieving (Elliot et al. 1994), and based on weight by centrifugation (Wander et al. 1994). Organic matter isolated by weight is also called light-fraction organic matter. Gregorich and Janzen define light-fraction as having a specific density less than 2g/cm$^3$, and macro-organic matter as .05 to 2 mm in size.

## SECTION 5: PHYSICAL INDICATORS

### Soil Structure

Only about half of soil volume is mineral and organic matter; the other half is water and air. Soil structure (how primary mineral and organic particles are bound into larger structures) determines how water and air move through the soil, bringing nutrients to microorganisms and plant roots. Structure is reflected in the amount and size of pore spaces, the size and stability of aggregates of soil particles, and the density of the soil. Aggregate stability and water infiltration have attracted attention as indicators of soil quality.

*Soil structure (how primary mineral and organic particles are bound into larger structures) determines how water and air move through the soil, bringing nutrients to microorganisms and plant roots.*

#### *Aggregate stability*

Soil is composed of sand, silt, and clay particles held together into larger aggregates. The size and distribution of these aggregates determine the amount and size of pores in the soil. Pore size determines the balance between air and water that is so critical to the growth of microbes and roots. If surface aggregates are highly unstable and fall apart in rain, soil pores will become clogged with loose clay particles, greatly reducing water infiltration.

The amount and type of clays, other inorganic materials, and biological activity are important to the creation and stability of aggregates. Fungal hyphae and mucilages secreted by bacteria help hold together the soil particles. Surface crop residue helps promote

*Fungal hyphae and mucilages secreted by bacteria help hold together the soil particles.*

stable aggregation by providing food for fungi and other microorganisms (Eash et al.).

Measures of aggregate stability reflect the level of biological activity in the soil and the soil's resistance to erosion.  There are three ways to assess soil aggregation:

1) Aggregate size classes (the proportion of aggregates that fall into different size ranges).
2) Stability: the percentage of the aggregates in a specified size class that remain intact after wet or dry sieving.
3) Distribution of stable aggregates: the proportion of stable aggregates that fall into different size ranges.

There are several ways to measure aggregate stability (wet vs. dry, sieving vs. agitation).  Lehrsch and Jolley compared methods to identify the most effective for differentiating among management systems.  Ultimately, which technique is most informative depends on the soil and climate.  Timing of measurement is also important.  Stability will drop between fall and spring, and will vary depending on the effects of temperature and moisture on clay chemistry and biological activity.

*Water infiltration integrates several physical and biological soil processes, and it is significantly different among management systems.*

***Water dynamics***

Infiltration, hydraulic conductivity, and water holding capacity are important measures for understanding how much water is available to plants over the growing season and how water moves through soil to reach surface and groundwater.

*Infiltration* is a measure of the rate at which water enters the soil.  If practical and meaningful field measures can be improved, infiltration promises to be a powerful indicator of soil quality for several reasons.  Infiltration is directly related to erosion, seed bed preparation, and water availability.  It integrates several physical and biological soil processes, and it is significantly different among management systems.  Higher infiltration generally means more water available for microbial and crop growth, and less loss of nutrients and sediment to erosion.  Infiltration is determined by soil structure (specifically pore space and size distribution).  Structure is affected by microbial activity, climatic cycles, tillage, soil type, and vegetation.  Biopores created by roots and fauna, fracture planes from tillage, and cracks due to drying, all provide avenues for the movement of water.  Tillage affects infiltration by reducing aggregation and by creating and destroying water channels.  Surface crusting reduces infiltration.  Surface residue and vegetation maintain infiltration by promoting biological aggregation, preventing sealing caused by rain impact, and holding water in place longer.

Infiltration shows wide variation depending on all of the above characteristics, plus the landscape position at which it is measured and the prior soil moisture status of the soil. This makes it difficult to recommend target ranges for infiltration rates.

<u>*Hydraulic conductivity*</u> is a measure of the rate of movement of water through soil. It is affected by the amount of organic matter, soil porosity, soil structure, and amount of water in the soil. It changes with depth in the soil profile.

<u>*Water holding capacity*</u> (the amount of water that can be held by soil to be used by plants) depends on the texture, organic matter, structure and percent of sand, silt and clay in the soil.

### *Soil depth*

This is a measure of the distance from the surface of the soil to a root restrictive layer such as stone, water table, or hardpan (dense soil layer). Shallowness reduces water holding capacity and root development.

### *Density and compaction (penetration resistance)*

Even when soil is not so dense as to prevent root penetration, it will affect root growth and water movement. Measures of bulk density reflect the soil texture, organic matter levels, porosity and aggregation.

## SECTION 6
## UNDERSTANDING THE RESEARCH

Here are some issues to consider when reading soil quality research.

### *The difference between what a test measures and what it indicates*

Measurements of soil characteristics can be divided into biological, chemical and physical categories, but it is important to remember that processes in the soil are integrated, not compartmentalized. For example, the chemistry of nitrogen involves microbial activity, which is affected by the physical dynamics of water, air, and temperature. Bulk density is an important physical test. Density is determined (in part) by tillage and soil organisms; and density affects water infiltration and root development. Therefore bulk density is an indicator of tillage, biological activity, water movement, and root growth.

*Measurements of soil characteristics can be divided into biological, chemical and physical categories, but it is important to remember that processes in the soil are integrated, not compartmentalized.*

### *Linking soil characteristics, processes, performance, and management*

It is difficult to design research that tests the connections among the four components of the soil system shown in Figure 1.2. Typically, research will test linkages between only two of these components and will make assumptions about the other linkages. It is important to recognize which linkage is actually being tested. It is equally important not to dismiss possible relationships because they cannot be readily tested using formal scientific methods.

### *Separating signal from noise in data*

Soil and all its characteristics go through daily and seasonal changes, in response to weather, longer-term climate trends, and seemingly randomly. Soil also changes across the space between crop rows, down a hill slope, between fields, and across regions. From among these normal variations, researchers are trying to pick out trends in soil attributes that are caused by management practices and that will give a land manager clues to how soil will perform in the short and long term. These problems of variability are addressed in the last section of this chapter.

### *Selecting methodologies*

The features of ideal soil quality indicators, discussed in Section 1, should guide both the selection of appropriate soil characteristics, and the selection of measurement techniques for each characteristic. There is no single best methodology for measuring a characteristic; this depends on the purpose of the assessment and the type of soil. For example, aggregate stability can be measured wet or dry. The method used depends in part on whether water or wind erosion is more important. The precision required depends on how the information will be used—for research, for education, to inform management decisions, to inform policy decisions, or to assess a piece of land for land use or valuation. A few important issues in selecting methodologies are described here.

*Volume vs. weight measurements:* Typically, measurements such as microbial biomass, nutrient levels, or organic carbon and nitrogen are expressed per gram of soil. It has been argued that volume measurements would be more ecologically relevant because roots penetrate a volume of soil not a mass of soil. When comparing fields with different bulk densities, conclusions may change dramatically depending on whether values are expressed by volume or by weight. For example, Reganold and Palmer (1995) found bulk densities ranging from 0.88 to 1.22 Mg/m$^3$ in a biodynamic pasture vs. a conventional vegetable farm. The cation exchange capacity of the pasture lands was 22% higher than that of the vegetable farm when expressed as volume, and 69% higher when expressed on the more conventional weight basis. Tiessen et al. (1982) suggested reporting values in terms of topsoil depth. This accounts for the fact that low density soils tend to be deeper than high density soils and thus have more soil into which roots can grow.

*Laboratory vs. field methods:* Laboratory methods have the advantage of control over weather and other variables, allowing the researcher to observe isolated processes.

However, variability due to weather and other known factors does exist and land managers need to understand what that variability is and how it affects the interpretation of soil measurements. Unknown sources of variability and interactions in the field may have gross and contradictory effects compared to results reached under tightly controlled laboratory conditions. Thus, it is important that researchers simultaneously do laboratory and on-farm systems research.

## SECTION 7
## ACCOUNTING FOR VARIABILITY IN SPACE AND TIME

When looking at a map of a soil characteristic or at a series of measurements over time, a manager would like to know how much of the variation is caused by different factors. For example, how much of the differences in compaction are explained by traffic patterns and how much by soil texture, water dynamics, or weather patterns?

The difficulty with using indicators to assess soil quality is determining how much change over time or space can be explained by management changes, how much by other causes, and how management interacts with other soil factors.

### Variability in Soils

Soils change across the landscape and through time. This simple fact has confounded attempts to draw physical and taxonomic boundaries. The transition between soil types or characteristics may be rather abrupt or so gradual as to be continuous.

Every introductory soil textbook describes the five soil forming factors identified by Jenny:

1) climate,
2) time,
3) parent geological material,
4) vegetation, and
5) slope.

Each of these takes on a different pattern across the landscape, and it is their combined patterns that explain soil variations. The study of soil quality requires learning how patterns of soil management interact with the patterns of the five soil forming factors to determine soil characteristics.

*The study of soil quality requires learning how patterns of soil management interact with the patterns of the five soil forming factors to determine soil characteristics.*

Important variability in soil quality occurs at all scales. Microscopic variation in temperature, moisture, pH, and air determines how many suitable environments are available for microbial activity. Soil temperature and compaction variations from the crop row to the interrow affect germination and weed growth. Organic matter differences between the hilltop and the footslope lead to different optimal nutrient and pesticide applications. The nutrient and microbial effects of manuring are high near endrows and the places near barns where manure tends to be spread more heavily. Infiltration rates will be different in parts of the county where soil is formed on sandy outwash compared to those formed on finer lake bottom parent material.

Temporal variability is equally significant. Microbial activity follows daily cycles related to temperature, and activity drops drastically during mid- to late-summer compared to the wetter spring and fall. Compaction varies as well. In turn, all of the soil characteristics that relate to biological activity and density (aggregation, infiltration, nitrogen cycling) change with the seasons.

## Accounting for Variability When Assessing Soil Quality

There are a number of ways that researchers account for soil variability. These can be categorized into: sampling techniques, geostatistical manipulations, measurement techniques, modeling, and the use of variability as an indicator.

### *Sampling techniques*

Simple random sampling is rarely appropriate for soils for two related reasons. First, statistics based on random sampling assumes that samples are independent of one another when, in fact, soil characteristics are highly autocorrelated (related to neighboring samples). Secondly, effective random sampling requires an impractical number of samples. Far more information can be learned from the same number of samples if sampling points are selected to reflect known variation on the landscape.

*Effective random sampling requires an impractical number of samples. Far more information can be learned from the same number of samples if sampling points are selected to reflect known variation on the landscape.*

Relatively small areas on a landscape may have disproportionate effects on some soil processes. Off-site effects of erosion may be determined by a relatively small grassed buffer strip. Germination will be most affected by crusting in the crop row and not the interrow. Random sampling may not give due attention to these locations.

Stratified random sampling can be more effective. Samples are taken randomly from within each of the strata that are thought to vary in important ways. (Strata are subpopulations of the sampling population. For example, one set of random samples might be taken from rows and another from interrow areas.)

Repeated samplings can be taken at the same time and/or place to avoid unwanted temporal or spatial variation. Sampling at the same time each year should be based on phenological or management events (such as when soil thaws or after tillage) rather than on calendar dates.

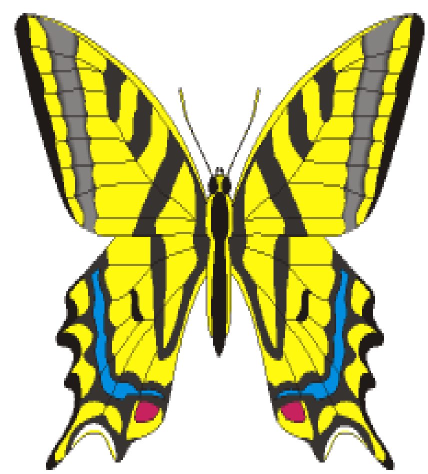
Repeated sampling at the same place has been accomplished using global positioning systems (GPS) to precisely locate sampling points.

Sampling in the same location is not possible if the measurement technique requires destroying the soil sample, the scale of variation of the attribute is very small, and small changes in attributes need to be detected. Papritz and Webster address this problem with regard to monitoring contaminated soils. They found that stratified random sampling was the most effective solution.

***Measurement techniques***

Each measurement technique has an inherent scale that summarizes different levels of variability, making them useful for different purposes. Point-scale measurements produce an average measure for the soil sample. Watershed-scale measurements produce an average for the whole watershed. (See “Commonly Used Indicators” near the beginning of this Chapter.)

An important way of accounting for normal temporal variation is by selecting soil quality indicators that are stable to short-term fluctuations in weather. For example, bacteria populations go through drastic swings in activity when soil temperatures and moisture change. Nematodes, on the other hand, survive temperature and moisture swings better than bacteria and so their populations are more stable. Counting bacteria-eating nematodes may give a more reliable picture of bacteria populations than attempting to measure bacteria directly. Another method of measuring biological activity is to place a cotton strip or popsicle stick in the soil and weigh how much has been lost to decomposition at the end of the season. This provides an aggregate measure of the biological activity over the course of the year, eliminating the problem of daily population swings. It does not deal with spatial variation or with climate variation between years.



The most careful repetition of the timing and place of a sample is not enough to insure an easily-interpreted time series of data. Although general seasonal cycles can be accounted for, weather conditions may differ from one year to the next, and may confound interpretations of the effect that management is having on soil conditions.

For this reason people do side-by-side plot experiments and cross-fence experiments where both pieces of land have been subjected to the same weather conditions. These are often not true controlled experiments, and it is impossible to know exactly which components of a management system are causing the observed changes.

Lab experiments are another solution to the problem of variability. Soil can be gathered from plots of known management histories, subjected to treatments such as different nutrient sources, and observed under controlled and repeatable climate conditions.

***Geostatistics***

Unlike conventional statistics, geostatistics do not assume that sample values are independent. Instead, geostatistical methods assess the likelihood that two points of a given distance apart are "autocorrelated" or share the same value.

There have been many attempts to improve maps and models of soil attributes by kriging. Kriging is a way of interpolating between sample points. The first step is to develop a semivariogram from a set of data. A semivariogram describes how similar two points are likely to be, given their distance apart. From this information, values at non-sampled points can be estimated. Because soils rarely vary in a truly continuous manner, kriging is of limited effectiveness. A large number of samples are required to estimate the semivariogram.

***Modeling***

Some researchers have dealt with confounding variation through modeling. Well-designed models can isolate the effects of management changes, holding weather constant from one season to the next. Models must be interpreted appropriately. They are valuable in assessing the sensitivity of a system to a change, but they are rarely useful in predicting absolute outcomes of real systems.

## Variability as an Indicator

Perhaps the best way of dealing with background variability is to deliberately describe it and use it as an indicator of soil quality. High quality soil could be identified by its resilience, and by the amount of variation in attributes over the growing season in response to weather patterns. In a healthy soil system, some attributes may respond dramatically and thus accommodate environmental changes, while other attributes will be highly buffered and change little.

*Perhaps the best way of dealing with background variability is to deliberately describe it and use it as an indicator of soil quality.*

One way to describe variability is to determine the *scale of variation*. For example, the quality of a pasture or range could be indicated by whether different plant species vary over a scale of inches or over much larger scales (Herrick and Whitford). Herrick and Whitford also used ratios of bare spots to vegetated spots as an indicator of range quality. Ratios of soil attribute values between rows and interrows or between different parts of the landscape might also be useful.

Another way to describe the quality of land is to describe the spatial or temporal *pattern of variability*. For example, it may be useful to monitor when aggregate stability peaks during the growing season. Perhaps the pattern of change in active organic matter over the crop rotation cycle would indicate the resilience of the system.

# Chapter IV
# MAKING SOIL QUALITY ASSESSMENTS

The previous chapter was about collecting data on individual soil characteristics; this chapter is about interpreting data to make a holistic soil assessment. The goal of soil quality assessment is to monitor changes, compare soils, or assess the effectiveness of management. After discussing how farmers assess soil, this chapter will examine how to:

- choose a set of indicators,
- combine the indicators into a concise description of the soil, and
- interpret results.

Some indexes and standards for comparing soils have been proposed, but all are immature. The difficulties in developing such assessment systems point to the importance of involving the land manager in making site-specific assessments of soil quality.

Many soil assessment systems have been developed that emphasize inherent soil characteristics such as slope and soil texture. They are aimed at large-scale land use planning. Examples include the Land Capability Classification, the Canadian Land Evaluation System, and the FAO Framework for Land Evaluation.

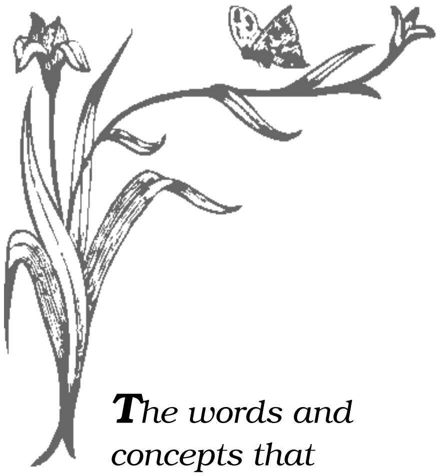
The soil quality assessments that are the focus of this publication differ from these well-established systems in their emphasis on:

- multiple soil functions in addition to crop productivity,
- dynamic soil characteristics,
- farm management practices,
- the local or farm-scale, and the involvement of land managers.

## Section 1:
## FARMERS' APPROACHES TO ASSESSING SOIL QUALITY

One notable feature of soil quality research is the importance of building linkages between scientists and farmers. Understanding and managing soil quality is a site-specific endeavor. It is about reading soil characteristics and selecting optimum practices for each unique situation. There is a limit to the usefulness of guidelines written for broad regions. Ultimately, researchers need to learn from the long-term, systems-oriented, and local observations of farmers and those who work with farmers.

*Ultimately, researchers need to learn from the long-term, systems-oriented, and local observations of farmers and those who work with farmers.*



*The words and concepts that farmers use can be linked to those of scientists in order to bridge the work of the two groups.*

Planners, researchers, and farm managers each observe soil differently, and communicate soil characteristics differently. The Wisconsin Soil Health Program (Romig et al.) has done extensive work with farmers to learn their priorities with regard to soil health. The goal of their project has been to integrate farmers' observational knowledge with scientists' analytical expertise (Garlynd et al., Harris & Bezdicek, Romig et al.).

Table 4.1 ranks the soil properties used by farmers to assess soil health, as identified by the Wisconsin Program. Besides observing different attributes, Romig et al. noted that farmers tend to have a stronger temporal perspective of their soil than do scientists. They can observe how a given field responds to different kinds of storms, or how crops respond to a variety of climatic extremes, and they have a feel for how soil aggrades or degrades over long periods of time. Farmers do not separate management and measurement of soil health. In fact, they seemed to focus more on the processes they believe create or destroy soil health than on the soil properties themselves (Romig et al., p. 233).

**Table 4.1: Soil Properties Used Most Often by Farmers to Assess Soil Health** (Romig et al.)

| | | | |
|---|---|---|---|
| 1. organic matter | 8. pH | 15. water retention | 22. growth rate |
| 2. crop appearance | 9. soil test | 16. phosphorus | 23. weeds |
| 3. earthworms | 10. yield | 17. nutrient deficiency | 24. fertility |
| 4. erosion | 11. compaction | 18. decomposition | 25. feel |
| 5. tillage ease | 12. infiltration | 19. potassium | 26. chem in groundwater |
| 6. drainage | 13. color | 20. roots | 27. surface cover |
| 7. structure | 14. nitrogen | 21. mature crop | 28. surface crust |

**F**armers observe how a given field responds to different kinds of storms, or how crops respond to a variety of climatic extremes, and they have a feel for how soil aggrades or degrades over long periods of time.

Romig et al. identify four implications of their work for scientists' study of soil quality:

1) The words and concepts that farmers use can be linked to those of scientists in order to bridge the work of the two groups.
2) Scientists could learn from the holistic viewpoint taken by farmers.
3) Farmers' priorities provide clues to priorities for soil quality research.
4) Scientists could learn from the dynamic rather than linear relationship that farmers perceive between management effects and soil health.

In other words, learning how farmers identify and communicate about soil quality will help researchers do more effective work and present it in a form that is useful in farm management.

## Section 2: CHOOSING A SET OF INDICATORS

Deciding which soil characteristics to consider when assessing land depends on the location and the purpose of the assessment. For example, electrical conductivity is more important to measure in semi-arid places susceptible to salt build-up. Different measurements would be used by someone assessing the value of the state's soil resources, a farmer deciding which tillage tool to use this spring, or a researcher trying to identify the processes that link soil quality and water quality.

Discussion has focused on developing a minimum data set—a list of specific soil measurements that could be the basis of all soil quality assessments. Most references to the minimum data set imply that the same minimum data set can be used for monitoring at the farm or regional scale. This assumes that aggregating data up or down is only a matter of designing the appropriate sampling scheme. Given how the variability of soils changes from one scale to another, this may not be a reasonable assumption. Amassing meaningful regional data from point level measurements may require an impractically dense sampling scheme. Unfortunately, non-point measurements (see beginning of Chapter III) have not been explored as much as have point indicators.

*A minimum data set—a list of specific soil measurements that could be the basis of all soil quality assessments.*

### Minimum Data Sets

The "minimum data set" is a set of measurements considered basic to assessing soil. Other measurements could be added depending on local goals and soil conditions. Table 4.2 lists a number of proposed minimum data sets.

Ideally, every soil quality researcher would make the minimum data set measurements in addition to measurements specific to their study. This would make it easier to compare studies and to construct larger databases of soil characteristics. The Soil Survey is a large data set of inherent soil characteristics, but there is little comparable information on characteristics affected by management. A data set of dynamic characteristics would illustrate the range of values possible or probable under different conditions.

The data set generated by making the minimum data set measurements can be expanded by using pedo-transfer functions to estimate further soil characteristics (formulas that estimate soil attributes by using data from basic soil measurements). This allows larger data sets to be calculated from a small set of tests. For example, water holding capacity can be estimated from soil texture.

## TABLE 4.2: PROPOSED MINIMUM DATA SETS

| *Site Characterization* | *A&C* | *Doran* | *K&P* | *L&P* | *NRC* | *NWAF* |
|---|---|---|---|---|---|---|
| landscape position | | | | | | X |
| soil classification | | | | | | X |
| management | | | | | | X |
| *Physical Characteristics* | | | | | | |
| particle size | | | | | | X |
| aggregate size/stability | X | | X | X | X | X |
| bulk density, penetration resistance | X | X | X | X | | |
| rooting depth | X | | X | X | X | |
| water holding capacity (WHC) | X | X | X | X | X | |
| infiltration, hydraulic conductivity | X | X | X | | | |
| water content | | X | | | | |
| water-filled pore space | | X | | | | |
| texture | | | | X | X | |
| *Chemical Characteristics* | | | | | | |
| nitrogen | | X | X | X | X | X |
| other nutrients | | | X | X | X | X |
| pH | X | X | X | X | X | X |
| electrical conductivity (EC), or salinity | X | X | X | X | X | X |
| total carbon:nitrogen | | | | | | X |
| organic matter | X | | X | | | X |
| cation exchange capacity (CEC) | X | | | | | X |
| base saturation (BS) | X | | | | | |
| exchangeable sodium percentage (ESP) | X | | | | | |
| *Biological Properties* | | | | | | |
| microbial biomass | | | | | | X |
| total organic carbon | | | | X | X | |
| active or labile carbon | | | | X | X | X |
| active nitrogen | | | | | | X |
| soil respiration | X | | X | | | |
| mineralizable nitrogen potential | | | X | | | |

A&C: Arshad and Coen identified these "key soil physical and chemical attributes."
Doran: Doran (1996) included these measurements in his Soil Health Kit.
K&P: MDS from Kennedy and Pappendick, p. 245.
L&P: MDS from Larson and Pierce (1994), p. 42.
NRC: MDS from the NRC's *Soil and Water Quality*.
NWAF: These are the measurements selected for use in a multi-state comparison of soil under conventional and alternative management systems which is funded by the Northwest Area Foundation (Karlen et al. 1996a).

## SECTION 3:
## COMBINING INDICATORS INTO QUANTITATIVE SOIL DESCRIPTIONS

Several quantitative methods have been proposed to describe soil quality. None are well-developed and tested.

As described in the section on variability in the previous chapter, a primary challenge to interpreting soil data is accounting for and summarizing spatial and temporal variation. Quantifying soil quality becomes especially tricky at the regional scale—soil types change drastically, and land use varies. The application of any of these approaches is limited by a lack of understanding of the numerical relationships between soil measurements and soil performance. For these reasons, indexes may be more useful in narrowly-defined soil assessments than for the general, all-purpose quantification of quality soil.

### Soil Quality Indexes

Several methods have been proposed to combine measurements of soil indicators into a numerical index. The purpose of an index is to monitor changes in soils or to compare soils at different places. In theory, this would be helpful in assessing the effects of different sets of management practices. In practice, it is unlikely that dissimilar soils could be meaningfully compared using a single index. Soil characteristics must be interpreted and weighted based on the soils' inherent characteristics.

*A numerical index may be more useful in narrowly-defined soil assessments than for the general, all-purpose quantification of quality soil.*

In addition to the soil quality indexes described below, many other formulas for assessing soil have been created this century. Most are limited to the assessment of crop productivity and inherent soil characteristics (e.g. Singh et al., Pierce et al. 1983). The indexes highlighted in these references attempt to account for soil's multiple functions.

These indexes each begin by specifying the functions soil performs, then the processes that are important to each function, and then one or more layers of soil characteristics that are indicators of the soil processes. The advantage of this hierarchical approach is that it accounts for soil's multiple functions, and the fact that a single characteristic may have different significance for each function. The same soil measurement may be given different importance and interpretation when calculating each facet of soil quality. For example, a sandy texture would have a positive effect on the infiltration of water into soil, but a negative effect on its ability to hold and deliver water to plants.

The general approach to indexes found in the soil quality literature is seen in Larson and Pierce (1991) and Pierce and Larson (1993). Soil quality can be defined numerically as a function of individual soil

attributes.  They emphasize that, although the absolute value of soil quality is important in quantifying the soil resource base, the change in soil quality is more important for understanding how to conserve and enhance soil quality.  It is impractical and unnecessary to try to define soil quality as a function of all attributes of soil, so it is necessary to develop a minimum data set that can be used to estimate the quality of soil.  Pierce and Larson point to the Productivity Index as an illustration of their concepts.

Larson and Pierce point out that not all attributes are significant in the same way for each of the different soil functions (i.e., plant growth medium, water flow regulator, environmental filter).  Doran and Parkin, and Karlen and Stott develop this idea more explicitly.

Doran and Parkin use a hierarchical system to identify relevant functions and indicators, weight their importance, and combine values into a single index.  They begin with six soil functions. The performance of each function is calculated by assessing five soil processes:

1) water flux,
2) nutrient and chemical flux,
3) root growth,
4) soil biotic habitat maintenance, and
5) the response to management and resistance to degradation.

Measurements of soil characteristics are used as indicators of soil processes.

Karlen and Stott take this same approach and develop it more formally by using systems engineering concepts (Karlen and Stott, Karlen et al. 1994).  Standard Scoring Functions[*] are used to define the relationship between soil indicators and soil functions. Then numerical or subjective ratings of each indicator can be converted to a unitless value between 0 and 1.  This unitless value is weighted depending on the importance of the attribute to the particular soil function, and all of the relevant characteristics can be multiplied into a single index.

This method accommodates a mix of subjective and objective measurements.  A major challenge to using Karlen and Stott's procedure is gathering the background data necessary to make informed estimates of how to weight soil functions and indicators.

[*] There are four different Standard Scoring Functions:  1) As the value of the indicator increases so does soil function.  2) There is an optimal range, outside of which function declines.  3) Function improves as the value of the indicator declines. 4) Soil performance is optimal except in an undesirable range.

## Statistical Quality Control: A way to measure sustainability

Measuring soil characteristics under two different management systems is a common approach for researching the effect of management and for assessing sustainability. Larson and Pierce argue against using such comparative studies of soil quality (Larson and Pierce 1994, Pierce and Larson 1993). Comparative measures at a few points in time do not necessarily assess long-term sustainability, and they do not provide information about soil process or about which practices created the measured outcome.

Instead, Larson and Pierce propose a dynamic assessment approach modeled after statistical quality control procedures used in industrial production. In this system, soil attributes are monitored regularly to identify their normal pattern and range of variation for the existing management system. A long-term upward or downward trend in a value indicates that the management system is, by definition, not sustainable.

Such monitoring also provides a baseline from which to observe the effect of a specific management change. It would illustrate the range and pattern of attribute values that are possible under the existing system. Then, any soil changes caused by subsequent management changes would become apparent as values begin to fall outside the established range.

## Multiple Variable Indicator Kriging

Smith, Halvorson, and Papendick (1993, 1994) describe this method to combine several soil quality indicators into a soil assessment. It requires that desirable ranges for each soil characteristic are specified.

First, each soil characteristic is sampled and mapped across an area. Measurements are then converted to 0 if they are acceptable or 1 if they are unacceptable, and kriging is used to estimate values at non-sampled points. (For more information about kriging see "Geostatistics" at the end of Chapter III.) A map is created showing the probabilities of each place having "acceptable" values for all of the characteristics. For example, the map created from this analysis might show where there is a 75%, 50%, and 25% chance that the soil has pH, particulate organic matter, and clay content meeting set criteria.

The cutoff values for 0 and 1, and the criteria for combinations of 0's and 1's that meet the definition of a "quality soil" can both be easily adjusted, allowing a single data set of soil characteristics to be used for multiple purposes.

Smith et al. tested kriging on a 100 X 100 meter plot. It is not clear that kriging works adequately on larger scales.

## Section 4: INTERPRETING RESULTS: SOIL QUALITY STANDARDS AND BENCHMARK SOILS

Interpreting soils data or soil quality indexes requires some standard for comparison (Table 4.3). Standards are necessary to judge whether a measurement value is desirable, and whether a given soil has the potential to be changed using management practices.

**Table 4.3: Standards for Comparison**
(After Granatstein and Bezdicek, 1992)

| |
|---|
| Native conditions |
| Another biome |
| Optimal performance conditions |
| Same place at a different time |

One potential standard is native conditions. Studies of agricultural soil quality in prairie regions frequently include samples from native prairies for comparison. This may make sense in prairie regions where small grains and even row crops have a life cycle that is similar to prairie grasses.

*Studies of agricultural soil quality in prairie regions frequently include samples from native prairies for comparison.*

In naturally-forested regions, it makes little sense to compare agricultural soils to forest soils where the life cycle and ecosystem is fundamentally different. In these regions, long term grass conditions such as at a cemetery may provide a more meaningful comparison.

Another potential standard is those "conditions that maximize agronomic, environmental, and economic performance," (Granatstein and Bezdicek p. 14). This requires identifying optimal and possible ranges for soil attributes for each soil type and potential use.

Long-term cropping studies could be valuable sources of data for establishing ranges of soil attributes that are possible under different management systems. These sites are invaluable because the soil has been under consistent and known management systems for decades. Their disadvantage is that they cover only a limited number of soils and do not represent the full range of values possible under different soil and climate conditions. Mitchell et al. lists and describes the long-term plots around the United States (see "Long-term studies" section of the "Suggested Topic Reading" appendix of this review).

One approach to setting standards is to identify ranges of values that are possible for each soil characteristic. Each characteristic may require different reference groups for setting standards. For example, potential bulk density ranges might be set for each textural class.

Ranges for another characteristic might have to be established for each soil series. Table 4.4 lists studies that measured soil characteristics from a large number of soils. These studies, and data from long-term research plots, could be starting points for establishing potential ranges for soil characteristics.

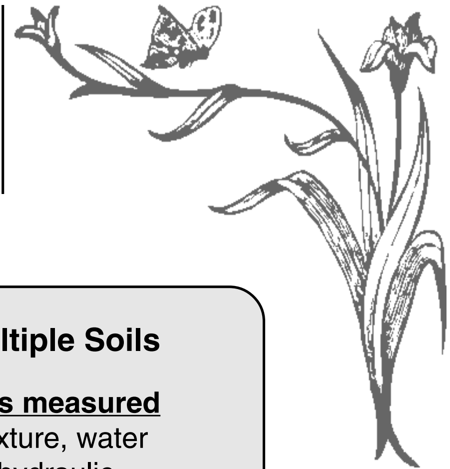


**Table 4.4: Studies Measuring Characteristics of Multiple Soils**

| Author(s) | Region or soils | Attributes measured |
|---|---|---|
| Lowery et al. | National benchmark soils identified by the NRCS in the North Central Region | Depth, texture, water content, hydraulic conductivity, bulk density |
| NC-40 | Representative soils in the North Central Region | Infiltration |
| Ankeny et al. | Iowa, Minnesota, Missouri, Nebraska, Wisconsin | Infiltration (tillage and traffic treatments) |
| Stauffer | Illinois (grass, not recently plowed) | Infiltration |
| Zwerman | Southeast United States | Infiltration (land use treatments) |
| Lehrsch & Jolley | Washington, Texas, Mississippi, Minnesota | Aggregation (seasonal changes) |
| Singh et al. | United States | Reviewed articles to set standards for: bulk density, penetration resistance, organic matter, aggregate uniformity, plasticity |

## Chapter V
# MANAGING FOR SOIL QUALITY

Writing Best Management Practices can be only one component of a successful effort to manage for soil quality.  There are trends with regard to how soil characteristics respond to management, but the way that soil characteristics interact together on a particular piece of land is unique.  Soil quality indicators require site-specific interpretations, and managing for soil quality requires site-specific recommendations.

This chapter reviews efforts to identify general principles about how management practices affect soil characteristics.  It does not address the problem of how to apply that understanding in specific situations. There is a need for planners and agricultural support staff to experiment with and create institutions and relationships that support continual learning about and monitoring of soil quality.

*There is a need for planners and agricultural support staff to experiment with and create institutions and relationships that support continual learning about and monitoring of soil quality.*

## Section 1:
## MANAGEMENT PRACTICES THAT ARE SIGNIFICANT TO SOIL QUALITY

*Tillage* has important effects on many soil characteristics.  By modifying the soil structure, it changes water infiltration, and the air and water dynamics that control microbial activity.  Tillage affects the amount of residue on the surface which changes soil temperature and water content.  The effect of tillage is determined by the shape of the implement, the number of passes, the speed and timing of tillage, and the water content and type of soil.

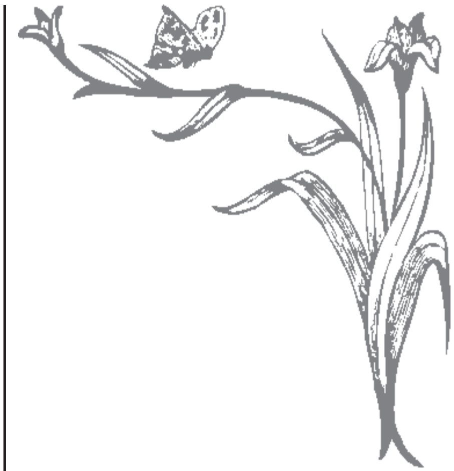
*Organic amendments* include manure, crop residue, municipal sludge and other wastes.  They are important as the food source for soil organisms and to protect the surface from temperature and moisture extremes.  The type and location of organic amendments in the soil will affect nutrient cycles, pest cycles, soil aggregation, and water movement.

The choice of *crop rotations and cover crops* affects soil quality because plants differ in their root structures, their use of nutrients, the quality and nature of the residue left behind, the type of soil manipulation required, and the pests supported.

*Pesticide* practices, the source and application of *nutrients*, and other management practices also change the soil environment.

One approach to managing for soil quality is to attempt to mimic natural systems. Doran et al. (1996:24) identify the principles that are common to what they call regenerative or biological farming systems:

- ⇑ replenish organic matter,
- ⇑ maintain living soil cover,
- ⇑ provide for a diversity of plants,
- ⇑ avoid inorganic fertilizers and pesticides, and
- ⇑ minimize tillage.



## Section 2: HOW MANAGEMENT AFFECTS SOIL QUALITY CHARACTERISTICS

### Biological and Chemical Characteristics

Biological activity depends on soil temperature, water, oxygen, pH, space (for larger organisms), and the location and nature of food sources. Any practice that changes these environmental conditions will change biological activity and related processes such as nutrient cycling, organic matter degradation, and aggregate stability.

#### *Organic matter*

The amount of organic matter in soil is a function of the amount of organic inputs, the rate of loss to biodegradation, and the rate of loss to erosion. In general terms, to increase soil organic matter it is necessary to increase the amount of residue left on the surface and in the soil, reduce tillage (aeration increases degradation), and reduce erosion. The maximum level of soil organic matter is limited by the soil texture and climate: high clay-content soils can hold more organic matter, and degradation rates increase in warmer climates.

*One approach to managing for soil quality is to attempt to mimic natural systems.*

Reicosky et al. provide a table of studies that monitored changes in soil organic matter under different management systems. Organic matter accumulation under no-till or conservation tillage ranged from 0 to 2000 lbs/ac/yr. The higher rates occurred in cooler climates and with higher residue deposition. (Negative rates, i.e., organic matter loss, occurred under some more intensive tillage systems.)

Erosion losses of organic matter can also have significant effects on organic matter levels. For example, a 5 ton/acre erosion rate of a soil with 2% organic matter would translate into 200 lbs/ac/yr of organic matter.

**Earthworms** are affected by the food supply (location, quality, and quantity), mulch protection (affects soil water and temperature), and chemical environment (fertilizers and pesticides) (Kladivko). Controlling surface residue may be the most important way to influence worm populations. This provides a food source and protects the soil from wide moisture and temperature swings. Because nightcrawlers require surface residues for food, they may not be present at all in plowed soils and will take some years to populate a field after reducing tillage. Other worms are generally present in all fields, and will increase rapidly in response to management changes.

Anhydrous ammonia will kill worms in the band where injected, but may not affect the field population. Most herbicides used in the Midwest are harmless to worms, but insecticides are commonly toxic. Fungicides and nematicides are especially toxic to earthworms (Kladivko).

***Systems research on biological and chemical characteristics*** *(Please refer to the general discussion on systems research in the Summary on page 3.)*
Wander et al. (1994, 1995) examined the effects of management on the biologically active soil organic matter pools. They used the Rodale Institute's Farming Systems Trial to compare three systems that had been running for 10 years:

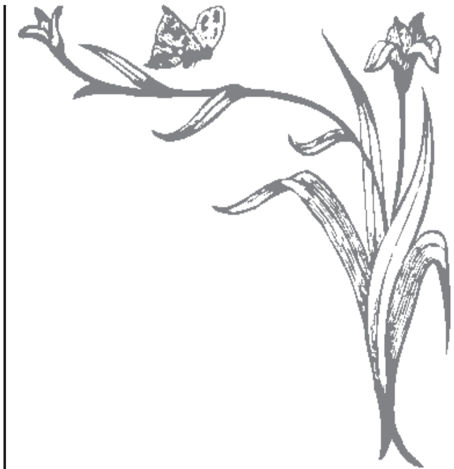
1) An organic corn/soybeans/wheat/hay rotation using animal manure as fertilizer.
2) An organic corn/soybeans/wheat/oat/barley/legume rotation using green manure as fertilizer.
3) A conventional corn/soybean rotation.

*Most herbicides used in the Midwest are harmless to worms, but insecticides are commonly toxic. Fungicides and nematicides are especially toxic to earthworms.*

The organic green manured system had accumulated the most organic matter, but the system using animal manure had more labile carbon. The organic matter in the two non-animal systems seemed to have a similar composition. Measurements suggested that the green manured system had the largest and most heterogeneous microbial population and the manured system was the least heterogeneous but the most metabolically active.

Wani et al. compared crop rotations to learn their effect on yield and on soil characteristics. They compared an 8-year rotation that included the return of plant residue and animal manure to the soil, a continuous barley system fertilized with nitrogen, and a 5-year rotation including forages and cereals but no return of residues or manure to the soil. The third treatment showed the lowest barley yields, and the first treatment showed increases in total C, N, and P; available N, P and K; CEC; microbial biomass; microbial respiration; and counts of bacteria, fungi, and mycorrhizae.

Reganold (1995) reviewed comparisons of conventional and biodynamic farming systems in Sweden, Germany, Australia, USA, and his own work in New Zealand. Biodynamic farming is similar to organic farming in that it emphasizes soil building and uses no synthetic chemical fertilizers and pesticides. It also adds eight specific preparations to soil, crops, and composts to enhance soil quality and biological processes. In general, Reganold found that soil under biodynamic systems showed improvements in physical characteristics, nutrient availability, and organic matter characteristics.



## Physical Characteristics

Bowen provides a thorough review of effects of management on soil compaction, and the formation of crusts and pans. The depth and degree of compaction is affected by:

- vehicle weight,
- weight distribution,
- soil type,
- soil water content,
- amount of traffic,
- wheel slip,
- drawbar pull, and
- vehicle speed.

There have been some efforts to combine these factors into equations that predict compaction.

Axle loads of more than 6 Mg may lead to subsoil compaction deeper than .4 meters that lasts for years. Annual winter freezing and thawing cannot be counted on to loosen subsoil compaction, and single events (such as plowing very wet soil) may be apparent in compaction and yield for years. Compaction restricts root growth and water movement. Its effect on yield depends on subsequent weather; there may be no yield loss if weather conditions are good.

*Permanent wheel traffic lanes not only improve yields by confining compaction, they also improve traction and decrease energy required for tillage.*

One approach to preventing yield losses is to establish permanent wheel traffic lanes used during all passes over the field. This not only improves yields by confining compaction, but improves tractive efficiency and mobility, and decreases the energy required for tillage.

Tillage used appropriately can loosen compaction, but is also to blame for some poor soil structure. Tillage mechanically disperses aggregates through the compaction and shearing action of implements, and causes oxidation of organic matter near the surface. The loss of organic matter means less biological activity to bind aggregates and increased rainfall impact on the bare soil.

Besides mechanical actions and oxidation, tillage changes the location of organic matter (Doran 1980). There are much higher levels of carbon, nitrogen, water, and microbes near the surface of no-till compared to conventionally-tilled soils. But the latter has more microbial activity between 7.5 and 15 cm.

### *Systems research on physical characteristics*

Researchers at the National Soil Tilth Laboratory in Ames, Iowa have compared soil quality characteristics on a conventionally- and an alternatively-managed farm, and on research plots in central Iowa

*The alternatively-managed soils showed higher water infiltration, macroporosity, and less runoff.*

*Farmers making management changes have to work through a transition period of several years before biological, physical, and productivity measures level out.*

(Thompson On-Farm Research, Logsdon et al., Berry and Karlen, Jordahl and Karlen). The conventional system had a corn/soybean rotation, used inorganic fertilizers, herbicides and pesticides, and tilled with a chisel plow and cultivator. The alternative system had a corn/beans/corn/oat/hay rotation, fertilized with manure and municipal sludge, ridge tilled, and used no herbicides.

The alternatively-managed soils showed higher water infiltration, macroporosity, and less runoff. These differences were statistically significant on the toeslope soils, but not on the hilltop soils. Very generally, increasing tillage decreased the number of earthworms. However, the effect of tillage varied from species to species. The alternative system had higher soil carbon, higher aggregate stability, and lower bulk density. The authors attributed these differences to the oats and hay in the rotation, ridge-tilling, and the addition of manure and municipal sludge.

### Further Research Needs

There has been a generous amount of research into the effects of management on specific soil characteristics. More work is needed that links management practices and soil characteristics to soil function.

The study of temporal patterns—over seasonal cycles and through management transition periods—has been neglected. There is little research that tracks the changes in soil characteristics over the year, or compares annual cycles among management systems.

Little work tracks soil changes over the transition period after a management change. (An important exception is described by Janke et al. pp. 292-4.) Researchers tend to monitor soil immediately before and after a change, or they compare management systems that have been in place for several years. Farmers making management changes have to work through a transition period of several years before biological, physical, and productivity measures level out. There is little research that will help them plan for and manage during that period.

## Section 3: INTERPRETING MANAGEMENT STUDIES

Here are some issues to consider when reading research about the relationship between management practices and soil quality.

### Relationships Among Soil Characteristics, Management, and Soil Function

Researching soil quality has meant studying soil characteristics, management practices, and soil function (Figure 1.2). Few studies simultaneously examine the relationships among all of these. Instead, they study just one of these linkages:

1) the effect of management on soil characteristics, especially key soil quality indicators;
2) the effect of management on soil function, especially yield; or
3) the relationship between soil characteristics and soil function.

When reading soil quality research, it is important to identify which of these relationships are actually being tested. There are limitations to each approach:

| Testing the link between... | provides evidence for... | but cannot show... |
|---|---|---|
| -management and soil characteristics *(e.g. comparing bulk density on a conventional and organic vegetable farm)* | -how to manipulate soil<br>-which characteristics are sensitive to management | -what are the characteristics of a well-functioning soil |
| -management and soil function *(e.g. comparing yield under no-till and conventional tillage)* | -how management affects function are involved<br>-which soil characteristics might serve as early indicators of a change in soil function | -why performance changed, or which soil processes |
| -soil characteristics and function *(e.g. comparing infiltration rate to surface water quality)* | -identifying indicators of soil function | -what caused those soil characteristics |

## Scale

Another feature to note when interpreting management and soil quality studies is at what scale the study is done and to what scale it might be relevant. Concerns about scale include:

Area — Does the study relate to a small plot, a field, a farm, a varied landscape, or a large region?

Depth — Does the research design explore processes in the top few centimeters of soil, the plow layer, the rooting zone, or 1 to 2 meters in depth? This is especially important in low-till treatments where the organic matter and biological activity are concentrated in the top 5 to 10 cm. Nutrient cycling and other processes will differ greatly beneath this depth.

Time — Does the study make single point measurements, several measurements over the annual cycle, or does it use indicators that integrate processes over time? Are measurements taken as a management change is happening, a few years after a change, or decades after a change?

## Long-Term Agricultural Research Plots

Soils under long-term experimental management are invaluable learning resources. One use of such plots is to compare soils under the established treatments. Perhaps more importantly, these plots are useful as tests of sustainability. Dick et al., for example, report the status of fields that have been under long-term no-tillage management. The yield performance varied with the soil type, but after 18 years, even the low-lying, wet soils matched conventional tillage in yield. Such information about how soil characteristics and soil function change over decades is only possible from a few research stations around the country.

Often, soils from long-term plots are used in laboratory experiments. Such research does not always directly test the treatments applied to the plots, but often takes advantage of the consistent and known management history. For example, Jordan et al. examined soil from the Sanborn Plots in Missouri to learn how microbial indicators differed under long-term cropping practices.

## GLOSSARY

**Aggregates —** soil particles held together in a small mass. Clay and organic compounds are important in binding aggregates.

**Aggregate stability —** a measure of how resistent aggregates are to destruction.

**Autocorrelation, spatial —** when the characteristics of a place are related to and can be used to predict the characteristics at a near-by place. Standard statistical tests assume that observations are independent and therefore not autocorrelated.

**Basal respiration —** the biological activity in a soil sample is usually measured by the level of carbon dioxide given off by the soil sample (see Substrate induced respiration).

**Cation exchange capacity (CEC) —** the amount of negative charges available on clay and humus to hold positively charged ions. This is the capacity of soil to hold nutrients for plant use.

**Density or Bulk density ($D_b$) —** the density of soil in the field.

**Electrical conductivity (EC) —** how well the soil conducts an electrical charge. It is a measure of salinity.

**Functional, or trophic, groups —** soil organisms grouped based on their role in the food web, e.g., detritivores, bacteriovores, or anearobic decay organisms.

**Global Positioning System (GPS) —** a system of satellites and receivers (which can be hand-held) which are used to identify the precise location of a place. This allows repeated sampling in the same location.

**Horizons —** visible layers that develop in soil as organic matter accumulates near the surface and clay and other compounds move to lower levels.

**Humus, humic compounds —** complex and highly varied compounds formed over time from organic matter. They are rather stable (resistant to biological degradation), and important in the water holding capacity and formation of soil aggregates.

**Hydraulic conductivity ($K_{sat}$) —** a measure of how easily water flows through soil (compare to infiltration).

**Immobilization —** the conversion by soil organisms of plant nutrients into microbial biomass. Immobilization makes nutrients temporarily unavailable to plants.

**Infiltration rate —** the rate at which water enters soil (compare to hydraulic conductivity).

**Keystone species —** a species which, if removed from an ecosystem, causes a dramatic change in the system, and which can be used as an indicator of the functioning of the system.

**Kriging —** a geostatistical method for estimating the value of a soil attribute at points that were not measured.

**Labile —** easily decomposed organic matter, in contrast to recalcitrant materials that are difficult for microorganisms to break down.

**Metabolic quotient ($qCO_2$) —** the ratio of microbial activity to microbial biomass.

**Minimum data set (MDS) —** a set of basic measurements for use by all researchers to assess soil quality (see Pedo-transfer functions).

**Organic matter (OM)** or **soil organic matter (SOM) —** the portion of soil derived from living organisms. Includes humus, residue at various stages of decomposition, and the cells and exudates of living organisms.

***particulate organic matter (POM)*** *or* ***light fraction (LF)*** **—** the low-density portion of soil organic matter separated out using sieving or centrifugation. It is associated with higher biological activity than the smaller, heavier fraction.

**Parent material** — the sediment, weathered rock, or other material from which a soil formed.
**Pedo-transfer functions (PTF)** — formulas that estimate soil attributes by using data from basic soil measurements. This allows a larger minimum data set from a small set of tests.
**Penetration resistance** — the ease with which a probe can be pushed into the soil.
**Potentially mineralizable nitrogen (PMN)** — organic nitrogen that could become available for use by plants.
**Soil solution** — the liquid phase of the soil including water and associated soluble material.
**Structure** — the size and arrangement of particles and pores in the soil (Oades 1984). The size, shape, and stability of aggregates. Words such as crumbly and cloddy refer to the soil structure.
**Substrate-induced respiration** — A measure of the amount of biological activity in a soil sample after adding a food source (normally sugar). It is measured by the amount of carbon dioxide given off by the soil sample.
**Texture** — the proportions of sand, silt, and clay in soil. For example, a silty-textured soil is dominated by silt-sized particles. A loamy-textured soil has a relatively even proportion of all three sizes of particles, and tends to have the optimal water and air dynamics for crop production. (Clay-sized particles are <.002mm; silt are .05-.002mm; and sand is >.05mm)
**Tilth** — a term referring to the overall physical character of soil, with regard to its suitability for crop production.
**Trophic group** — see *functional group*.
**Water holding capacity (WHC)** — the amount of water that can be held in soil against the pull of gravity. WHC is higher in loamy-textured soils and soils with high organic matter, and also depends on the structure and mineralogy of the soil.

# ABBREVIATIONS AND ACRONYMS

**AWHC** — available water holding capacity

**C** — carbon

**CEC** — cation exchange capacity

**$D_b$** — bulk density

**EC** — electrical conductivity

**EII** — Environmental Indicators Initiative (a MNDNR program)

**EMAP** — Environmental Monitoring and Assessment Program (an EPA program)

**ESAP** — Energy and Sustainable Agriculture Program (part of MDA)

**ESP** — exchangeable sodium percentage

**GPS** — global positioning system

**K** — potassium

**$K_{sat}$** — hydraulic conductivity

**MDA** — Minnesota Department of Agriculture

**MDS** — minimum data set

**MES** — Minnesota Extension Service

**N** — nitrogen

**NRCS** — Natural Resources Conservation Service (formerly SCS)

**OM** — organic matter

**P** — phosphorous

**POM** — particulate organic matter

**PMN** — potentially mineralizable nitrogen

**PTF** — pedo-transfer functions

**$qCO_2$** — metabolic quotient

**SAR** — sodium adsorption ratio

**SIR** — substrate-induced respiration

**SOM** — soil organic matter

**SSSA** — Soil Science Society of America

**WHC** — water holding capacity

## SUGGESTED TOPIC READING

## CHAPTER II

### *History*

Karlen et al. 1990 — Reviews past perceptions of the concept of soil tilth.

***Major soil quality publications*** *(See Chapter II for descriptions.)*

Acton and Gregorich. 1995 — Describes the Canadian approach to understanding and managing soil health.

*American Journal of Alternative Agriculture*. 1992 — Volume 7, No. 1/2.

Doran, J.W., D.C. Coleman, D.F. Bezdicek, B.A. Stewart (eds.) 1994 — *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35.

Doran, J.W., M. Sarrantonio, and M.A. Liebig. 1996 — Soil health and sustainability. *Advances in Agronomy* 56:1-56.

*Journal of Soil and Water Conservation*. 1995 — Volume 50, No. 3.

Larson, W.E. and F.J. Pierce. 1991 — Conservation and enhancement of soil quality. In: Evaluation for Sustainable Land Management in the Developing World Proceedings of the International Workshop on Evaluation for Sustainable Land Management in the Developing World, Chiang Rai, Thailand, 15-21 September 1991. [Bangkok, Thailand: International Board for Soil Research and Management, 1991], pp. 175-203.

National Research Council. 1993 — *Soil and Water Quality: An Agenda for Agriculture*. Washington DC: National Academy Press.

Papendick, R.I (ed.) 1991 — International Conference on the Assessment and Monitoring of Soil Quality Emmaus, PA, July 11-13, 1991. (Many of these papers appear in Volume 7, No. 1/2 of the *American Journal of Alternative Agriculture*.)

Soil Science Society of America. 1992 — *Proceedings of the Soil Quality Standards Symposium San Antonio October 23, 1990*. Washington: USDA Forest Service, WO-WSA-2.

## CHAPTER III

### *Soil quality indicators*

Hammond et al. 1995 — Describes the pressure-state-response framework for environmental indicators.

Doran, J.W. and A.J. Jones. 1996 — *Methods for Assessing Soil Quality*. Madison: Soil Science Society of America Special Publication.

NRC. 1993 — Chapters 6 & 7 and the Appendix describe methods and results of creating N and P balance sheets at the state level.

***Doran Kit***

For a description of the tests or information about acquiring the Doran Kit, contact John Doran, USDA-ARS; 116 Keim Hall, University of Nebraska, Lincoln NE 68583; 402-472-1510.

ATTRA (Appropriate Technology Transfer for Rural Areas) has a free resource package about the Doran Kit. They call it the U.S.D.A./Rodale Soil Health Kit. Call 800-346-9140.

Craig Cramer wrote a series of articles about the Doran Kit tests for New Farm Magazine: Jan 1994, pp. 17-21; Feb 1994, pp. 40-45; May/Jun 1994, pp. 46-51.

### *Reviews of biological indicators of soil quality*

Berry. 1994 — A twenty-page review of the characterisitics and actions of earthworms and other fauna. Includes a large bibliography.

Dick. 1994 — Review of which enzymes are in soil, what they do, what they indicate, and how they can be assayed and interpreted.

Hatfield and Stewart. 1994 — An edited volume titled *Soil Biology: Effects on Soil Quality*. Includes chapters on microbial ecology of reduced tillage systems, vesicular-arbuscular mycorrhizae, earthworms, nitrogen cycling, and pesticide degradation.

Kennedy and Papendick. 1995— A brief five page introduction to microbial indicators including a list of important activities of microorganisms in soil, and the major types of microbial measurements.

Linden et al. 1994 — A review of how fauna, especially earthworms, are studied, how they affect the soil, and their use as soil quality indicators. Extensive bibliography.

Stork and Eggleton. 1992 — Eight-page review includes description of activities of major types of soil invertebrates (includes springtails, earthworms, nematodes, and termites). Explanation of important measurements, and practical problems with using invertebrates as indicators.

Turco, Kennedy, and Jawson. 1994 — A chapter-length summary including many references to studies using specific microbial assays.

Visser and Parkinson. 1992 — Comparisons of three approaches to studying microbes: population (species), community (mix of species), ecosystem (soil processes).

Weaver et al. 1994 — Detailed and comprehensive descriptions of microbiological and biochemical analysis techniques.

### *Examples of studies examining microbial biomass or activity*

Anderson and Domsch. 1978 — Original description of the substrate-induced respiration technique.

Beyer. 1995 — Compared microbial activity as measured by SIR with the type of compounds in the OM. Biological activity was highly correlated with the level of aromatic SOM units.

Christensen et al. 1992 — An example of the use of nematodes to estimate bacterial activity.

Fauci and Dick. 1994a,b — Measured $qCO_2$, enzyme activity, and microbial N and C to learn whether these methods differentiate among fertilizer treatments used over the long- (59 years) and short-term. Both the fertilizing history and present practice have significant effects on biological activity.

Franzeleubbers et al. 1994 — Compared microbial biomass measures under different wheat rotations and tillage practices. The type, quantity, and placement of crop residues resulted in different biological activity.

Houot and Chaussod. 1995 — Examined how microbial biomass (measured by fumigation extraction) changed over the three years following a transition from a wheat-beet rotation to continuous corn.

Jordan et al. 1995 — Compared microbes in several of Missouri's Sanborn Plots and a nearby prairie. Microbial biomass C and enzyme assays were better indicators of cropping histories than phospholipid analyses or direct counts of fungal and bacterial biomass.

Sparling. 1992 — Measured microbial carbon and soil organic carbon in a range of soils. Showed that the ratio between the two was a more informative indicator than either alone.

Wardle et al. 1995 — An example of the potential usefulness of community level studies. They assessed the effect of management practices on three trophic levels: bacteria and fungi, bacterial and fungal feeders, and predatory nematodes. They found that management practices had different effects on the balance of these three levels, and that responses correlated better with prior environmental (weather) conditions than with concurrent conditions.

Wardle and Ghani. 1995 — Examined the correlation among SIR, fumigation-incubation, and fumigation-extraction. The correlation found at one spatial scale or range of soil variation, did not translate to other scales or levels of variation.

Winter and Beese. 1995 — Used SIR and $qCO_2$ to compare microbial activity in and between crop rows and for different soil textures.

### *Examples of studies of nitrogen cycling*

Duxbury and Nkambule. 1994 — Describes and assesses methods of measuring organic nitrogen as indicators of soil quality.

Franzluebbers et al. 1995 — A comparison of the usefulness of various methods for assessing carbon and nitrogen mineralization.

Smith. 1994 — Examines the role of microbes in nitrogen cycling and asks whether soil microbial biomass can be managed for optimal nitrogen use.

Stanford and Smith. 1972 — The original article describing the method for measuring potentially mineralizable nitrogen.

### *Examples of studies of soil fauna*

Berry and Karlen. 1993 — Observed how long-term management affects the amount and types of earthworms in Iowa.

Bohlen and Edwards. 1994 — Examined nematode communities under corn in response to a variety of nutrient sources. Includes a brief literature review of nematode studies.

Griffiths et al. 1994 — Tracks nematode populations under barley vs. fallow and under different types of manure.

Neher et al. 1995 — Examines methods of using nematodes as indicators, especially as regional scale indicators.

### *Review of physical and chemical indicators*

Arshad and Coen. 1992 — Brief introduction to physical and chemical indicators. Almost nothing about organic matter.

### *Organic matter studies*

Extensive organic matter research has been done. The following are examples of studies that examined organic matter fractions:

Bremer. 1995 — Long-term LF carbon dynamics under wheat-fallow.

Elliot et al. 1994 — Of several types of organic matter measures, they found that POM carbon and carbon mineralization were the most sensitive indicators of management differences.

Wander et al. 1994 — Describe the differences in the type of organic matter accumulated in three Rodale farming systems trials: organic manure-based, organic cover crop-based, conventional corn-beans. The cover-cropped soil accumulated the most organic matter, but the manured soil had more labile carbon.

Wander et al. 1995 — Same systems as above. Organic cover-cropped soil had the largest and most heterogeneous microbial population, and the organic-manure amended soil had the least heterogeneous and most metabolically active population.

### *Physical attributes*

Klute. 1986 — Detailed and comprehensive descriptions of physical and mineralogical analysis techniques.

Singh et al. 1992 — In developing a soil tilth index, the authors review studies that establish common ranges of values for bulk density, cone index, aggregate uniformity coefficient, organic matter, and plasticity.

### *Aggregation studies*

Beare et al. 1994 — Examined the difference in sizes of aggregates under long-term conventional and no-till.

Blackman. 1992 — Found that aggregate stability varied less over the course of the year in soils with higher levels of organic matter.

Lal et al. 1994 — Compared measures of aggregation and other physical and chemical measures under several long-term (28 years) tillage and rotation treatments.

Lehrsch and Jolley. 1992 — Measured seasonal changes in aggregate stability. Compared measurement techniques.

Monreal et al. 1995 — Identified the classes of organic compounds in abundance in soil aggregates of different sizes and under different wheat rotations.

Mulla et al. 1992 — Compared aggregate stability changes from October to March to June, and from topslope to backslope to footslope, on conventional and alternative Washington farms.

Rasiah and Kay. 1994 — Created a graphical model of the improvement in wet aggregate stability after the introduction of forage.

Unger. 1995 — Examined variation in OM and distribution of water-stable aggregates across a ridge-tilled surface.

Wagner et al. 1992 — Examined how tillage, the water content of the soil at the time of tillage, and the texture of the soil, interact to affect aggregation.

### *Infiltration studies*

Ankeny et al. 1995 — Illustrates the amount of variation in infiltration found in different tillage systems, between trafficked and un-trafficked interrows, and in different places that are apparently using the same management practices.

Logsdon et al. 1993 — Examines the effectiveness of four methods of measuring water infiltration to compare two farm management systems.

Radke and Berry. 1993 — Examines the usefulness of infiltration as a tool for detecting soil changes under different management systems. Uses three long-term cropping system experiments. Found that infiltration identified differences more often than did other measures, but the differences took several years to develop.

**data sets** — North Central Regional Committee -40 (1979) measured infiltration around the Midwest. Stauffer (1938) measured infiltration in Illinois soils.

### *Variability*

Herrick and Whitford. 1995 — A summary of ways to respond to soil variability, including using it as an indicator. Focus on rangeland.

Mausbach and Wilding. 1991 — An edited volume exploring spatial variability in soils.

Neher et al. 1995 — Examines variability of nematodes in order to determine the necessary sampling scheme for regional-scale monitoring.

Smith et al. 1993, 1994 — Describe a method for using kriging to identify areas on a landscape that meet set criteria.

# CHAPTER IV

### *Existing soil assessment systems*

Davidson. 1992 — A text on land evaluation.

Hellkamp et al. 1995 — Explains the EPA's Environmental Monitoring and Assessment Program (EMAP).

Knisel. 1980 — Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS), a model of transport and delivery.

Laflen et al. 1991a,b — Water Erosion Prediction Project (WEPP)

Leonard et al. 1987 — Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), a model of transport and delivery.

NRC. 1993, pp. 342-351 — A review of several sediment and nutrient transport models.

NRC. 1993, pp. 325-329 — A review of modeling pesticide fate and transport.

Nusser and Goebel. 1996 — Describe the National Resources Inventory (NRI) which has gathered data on about one million locations across the country. The NRI includes USLE data, and carbon values indicating cropping and management practices. It does not include WEPP data.

Renard. 1991 — Revised Universal Soil Loss Equation RUSLE

Sharpley and Williams. 1990 — Erosion/Productivity Impact Calculator (EPIC)

County Soil Surveys — Soil survey data has been compiled electronically into Soils-5 (more formally called SCS-SOI-5). For examples of application of soil survey data, see Bouma. 1989, and Bouma et al. 1993.

### *Indexes*

Granatstein and Bezdicek. 1992 — Summary of uses of and requirements for a soil quality index. Does not review specific indexes.

### *Long-term studies*

Janke et al. 1991 — An extensive summary of results from three longer-term studies of low-input systems: the Rodale Farming Systems Trial (established 1981), the Cornell Cropping Systems Experiment (established 1989), and the Rodale Low-Input, Reduced-Tillage Experiment (established 1988).

Leigh and Johnston. 1995 — A book of articles celebrating the 150th anniversary of the Rothamsted Experimental Station. Chapters 2 and 3 tell the histories of the Rothamsted and Sanborn plots. Other trials discussed are in Australia, Poland, other Eastern European countries, developing countries, and one in the Netherlands.

Mitchell et al. 1991 — Includes a complete list of research plots in North America more than 25 years old. Summarizes conclusions reached at the four oldest: Illinois' Morrow Plots, Missouri's Sanborn Field, Oklahoma's Magruder Plots, and Alabama's Old Rotation.

Rasmussen and Parton. 1994 — Use plots in Pendleton OR (begun 1931) to examine changes in soil C and N levels related to residue input. Changes have been linear over time.

# CHAPTER V

### *Reviews of effects of management*

Bowen et al. 1994 — Detailed and extensive laundry list of research into soil-plant interactions, especially compaction in relation to root development and traffic patterns.

Hornick. 1992 — Review of what factors determine the nutrient content of food.

Moncrief and Breitbach. 1995 — A guidebook to managing crop residue in Minnesota, written for NRCS and MES field workers.

Doran and Linn. 1994 — Review of how tillage affects the soil environment.

Karlen et al. 1992 — Reviews effects of conservation tillage, cover crops, and crop rotations on soil quality indicators. They emphasize the importance of raising soil carbon levels.

Moorman. 1994 — Description of how environmental factors affect pesticide degradation.

Reicosky et al. 1995 — Review of how tillage affects organic matter.

Reganold. 1995 — Review of studies of biodynamic farming and soil quality.

### *Other systems research*

Karlen et al. 1996a — Some results of a multi-state study using soil quality indicators to compare CRP land to conventionally-farmed land. For information about the Minnesota component of this project contact Maggie Alms (Blue Earth Agronomics) 507-947-3362; David Huggins (Lamberton Research Station) 507-752-7372; or Deborah Allan (UMN Dept. of Soil, Water and Climate) 612-625-3158.

Thompson On-Farm Research — Annual reports of trials on their alternatively-managed farm and comparisons to a neighboring farm.

### *Management and organic matter*

Elliot et al. 1994 — Levels of several carbon pools were compared on long-term research plots across the Great Plains and Corn Belt in order to assess the potential to sequester carbon in the soil. The measurements most affected by management were carbon mineralization and POM carbon.

Wander et al. 1994, 1995 — Compares the characteristics of organic matter under the Rodale Farming Systems Trials. These compare an organic animal-manured system, an organic green-manured system, and a conventional system.

### *Management and physical characteristics*

Jordahl and Karlen. 1993, & Logsdon et al. 1993 — Compared physical characteristics under conventional and alternative farms in central Iowa.

# BIBLIOGRAPHY


Acton, D.F. and L.J. Gregorich (eds.) 1995. *The Health of our Soils: Toward Sustainable Agriculture in Canada*. Centre for Land and Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Ontario.

Anderson, J.P.E. and K.H. Domsch. 1978. A physiological method for quantitative measurement of microbial biomass in soils. *Soil Biology and Boichemistry* 10:215-221.

Ankeny, M.D., T.C. Kaspar, and M.A. Prieksat. 1995. Traffic effects on water infiltration in chisel-plow and no-till systems. *Soil Science Society of America Journal* 59:200-204.

Arshad, M.A. and G.M. Coen. 1992. Characterization of soil quality: Physical and chemical criteria. *American Journal of Alternative Agriculture* 7:25-32

Beare, M.H., P.F. Hendrix, and D.C. Coleman. 1994. Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. *Soil Science Society of America Journal* 58:777-786.

Berry, E.C. 1994. Earthworms and other fauna in the soil. In: Hatfield, J.L. and B.A. Stewart (eds.) *Soil Biology: Effects on Soil Quality*. Boca Raton: Lewis Publishers, pp. 61-90.

Berry, E.C. and D.L. Karlen. 1993. Comparison of alternative farming systems. II. Earthworm population density and species diversity. *American Journal of Alternative Agriculture* 8:21-26.

Beyer, L. 1995. Soil microbial biomass and organic matter composition in soils under cultivation. *Biology and Fertility of Soils* 19:197-202.

Blackman, J.D. 1992. Seasonal variation in the aggregate stability of downland soils. *Soil Use and Management* 8:142-150.

Blaikie, P. and H. Brookfield. 1987. *Land Degradation and Society*. London: Methuen.

Bohlen, P.J. and C.A. Edwards. 1994. The response of nematode trophic groups to organic and inorganic nutrient inputs in agroecosystems. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 235-244.

Bouma, J. 1989. Using soil survey data for quantitative land evaluation. *Advances in Soil Science* 9:177-213.

Bouma, J., R.J. Wagenet, M.R. Hoosbeek, and J.L. Hutson. 1993. Using expert systems and simulation modeling for land evaluation at farm level: A case study from New York State. *Soil Use and Management* 9:131-139.

Bowen, H.D., T.H. Garner, and D.H. Vaughn. 1994. Advances in soil-plant dynamics. In: *Advances in Soil Dynamics, Vol. I*. ASAE Monograph No. 12, pp. 255-280, 299-304.

Bremer, E. 1995. Total and light-fraction carbon dynamics during four decades after cropping changes. *Soil Science Society of America Journal* 59:1398-1403.

Christensen, H., B. Griffiths, and S. Christensen. 1992. Bacterial incorporation of tritiated thymidine and populations of bacteriophagous fauna in the rhizosphere of wheat. *Soil Biology and Biochemistry* 24:703-709.

Cramer, C. 1994. Test your soils' health: more tests to help track soil quality. *New Farm* 16:40-45.

Davidson, D.A. 1992. *The Evaluation of Land Resources*. New York: John Wiley & Sons.

DeLuca, T.H. 1995. Putting America's soils on a white bread diet. *Journal of Soil and Water Conservation* 50:262-263.

Dick, R.P. 1994. Soil enzyme activities as indicators of soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 107-124.

Dick, W.A., E.L. McCoy, W.M. Edwards, and R. Lal. 1991. Continuous application of no-tillage to Ohio soils. *Agronomy Journal* 83:65-74.

Doran, J.W. 1980. Soil microbial and biochemical changes associated with reduced tillage. *Soil Science Society of America Journal* 44:765-771.

Doran, J.W. 1996. On-Farm Measurement of Soil Quality Indexes. Available from author at: USDA-ARS, 116 Keim Hall, University of Nebraska, Lincoln NE 68583.

Doran, J.W. and A.J. Jones. 1996. *Methods for Assessing Soil Quality*. Soil Science Society of America, Madison, WI, Special Publication 49.

Doran, J.W. and D.M. Linn. 1994. Microbial ecology of conservation management systems. In: J.L. Hatfield and B.A. Stewart (eds.) *Soil Biology: Effects on Soil Quality,* pp. 61-120.

Doran, J.W., D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (eds.) 1994. *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35.

Doran, J.W. and T.B. Parkin. 1994. Defining and assessing soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 3-22.

Doran, J.W., M. Sarrantonio, and M.A. Liebig. 1996. Soil health and sustainability. *Advances in Agronomy* 56:1-54.

Duxbury, J.M. and S.V. Nkambule. 1994. Assessment and significance of biologically active soil organic nitrogen. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 125-147.

Eash, N.S., D.L. Karlen, and T.B. Parkin. 1994. Fungal contributions to soil aggregation and soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 221-228.

Elliot, E.T. et al. 1994. Terrestrial carbon pools in grasslands and agricultural soils: Preliminary data from the Corn Belt and Great Plains regions. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 179-192.

Fauci, M.F. and R.P. Dick. 1994a. Microbial biomass as an indicator of soil quality: Effects of long-term management and recent soil amendments. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 229-234.

Fauci, M.F. and R.P. Dick. 1994b. Soil microbial dynamics: Short- and long-term effects of inorganic and organic nitrogen. *Soil Science Society of America Journal* 58:801-806 (This is a more extensive version of the previous citation).

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994. Long term changes in soil carbon and nitrogen pools in wheat managment systems. *Soil Science Society of America Journal* 58:1639-1645.

Franzluebbers, A.J., D.A. Zuberer, and F.M. Hons. 1995. Comparison of microbiological methods for evaluating quality and fertility of soil. *Biology and Fertility of Soils* 19:135-140.

Garlynd, M.J., A.V. Kurakov, D.E. Romig, and R.F. Harris. 1994. Descriptive and analytical characterization of soil quality/ health. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 159-168.

Granatstein, D. and D.F. Bezdicek. 1992. The need for a soil quality index: Local and regional perspectives. *American Journal of Alternative Agriculture* 7:12-16.

Griffiths, B.S., K. Ritz, and R.E. Wheatley. 1994. Nematodes as indicators of enhanced microbiological activity in a Scottish organic farming system. *Soil Use and Management* 10:20-24.

Hammond, A., A. Adriaanse, E. Rodenburg, D. Bryant, and R. Woodward. 1995. *Environmental Indicators: A Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development*. World Resources Institute.

Harris, R.F. and D.F. Bezdicek. 1994. Descriptive aspects of soil quality/health. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 23-35.

Hatfield, J.L. and B.A. Stewart (eds.) 1994. *Soil Biology: Effects on Soil Quality*. Boca Raton: Lewis Publishers.

Hellkamp, A.S., J.M. Bay, K.N. Easterling, G.R. Hess, B.F. McQuaid, M.J. Munster, D.A. Neher, G.L. Olson, K. Sidik, L.A. Stefanski, M.B. Tooley, and C.L. Campbell. 1995. *Environmental Monitoring and Assessment Program: Agricultural Lands Pilot Field Program Report-1993*. EPA/620/R-95/004. U.S. Environmental Protection Agency, Washington, D.C., 64 pp.

Herrick, J.E. and W.G. Whitford. 1995. Assessing the quality of rangeland soils. *Journal of Soil and Water Conservation* 50:237-242.

Hornick, S.B. 1992. Factors affecting the nutritional quality of crops. *American Journal of Alternative Agriculture* 7:63-69.

Houot, S. and R. Chaussod. 1995. Impact of agricultural practices on the size and activity of the microbial biomass in a long-term field experiment. *Biology and Fertility of Soils*. 19:309-316.

Janke, R.R., J. Mt. Pleasant, S.E. Peters, and M. Böhlke. 1991. Long-term, low-input cropping systems research. In: Board on Agriculture, NRC. *Sustainable Agriculture Research and Education in the Field: A Proceedings*. Washington D.C.: National Academy Press.

Jenny, H. 1941. *Factors of Soil Formation*. New York: McGraw-Hill.

Jordahl, J.L. and D.L. Karlen. 1993. Comparison of alternative farming systems. III. Soil aggregate stability. *American Journal of Alternative Agriculture* 8:27-33.

Jordan, D., R.J. Kremer, W.A. Bergfield, K.Y. Kim, and V.N. Cacnio. 1995. Evaluation of microbial methods as potential indicators of soil quality in historical agricultural fields. *Biology and Fertility of Soils* 19:297-302.

Joshi, J.R. 1992. *Tillage Effects on the Fate of Nitrogen Applied to Corn as Animal Manure and Fertilizer*. PhD Thesis, University of Minnesota.

Karlen, D.L., N.S. Eash, and P.W. Unger. 1992. Soil and crop management effects on soil quality indicators. *American Journal of Alternative Agriculture* 7:48-55.

Karlen, D.L., D.C. Erbach, T.C. Kaspar, T.S. Colvin, E.C. Berry, and D.R. Timmons. 1990. Soil tilth: A review of past perceptions and future needs. *Soil Science Society of America Journal* 54:153-161.

Karlen, D.L., J.C. Gardner, and M.J. Rosek. 1998. A Soil Quality Framework for Evaluating the Impact of CRP. *Journal of Production Agriculture* 11:56-60.

Karlen, D.L, M.J. Mausbach, J.W. Doran, R.G. Cline, R.F. Harris, and G.E. Schuman. 1997. Soil quality: A concept, definition, and framework for evaluation. *Soil Science Society of America Journal* 61:4-10.

Karlen, D.L. and D.E. Stott. 1994. A framework for evaluating physical and chemical indicators of soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 53-72.

Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L. Jordahl. 1994. Crop residue effects on soil quality following 10-years of no-till corn. *Soil & Tillage Research* 31:149-167.

Kennedy, A.C. and R.I. Papendick. 1995. Microbial characteristics of soil quality. *Journal of Soil and Water Conservation* 50:243-248.

Kennedy, A.C. and K.L. Smith. 1995. Soil microbial diversity and the sustainability of agricultural soils. *Plant and Soil* 170:75-86.

Kladivko, E.J. *Earthworms and Crop Management*. Purdue University Cooperative Extension Service. Agronomy Guide AY-279.

Klute, A. (ed.) 1986. *Methods of Soil Analysis, Part 1: Physical and Mineralogical Methods, 2nd Ed.* Agronomy Monographs, No. 1. Madison: American Society of Agronomy.

Knisel, W.G. 1980. *CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems.* Conservation Research Report no. 26. Washington, D.C.: Agricultural Research Service, U.S. Department of Agriculture.

Laflen, J.M., W.J. Elliot, J.R. Simanton, C.S. Holzhey, and K.D. Kohl. 1991a. WEPP, soil erodibility experiments for rangeland and cropland soils. *Journal of Soil and Water Conservation* 46:39-44.

Laflen, J.M., L.J. Lane, and G.R. Foster. 1991b. WEPP, a new generation of erosion prediction technology. *Journal of Soil and Water Conservation* 46:34-38.

Lal, R., A.A. Mahboubi, and N.R. Fausey. 1994. Long-term tillage and rotation effects on properties of a central Ohio soil. *Soil Science Society of America Journal* 58:517-552.

Lal, R., J. Kimble, E. Levine, and B.A. Stewart (eds.) 1995a. *Soils and Global Change*. Boca Raton: Lewis Publishers.

Lal, R., J. Kimble, E. Levine, and B.A. Stewart (eds.) 1995b. *Soil Management and Greenhouse Effect*. Boca Raton: Lewis Publishers.

Larson, W.E. and F.J. Pierce. 1994. The dynamics of soil quality as a measure of sustainable management. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 37-51.

Larson, W.E. and F.J. Pierce. 1991. Conservation and enhancement of soil quality. Evaluation for sustainable land management in the developing world. *Proceedings of the International Workshop on Evaluation for Sustainable Land Management in the Developing World, Chiang Rai, Thailand, 15-21 September 1991* [Bangkok, Thailand: International Board for Soil Research and Management, 1991], pp. 175-203.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: Groundwater loading effects of agricultural management systems. *Transactions of the American Society of Agricultural Engineers* 30:1403-1418.

Lehrsch, G.A. and P.M. Jolley. 1992. Temporal changes in wet aggregate stability. *Transactions of the American Society of Agricultural Engineers* 35:493-498.

Leigh, T.A. and A.E. Johnston. 1995. *Long Term Experiments in Agriculture and Ecological Sciences*. Oxford: CAB International (Reviewed in *Science* July 1995, p. 421).

Linden, D.R., P.F. Hendrix, D.C. Coleman, and P.C.J. van Vliet. 1994. Faunal indicators of soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 91-106.

Logsdon, S.D., J.K. Radke, and D.L. Karlen. 1993. Comparison of alternative farming systems. I. Infiltration techniques. *American Journal of Alternative Agriculture* 8:15-20.

Lowery, B., J. Swan, T. Schumacher, and A. Jones. 1995. Physical properties of selected soils by erosion class. *Journal of Soil and Water Conservation* 50:306-311.

Mausbach, M.J. and L.P. Wilding (eds.) 1991. *Spatial Variabilities of Soils and Landforms*. Soil Science Society of America, Madison, WI, Special Publication 28.

Mitchell, C.C., R.L. Westerman, J.R. Brown, and T.R. Peck. 1991. Overview of long-term agronomic research. *Agronomy Journal* 83:24-29.

Molina, J.A.E, H.H. Cheng, B. Nicolardot, R. Chaussod, and S. Houot. 1994. Biologically active soil organics: A case of double identity. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 169-177.

Moncrief, J.F. and D.D. Breitbach. 1995. *Crop Residue Management Systems for the Upper Midwest: A Guide for Implementation with Crop Production and Environmental Quality Perspectives*. NRCS and Minnesota Cooperative Extension Service.

Monreal, C.M., M. Schnitzer, H.R. Schulten, C.A. Campbell, and D.W. Anderson. 1995. Soil organic structures in macro and microaggregates of a cultivated brown chernozem. *Soil Biology and Biochemistry* 27:845-853.

Moorman, T.B. 1994. Pesticide degradation by soil microorganisms: Environmental, ecological, and management effects. In: J.L. Hatfield and B.A. Stewart (eds.) *Soil Biology: Effects on Soil Quality,* pp. 121-165.

Mulla, D.J., L.M. Huyck, and J.P. Reganold. 1992. Temporal variation in aggregate stability on conventional and alternative farms. *Soil Science Society of America Journal* 56:1620-1624.

National Research Council. 1993. *Soil and Water Quality: An Agenda for Agriculture*. Washington DC: National Academy Press.

Neher, D.A., S.L. Peck, J.O. Rawlings, and C.L. Campbell. 1995. Measures of nematode community structure and sources of variability among and within agricultural fields. *Plant and Soil* 170:167-181.

North Central Regional Committee 40 (NC-40). 1979. *Water Infiltration Into Representative Soils of the North Central Region*. University of Illinois Ag. Exp. Stn. Bull. #760; North Central Regional Research Publication #259.

Nusser, S.M. and J.J. Goebel. 1997. The national resources inventory: A long-term multi-resource monitoring program. *Environmental and Ecological Statistics* 4:181-204.

Papendick, R.I. (ed.) 1991. *International Conference on the Assessment and Monitoring of Soil Quality: Conference Reports and Abstracts*. Emmaus, PA: Rodale Institute. (Most of these papers were published in the *American Journal of Alternative Agriculture* Vol 7(1/2).)

Papritz, A. and R. Webster. 1995. Estimating temporal change in soil monitoring: I. Statistical theory; II. Sampling from simulated fields. *European Journal of Soil Science* 46:1-12; 13-27.

Parton, W.J., D.S. Ojima, and D.S. Schimel. 1996. Models to evaluate soil organic matter storage and dynamics. In: *Structure and Organic Matter Storage in Agricultural Soils*. M.R. Carter and B.A. Stewart (eds.) Boca Raton: Lewis Publishers, pp. 421-448.

Pierce, F.J. and W.E. Larson. 1993. Developing criteria to evaluate sustainable land management. In: J.M. Kimble *Proceedings of the Eighth International Soil Management Workshop: Utilization of Soil Survey Information for Sustainable Land Use—May 1993*. USDA, Soil Conservation Service, National Soil Survey Center.

Pierce, F.J., W.E. Larson, R.H. Dowdy, and W.A.P. Graham. 1983. Productivity of soils: Assessing long-term changes due to erosion. *Journal of Soil and Water Conservation* 38:39-44.

Radke, J.K. and E.C. Berry. 1993. Infiltration as a tool for detecting soil changes due to cropping, tillage, and grazing livestock. *American Journal of Alternative Agriculture* 8:164-174.

Rasiah, V. and B.D. Kay. 1994. Characterizing changes in aggregate stability subsequent to introduction of forages. *Soil Science Society of America Journal* 58:935-942.

Rasmussen, P.E. and W.J. Parton. 1994. Long-term effects of residue management in wheat-fallow. I. Inputs, yield, and soil organic matter. *Soil Science Society of America Journal* 58:523-530.

Reganold, J.P. 1995. Soil quality and profitability of biodynamic and conventional farming systems: A review. *American Journal of Alternative Agriculture* 10:36-45.

Reganold, J.P. 1994. Statistical analyses of soil quality: Response. *Science* 264:282-283.

Reganold, J.P. and A.S. Palmer. 1995. Significance of gravimetric versus volumetric measurements of soil quality. *Journal of Soil and Water Conservation* 50:298-305.

Reicosky, D.C., W.D. Kemper, G.W. Langdale, C.L. Douglas Jr., and P.E. Rasmussen. 1995. Soil organic matter changes resulting from tillage. *Journal of Soil and Water Conservation* 50:253-261.

Renard, K.G., G.R. Foster, G.A. Weesies, and J.P. Porter. 1991. RUSLE: The revised universal soil loss equation. *Journal of Soil and Water Conservation* 46:30-33.

Romig, D.E., M.J. Garlynd, R.F. Harris, and K. McSweeney. 1995. How farmers assess soil health and quality. *Journal of Soil and Water Conservation* 50:229-236.

Sharpley, A.N., and J.R. Williams (eds.) 1990. *EPIC—Erosion/Productivity Impact Calculator. 1. Model Documentation*. Technical Bulletin No. 1768. Washington, D.C.: U.S. Department of Agriculture, Agricultural Research Service.

Singh, K.K., T.S. Colvin, D.C. Erbach, and A.Q. Mughal. 1992. Tilth index: An approach to quantifying soil tilth. *Transactions of the ASAE* 35:1777-1785.

Smith, J.L. 1994. Cycling of nitrogen through microbial activity. In: J.L. Hatfield and B.A. Stewart (eds.) *Soil Biology: Effects on Soil Quality,* pp. 91-120.

Smith, J.L., J.J. Halvorson, and R.I. Papendick. 1993. Using multivariable indicator kriging for evaluating soil quality. *Soil Science Society of America Journal* 57:743-749.

Smith, J.L., J.J. Halvorson, and R.I. Papendick. 1994. Multiple variable indicator kriging: a procedure for integrating soil quality indicators. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 149-157.

Sparling, G.P. 1992. Ratio of microbial biomass carbon to soil organic carbon as a sensitive indicator of changes in soil organic matter. *Australian Journal of Soil Research*. 30:195-207.

Stanford, G. and S.J. Smith. 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America Proceedings* 36:465-472.

Stauffer, R.S. 1938. Infiltration capacity of some Illinois soils. *Journal of the American Society of Agronomy* 30:493-500.

Stork, N.E. and P. Eggleton. 1992. Invertebrates as determinants and indicators of soil quality. *American Journal of Alternative Agriculture* 7:38-47.

Thompson On-Farm Research. *Thompson On-Farm Research with Wallace Institute, 1994 Report*. Available from the author at 2035 - 190th St., Boone, IA 50036-7423; 515-432-1560.

Tiessen, H. 1994. The role of soil organic matter in sustaining soil fertility. *Nature* 371:783-785.

Turco, R.F., A.C. Kennedy, and M.D. Jawson. 1994. Microbial indicators of soil quality. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 73-90.

Unger, P.W. 1995. Residue management for continuous winter wheat. *Journal of Soil and Water Conservation* 50:317-320.

USDA Forest Service. 1992. *Proceedings of the Soil Quality Standards Symposium, San Antonio, TX, October 23, 1990*. WO-WSA-2.

Visser, S. and D. Parkinson. 1992. Soil biological criteria as indicators of soil quality: Soil microorganisms. *American Journal of Alternative Agriculture* 7:33-37.

Wagner, L.E., N.M. Ambe, and P. Barnes. 1992. Tillage-induced soil aggregate status as influenced by water content. *Transactions of the American Society of Agricultural Engineers* 35:499-504.

Wander, M.M., S.J. Traina, B.R. Stinner, and S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal* 58:1130-39.

Wander, M.M., D.S. Hedrick, D. Kaufman, S.J. Traina, B.R. Stinner, S.R. Kehrmeyer, and D.C. White. 1995. The functional significance of the microbial biomass in organic and conventionally managed soils. *Plant and Soil* 170:87-97.

Wani, S.P., W.B. McGill, K.L. Haugen-Kozyra, J.A. Robertson, and J.J. Thurston. 1994. Improved soil quality and barley yields with fababeans, manure, forages and crop rotation on a Gray Luvisol. *Canadian Journal of Soil Science* 74:75-84.

Wardle, D.A. 1994. Statistical analyses of soil quality. *Science* 264:281-282.

Wardle, D.A. and A. Ghani. 1995. Why is the strength of relationships between pairs of methods for estimating soil microbial biomass often so variable? *Soil Biology and Biochemistry* 27:821-828.

Wardle, D.A., G.W. Yeates, R.N. Watson, and K.S. Nicholson. 1995. The detritus food-web and the diversity of soil fauna as indicators of disturbance regimes in agro-ecosystems. *Plant and Soil* 170:35-43.

Weaver, R.W. (chair, ed. comm.) 1994. *Methods of Soil Analysis, Part 2: Microbiological and Biochemical Properties*. Madison: Soil Science Society of America.

Weil, R.R., K.A. Lowell, and H.M. Shade. 1993. Effects of intensity of agronomic practices on a soil ecosystem. *American Journal of Alternative Agriculture* 8:5-14.

Winter, K. and F. Beese. 1995. The spatial distribution of soil microbial biomass in a permanent row crop. *Biology and Fertility of Soils* 19:322-326.

# FURTHER INFORMATION


Alexander, E.B. and J.C. McLaughlin. 1992. Soil porosity as an indication of forest and rangeland soil condition (compaction) and relative productivity. In: USDA Forest Service, *Proceedings of the Soil Quality Standards Symposium*, pp. 52-61.

Angers, D.A., R.P. Voroney, and D. Cote. 1995. Dynamics of soil organic matter and corn residues affected by tillage practices. *Soil Science Society of America Journal* 59:1311-1315.

Barrow, C.J. 1991. *Land Degradation: Development and Breakdown of Terrestrial Environments*. Cambridge/New York: Cambridge University Press.

Barth, H. and P. L'Hermite (eds.) 1987. *Scientific Basis for Soil Protection in the European Community*. New York: Elsevier Science Publishing Co. Inc.

Beck, A.J., S.C. Wilson, R.E. Alcock, and K.C. Jones. 1995. Kinetic constraints on the loss of organic chemicals from contaminated soils: implications for soil-quality limits. *Critical Review of Environmental Science and Technology* 25:1-43.

Bhalla, Surjit S. 1988. Does land quality matter? *Journal of Development Economics* 29:45-62.

Boels, D., D.B. Davies, and A.E. Johnston. 1982. *Soil Degradation*. Rotterdam: A.A. Balkema.

Brklacich, M. and K.B. MacDonald. 1992. Prototype agricultural land evaluation systems for Canada: II. Selected applications and prospects. *Soil Use and Management* 8:8-15.

Carter, M.R. and B.A. Stewart (eds.) 1996. *Structure and Organic Matter Storage in Agricultural Soils*. Boca Raton: Lewis Publishers.

Cavigelli, M.A., S.R. Deming, L.K. Problyn, and R.R. Harwood (eds.) 1998. Michigan Field Crop Ecology: Managing biological processes for productivity and environmental quality. Michigan State University Extension Bulletin E-2646, 92 pp.

Christopherson, J. and E. Smith. 1995. The Tahoe landscape: A BMP education program. *Journal of Soil and Water Conservation* 50:272-274.

Dormaar, J.F. and W.D. Willms. 1990. Effect of grazing and cultivation on some chemical properties of soils in the mixed prairie. *Journal of Range Management* 43:456-460.

Easter, K.W. and M.L. Cotner. 1982. Evaluation of current soil conservation strategies. In: Halcrow et al. (eds.) *Soil Conservation Policies, Institutions, and Incentives*. Ankeny, IA: Soil Conservation Society of America.

Gomez, A. and C. Juste. 1987. Soil protection programmes and strategies in other community member states: setting up of an observation network for soil quality in France. In: *Scientific Basis for Soil Protection in the European Community.* Edited by H. Barth and P. L'Hermite. London: Elsevier Applied Science, pp. 437-443.

Gregorich, E.G. and H.H. Janzen. 1996. Storage of soil carbon in the light fraction and macroorganic matter. In Carter, M.R. and B.A. Stewart (eds.) *Structure and Organic Matter Storage in Agricultural Soils*. Boca Raton: Lewis Publishers.

Griffith, R.W., C. Goudey, and R. Poff. 1992. Current application of soil quality standards. In: USDA Forest Service, *Proceedings of the Soil Quality Standards Symposium,* pp. 1-5.

Guggenberger, G., W. Zech, L. Haumaier, and B.T. Christensen. 1995. Land-use effects on the composition of organic matter in particle-size separates of soils: II. CPMAS and solution 13C NMR analysis. *European Journal of Soil Science* 46:147-158.

Gupta, V.V.S.R., P.R. Grace, and M.M. Roper. 1994. Carbon and nitrogen mineralization as influenced by long-term soil and crop residue management systems in Australia. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 193-200.

Haan, F.A.M.-de. 1987. Effects of agricultural practices on the physical, chemical and biological properties of soils. III. Chemical degradation of soil as the result of the use of mineral fertilizers and pesticides: aspects of soil quality evaluation. In: *Scientific Basis for Soil Protection in the European Community.* Edited by H. Barth and P. L'Hermite. London: Elsevier Applied Science, pp. 211-236.

Haberern, J. 1992. A soil health index. *Journal of Soil and Water Conservation* 47:6.

Haberern, J. 1994. Prologue. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, p. xiii.

Haberern, J. 1992. Coming full circle—The new emphasis on soil quality. *American Journal of Alternative Agriculture* 7:3-4.

Halvorson, A.D. and C.A. Reule. 1994. Nitrogen fertilizer requirements in an annual dryland cropping system. *Agronomy Journal* 86:315-318.

Johnson, M.G., D.A. Lammers, C.P. Anderson, P. Rygiewicz, and J.S. Kern. 1992. Sustaining soil quality by protecting the soil resource. In: USDA Forest Service, *Proceedings of the Soil Quality Standards Symposium*, pp. 72-80.

Kozin, V.K. 1990. Energy supply of humus as a criterion for soil quality evaluation. *Soviet Soil Science* 22:122-125.

Lighthall, D.R. 1995. Farm structure and chemical use in the corn belt. *Rural Sociology* 60:505-520.

MacDonald, K.B. and M. Brklacich. 1992. Prototype agricultural land evaluation systems for Canada: I. Overview of systems development. *Soil Use and Management* 8:1-8.

Mancino, C.F. and I.L. Pepper. 1992. Irrigation of turfgrass with secondary sewage effluent: soil quality. *Agronomy Journal* 84:650-654.

Manley, J.T., G.E. Schuman, J.D. Reeder, and R.H. Hart. 1995. Rangeland soil carbon and nitrogen responses to grazing. *Journal of Soil and Water Conservation* 50:294-297.

McBride, R.A., A.M. Gordon, and P.H. Groenevelt. 1989. Treatment of landfill leachate by spray irrigation: an overview of research results from Ontario, Canada. II. Soil quality for leachate disposal. *Bulletin of Environmental Contamination and Toxicology* 42:518-525.

McBride, R.A., A.M. Gordon, and S.C. Shrive. 1990. Estimating forest soil quality from terrain measurements of apparent electrical conductivity. *Soil Science Society of America Journal* 54:290-293.

Moore, P.A., Jr., T.C. Daniel, A.N. Sharpley, and C.W. Wood. 1995. Poultry manure management. *Journal of Soil and Water Conservation* 50:321-327.

Oades, J.M. 1984. Soil organic matter and structural stability: Mechanisms and implications for management. *Plant and Soil* 76:319-337.

Ontario Ministry of Agriculture, Food and Rural Affairs. 1997. Best Management Practices, Soil Management., 72 pp.

Parr, J.F., R.I. Papendick, S.B. Hornick, and R.E. Meyer. 1992. Soil quality: Attributes and relationship to alternative and sustainable agriculture. *American Journal of Alternative Agriculture* 7:5-11.

Reganold, J.P., A.S. Palmer, J.C. Lockhart, and A.N. Macgregor. 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. *Science* 260:344-349.

Rice, C.W. and F.O. Garcia. 1994. Biologically active pools of carbon and nitrogen in tallgrass prairie soil. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 201-208.

Salunkhe, D.K. and B.B. Desai. 1988. Effects of agricultural practices, handling, processing, and storage on vegetables. In: E. Karmas and R.S. Harris (eds.) *Nutritional Evaluation of Food Processing 3rd ed*. New York: Van Nostrand Reinhold, pp. 23-71.

Sanders, D.W. 1992. International activities in assessing and monitoring soil degradation. *American Journal of Alternative Agriculture* 7:17-24.

Schumacher, T. 1994. *Tillage and Nitrogen Source Interactions on Macroporous Flow and Soil Quality*. MS Thesis, University of Minnesota.

Soil Science Society of America. 1992. *Proceedings of the Soil Quality Standards Symposium San Antonio October 23, 1990*. Washington: USDA Forest Service, WO-WSA-2.

Stockle, C.O., R.I. Papendick, K.E. Saxton, G.S. Campbell, and F.K. Van-Evert. A framework for evaluating the sustainability of agricultural production systems. *American Journal of Alternative Agriculture* 9:45-50.

Updegraff, K., S.D. Brigham, J. Pastor, and C.A. Johnston. 1994. In: J.W. Doran et al. (eds.) *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America, Madison, WI, Special Publication 35, pp. 209-219.

USDA. 1938. *Soils and Men.* USDA Yearbook of Agriculture.

Van-Kooten, G.C., W.P. Weisensel, and D. Chinthammit. 1990. Valuing trade-offs between net returns and stewardship practices: the case of soil conservation in Saskatchewan. *American Journal of Agricultural Economics* 72:104-113.

Verity, G.E. and D.W. Anderson. 1990. Soil erosion effects on soil quality and yield. *Canadian Journal of Soil Science* 70:471-484.

Warkentin, B.P. 1995. The changing concept of soil quality. *Journal of Soil and Water Conservation* 50:226-228.

Wolf, S. 1995. Cropping systems and conservation policy: The roles of agrichemical dealers and independent crop consultants. *Journal of Soil and Water Conservation* 50:263-270.

Wright, S.F. and P.D. Millner. 1994. Dynamic processes of vesicular-arbuscular mycorrhizae: A mycorrhizosystem within the agroecosystem. In: J.L. Hatfield and B.A. Stewart (eds.) *Soil Biology: Effects on Soil Quality,* pp. 29-59.

Xu, F. and T. Prato. 1995. On-site erosion damages in Missouri corn production. *Journal of Soil and Water Conservation* 50:312-316.

Zwerman P.J. 1948. The value of improved land use as measured by preliminary data on relative infiltration rates. *Journal of the American Society of Agronomy* 39:135-140.

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