Cornell Soil Health Assessment Training Manual

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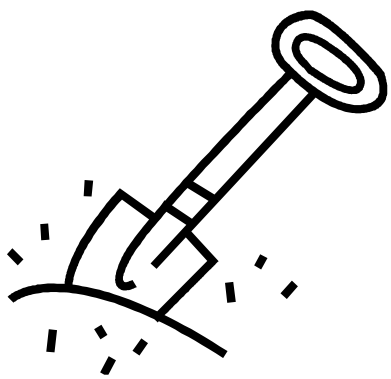
Second Edition

Cornell University
College of Agriculture and Life Sciences

Cornell Soil Health Assessment Training Manual



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Purpose of this publication

- Provide an overview of the concept of soil health
- Describe soil constraints and soil quality issues common to soils in New York and the Northeast region, especially in vegetable and field crop production systems
- Provide guidelines on how to conduct in-field qualitative and quantitative soil health assessment
- Provide a how-to guide for proper soil sampling
- Provide an overview of laboratory methods used to assess the health status of soil, the soil health report and their interpretation
- Identify management strategies for improving soil health based on measured constraints and
- Provide links to additional soil health and soil management resources.

What is soil?

Briefly, soil is composed of four basic components: mineral solids, water, air and organic matter (including living biota). The ***mineral solids*** are stone fragments, sand, silt, and clay. It is the proportion of the latter three that determines the soil's texture. For example, a soil that is composed of 70% silt, 20% sand and 10% clay can be classified as a silt loam using the soil texture triangle (Figure 1). Soil texture contributes to the inherent soil quality, the characteristics of the soil that result from soil forming processes. These characteristics are difficult to change through soil management.

Water is essential for soil life. Water is the medium that facilitates nutrient transport through the soil and enables plant nutrient uptake. Water also enables/facilitates the movement of microbes such as nematodes and bacteria through the soil.

Air is constantly moving in and out of the soil. Air provides the oxygen required for cell functioning in aerobic organisms including plant roots. Both air and water occupy the pore spaces (Figure 2) created within and between soil aggregates (clusters of sand, silt and clay particles bound together by particle surface chemistry and microbial and plant exudates).

Organic matter is any material that is part of or originated from living organisms. Organic matter may be divided into three fractions, the living, the dead (active fraction) and the very dead (stable fraction). The living soil organic matter fraction includes microorganisms, soil-dwelling insects, microarthropods, animals and plants. The dead fraction consists primarily of fresh residues from crops, recently dead microorganisms and insects, sloughed-off root cells, leaf litter, and manure, etc. This fraction is considered active. The sugars, proteins, cellulose and other simple compounds are quickly broken down (degraded) by soil microbes and used as a food source which fuels the soil microbial population. The exudates (sticky substances) produced by the microbes (and roots) as well as the microbes themselves (e.g. fungi) help bind the mineral particles together to form soil aggregates. Good soil aggregation is important for maintaining good (crumbly) soil structure and enabling adequate air exchange and water drainage. The very dead organic matter fraction is also called humus. Humus is very stable and resists further degradation. Although it is not an important food source for microbes, it is important for storing nutrients and water, binding toxic chemicals and contributing to improved aggregate stability.

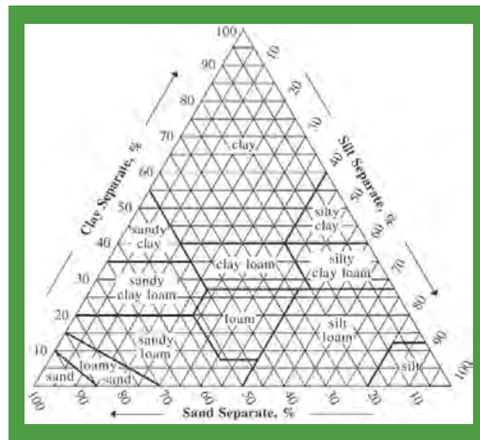


Figure 1. *The soil textural triangle.*

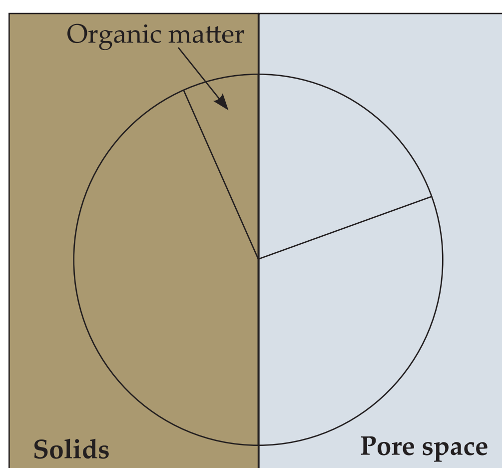
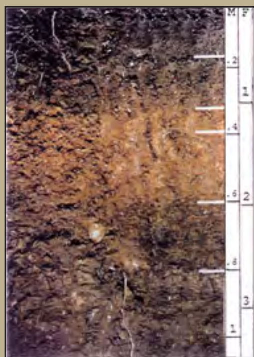
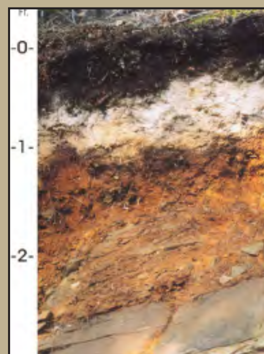


Figure 2. *Distribution of solids and pores in the soil.*

Representative and State Soils in the Northeast:

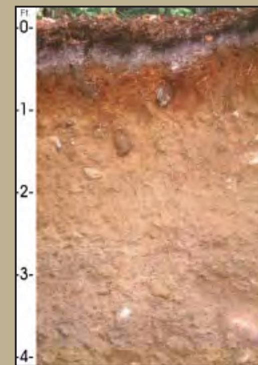


Honeoye (NY)



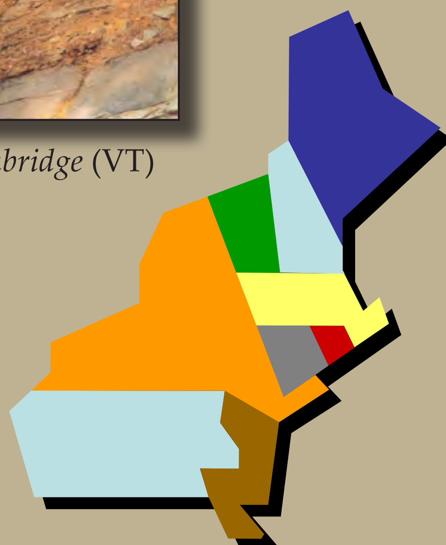
Tunbridge (VT)

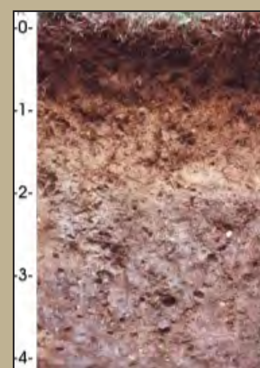
Marlow (NH)



Chesuncook (ME)

Hazleton (PA)

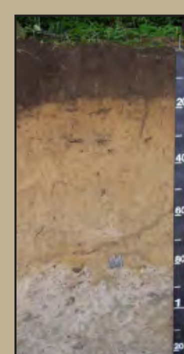




Paxton (MA)

Downer (NJ)

Windsor (CT)



Narragansett (RI)

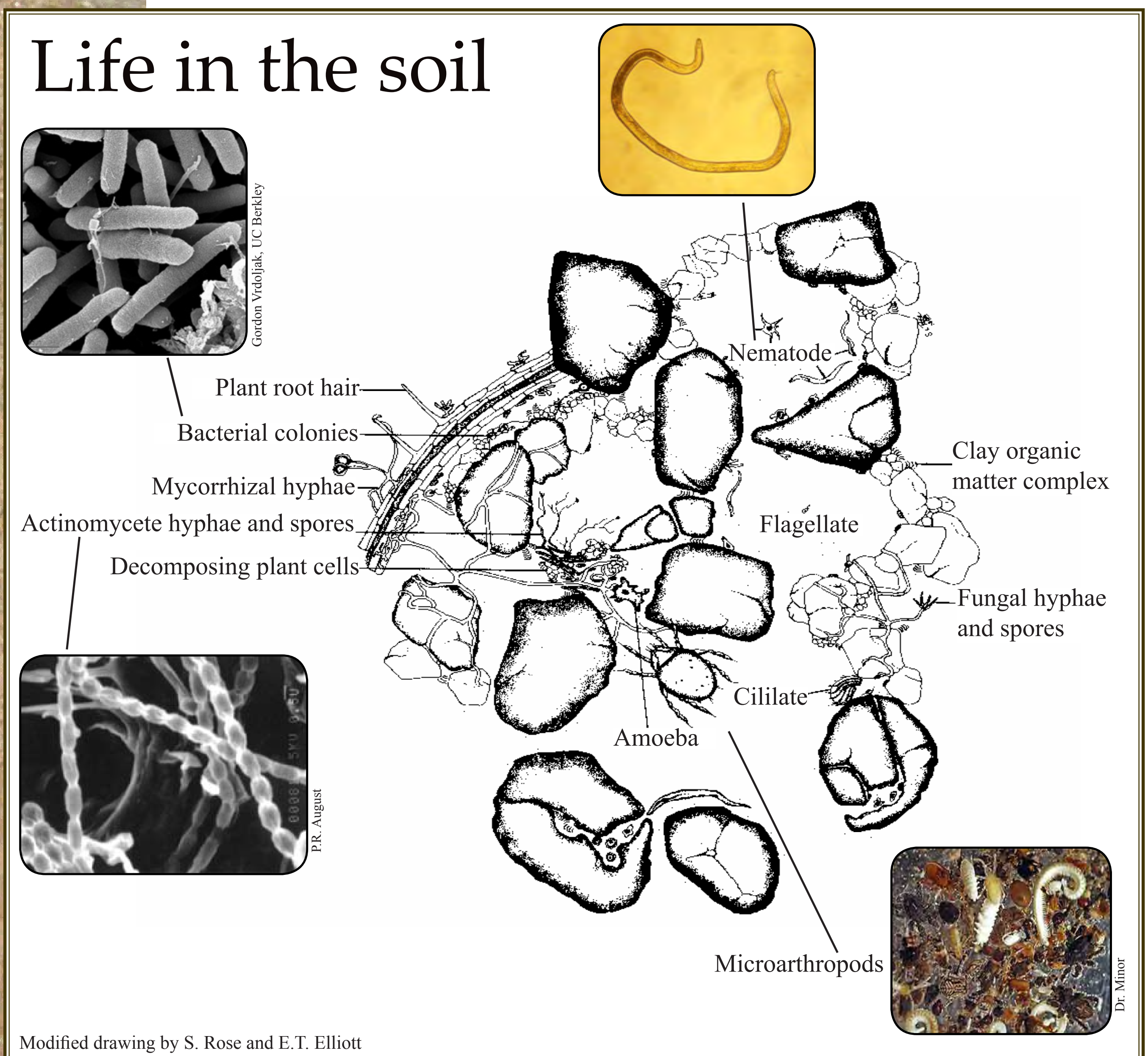
According to the National Resources Conservation Service, a state soil is represented by a soil series that has special significance to a particular state. Each state has selected a state soil. Of those, 20 have been legislatively established as "Official State Soils" and share the same level of distinction as official state flowers and birds. Areas of similar soils are grouped and labeled as a soil series. The series name is usually derived from a town or landmark in the area where the soil was first recognized. Soil series are not bound by geographic boundaries, therefore a given soil series does not necessarily occur within the confines of only one state.

Information and soil profile images from USDA - NRCS

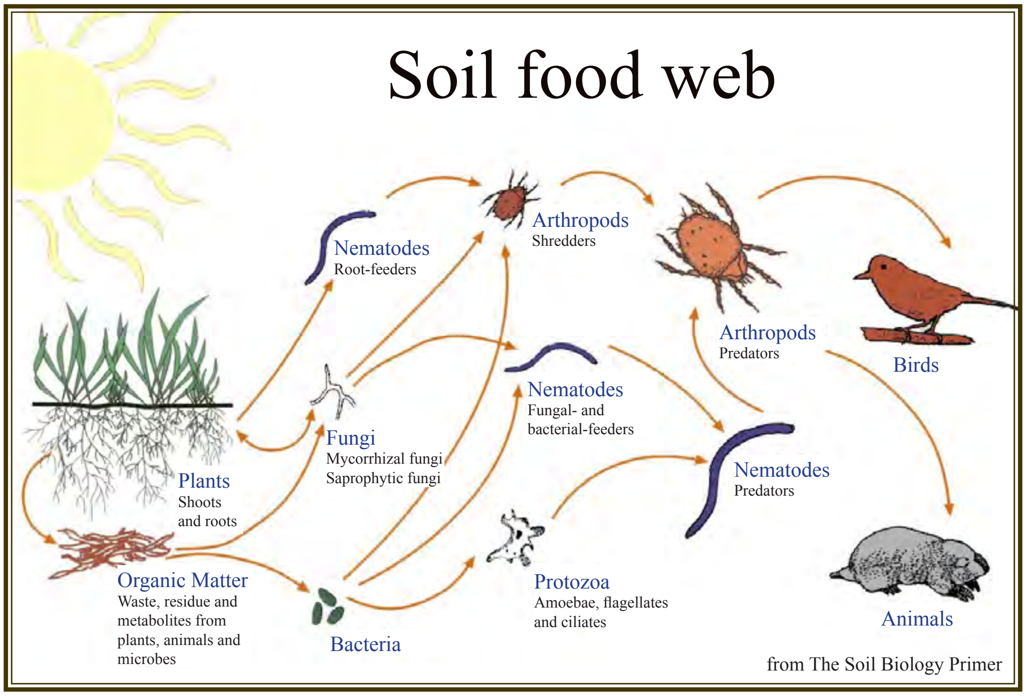
The soil is teeming with life. Soil microbes range from microscopic bacteria to macroscopic earthworms and microarthropods. Some soil scientists say that there are more species of organisms in a shovel full of garden soil than can be found above ground in the entire Amazon rain forest (NRCS).

B*acteria* are the most abundant cells in the soil. They can occur singly or join together in groups. The bacteria (as well as other organisms) in the soil are responsible for the decomposition of residues. They secrete enzymes that break down molecules such as sugars and starches into basic chemical components like carbon and nitrogen, which the bacteria can use for energy. If the nutrients are not needed by the bacteria (or other degrading organisms) then they are released into the soil and become available for plant uptake. Other types of bacteria such as rhizobia form specific associations with plants (e.g. legumes). The symbiotic relationship results in the formation of nodules by the plant. These bacteria fix nitrogen from the air and convert it to ammonium nitrogen, a form that can be used by the plant.

Actinomycetes, are another type of bacteria from which numerous antibiotics have been derived. They function to degrade the



Modified drawing by S. Rose and E.T. Elliott



larger lignin molecules in organic residues. They are also responsible for the "earthy" smell of the soil from the production of geosmin.

Fungi are also important in the decomposition of crop residues, especially the recalcitrant compounds such as hemicellulose and lignins. They are also less sensitive than bacteria to acidic conditions. Ninety percent of plants with the exception of those in the Brassica family and a few others form a symbiotic relationship with certain fungi called ***mycorrhizal fungi***. Mycorrhiza means fungus root. The fungus penetrates the root cells and forms specialized structures called arbuscules that are the site of nutrient exchange between the plant and fungus. The fungus also produces hyphae that grow out into the soil and absorb water and nutrients, especially phosphorus, and translocate them to the plant. In return, the fungus receives sugars from the plant that are used as a source of energy. Some soil-borne fungi are also pathogenic and cause diseases.

Nematodes are generally the most abundant multicellular organisms in soils. They are involved in organic matter decomposition and nutrient cycling, biological control of insects and other organisms, as well as serve as food for other soil organisms. A number are also parasites of plants and animals.

Algae are abundant in habitats with accessible light and adequate moisture. They can exist as single cells or can form long chains. Similar to plants, algae contains chlorophyll and therefore are able to convert sunlight into energy or form more complex compounds.

Protozoa are single celled animals that are classified based on their means of locomotion (cilia, flagella, etc.). They can feed directly upon microbial cells such as bacteria and fungi or they can adsorb solubilized organic and inorganic compounds. It is thought that through feeding on other soil microbes, protozoa are instrumental in mineralizing nitrogen in agricultural systems.

Large macroscopic organisms such as ***earthworms***, ***insects*** and ***millipeeds*** are important for improving aggregation, soil drainage, and aeration due to their burrowing/-channeling nature.

All the life in the soil interacts together in what is termed the **soil food web**. With organic matter as the initial primary food source the bacteria, fungi, actinomycetes and nematodes feed and release nutrients for plant uptake. Then they themselves are fed upon by larger soil organisms such as arthropods, earthworms and so on (see above diagram).

SOME KEY FUNCTIONS OF SOIL MICROBES INCLUDE:

- Decomposition of organic matter (crop residue)
- Mineralization and recycling of nutrients
- Fixation of nitrogen
- Detoxification of pollutants
- Maintenance of soil structure
- Biological suppression of plant pests
- Parasitism and damage to plants

What is soil health?

The terms soil health and soil quality are becoming increasingly familiar worldwide. Doran and Parkin (1994) defined soil quality as "the capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health." In general, soil health and soil quality are considered synonymous and can be used interchangeably. The National Resources Conservation Service (NRCS) defines soil quality or soil health similarly, but add inherent and dynamic soil quality to the definition. The inherent soil quality is defined as "the aspects of soil quality relating to a soil's natural composition and properties influenced by the factors and processes of soil formation, in the absence of human impacts." While, dynamic soil quality "relates to soil properties that change as a result of soil use and management over the human time scale."

Important soil functions related to crop production include:

- infiltration and storage of water
- retention and cycling of nutrients
- pest and weed suppression
- detoxification of harmful chemicals
- sequestering of carbon
- production of food and fiber

When the soil is not functioning to its full capacity as a result of soil constraints (see page 8) then sustainable productivity and net farmer profits over the long term are jeopardized. Below are some examples of the economic benefits of maintaining and improving soil health:

- better plant growth and yield by compaction remediation;
- reduced risk of yield loss and/or better field access during periods of environmental stress (e.g., heavy rain, drought, pest or disease outbreak);
- reduced input costs by requiring less tillage;
- reduced input costs by reducing fertilizer, pesticide, and herbicide requirements.

CHARACTERISTICS OF A HEALTHY SOIL

1. Good soil tilth

Soil tilth refers to the overall physical character of the soil in the context of its suitability for crop production (Figure 3).

2. Sufficient depth

Sufficient depth refers to the extent of the soil profile to which roots are able to grow and function. A soil with a shallow depth as a result of a compaction layer or past erosion is more susceptible to extreme fluctuations in the weather, thus predisposing the crop to drought or flooding stress.

3. Sufficient but not excess supply of nutrients

An adequate and accessible supply of nutrients is necessary for optimal plant growth and for maintaining balanced cycling of nutrients within the system. Excess nutrients can lead to leaching and potential ground water pollution, high nutrient runoff and greenhouse gas losses, as well as toxicity to plants and microbial communities.

4. Small population of plant pathogens and insect pests

In agricultural production systems, plant pathogens and pests can cause diseases and damage to the crop. In a healthy soil, the population of these organisms is low and/or inactive. This could result from direct competition from other soil organisms for nutrients or niche habitats, hyperparasitism, etc. Also, healthy plants are better able to defend themselves against a variety of pests (similar to the human immune system).

5. Good soil drainage

Even after a heavy rain, a healthy soil will drain more rapidly as a result of good soil structure and an adequate distribution of different size pore spaces, but also retain adequate water for plant uptake.

6. Large population of beneficial organisms

Soil microbes are important to the functioning of the soil. They help nutrient cycling, decomposition of organic matter, maintenance of soil structure, biological suppression of plant pests, etc. A healthy soil will have a high and diverse population of beneficial organisms to carry out these functions and thus help maintain a healthy soil status.

7. Low weed pressure

Weed pressure is a major constraint in crop production. Weeds compete with crops for water and nutrients that are essential for plant growth. Weeds can interfere with stand establishment, block sunlight, interfere with harvest and cultivation operations, and harbor disease causing pathogens and pests.

8. Free of chemicals and toxins that may harm the crop

Healthy soils are either devoid of harmful chemicals and toxins or can detoxify and/or bind such chemicals making them unavailable for plant uptake due to their richness in stable organic matter and diverse microbial communities.

9. Resistant to degradation

A healthy, well aggregated soil is more resistant to adverse events including erosion by wind and rain, excess rainfall, extreme drought, vehicle compaction, etc.

10. Resilience when unfavorable conditions occur

A healthy soil will rebound more quickly after a negative event such as harvesting under wet soil conditions or if land constraints restrict or modify planned rotations.

Figure 3. *The effect of organic matter on the same soil type managed using conventional plow tillage (left) or zone tillage for 10 years (right).*

Common soil constraints

It is important to define and characterize the major soil constraints that limit crop productivity, farm sustainability, and environmental quality. Below is a listing of soil constraints commonly observed in New York and the Northeast region of the U.S. Along with each constraint is a listing of some of the contributing factors and resulting soil conditions. Take note of where these constraints may be present on the farm or fields being monitored.

Tillage when the soil is too wet (plastic) resulting in clodding and compaction.

Soil Compaction

Ruts resulting from late fall harvest when soils are wet.

Contributing factors

- Traffic when soil is wet
- Tilling wet (plastic) soils
- Heavy equipment and loads
- Uncontrolled traffic

Can result in

- Reduced root growth
- Limited water infiltration, runoff, and erosion
- Ponding and poor aeration
- Drought sensitivity
- Increased cost of tillage
- Lower yields

Poor Aggregation and Crusting

Surface crusting in mid-spring.

Contributing factors

- Poor aggregate stability
- Low organic matter or limited organic additions
- Intensive tillage
- Limited use of soil building crops

Can result in

- Poor seedling emergence and stand establishment
- Poor water infiltration and increased occurrence of erosion and runoff
- Reduced root growth
- Less active microbial communities
- Reduced aeration
- Increased erosion

Weed Pressure

Weedy beet field.

Contributing factors

- Poor crop rotations
- Resistance to herbicides
- Poor weed management/ timing of management practices

Can result in

- Poor stand establishment and crop growth
- Poor crop quality and reduced yield
- Increased disease and pest damage
- Interference with cultural practices and harvest
- Increased cost of weed control

High Population of Soilborne Pathogens and Root Diseases

Symptoms of root rot diseases on pea roots.

Contributing factors

- Poor crop rotations
- Poor sanitary practices (people and/or equipment)
- Ineffective/ poor timing of management practices
- Low organic matter, poor physical soil quality, low microbial diversity

Can result in

- Damaged and diseased roots
- Uneven and poor growth
- Reduced yields

Low Water and Nutrient Retention

Application of liquid manure.

Contributing factors

- Low organic matter
- Poor retention/ recycling of nutrients
- Poor structure
- Excessive tillage
- Low water-holding capacity

Can result in

- Ground water pollution
- Reduced microbial community
- Nutrient deficiencies and poor plant growth
- Drought stress

Cornell Soil Health Team

Our definition of soil health...

Over the years the concepts and understanding of the importance of the soils' physical and chemical properties have been well accepted. However, it has not been until recently that the importance of understanding soil biology and biological properties has become a focus. It has been even more recent that researchers and growers have begun trying to manage the soil in a way to improve its biological properties. To us, soil health is a concept that deals with the integration and optimization of the physical, chemical and biological properties of soil for improved productivity and environmental quality (Figure 4).

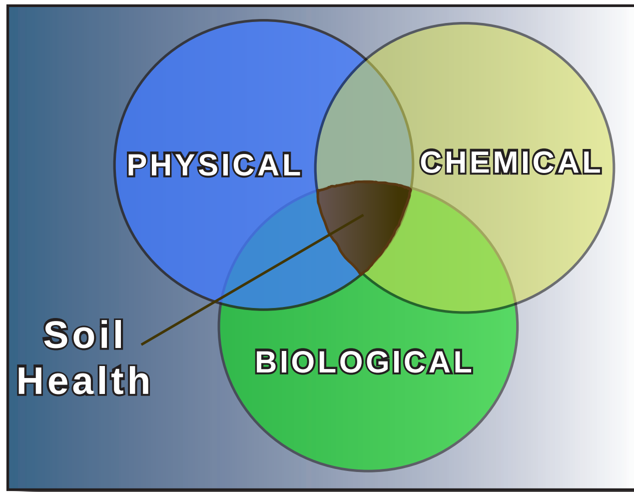


Figure 4. *The concept of soil health deals with integrating the physical, chemical and biological components of the soil (Adapted from the Rodale Institute).*

Our approach...

The Cornell Soil Health Team has been working to address soil degradation issues that have resulted in reduced soil quality, and lower crop productivity and farm profitability. Among the causes of soil degradation are soil compaction, surface crusting, low organic matter, increased pressure and damage from diseases, weeds, insects and other pests, as well as lower density and diversity of beneficial organisms. To address these issues, a group of interested growers, extension educators, researchers and private consultants established a Program Work Team with support from Cornell Cooperative Extension. One of the major accomplishments has been the development of a cost-effective protocol for assessing the health status of soils in New York and the Northeast region. The protocol is the outcome of an elaborate research process where 39 potential indicators (Table 1) were evaluated for their use in rapidly assessing soil health based on cost, response to management, etc.

Table 1. *Thirty-nine potential indicators evaluated for use in the soil health assessment protocol.*

	Physical		*Biological*		*Chemical*
1.	Bulk density	17.	Root health assessment	28.	Phosphorus
2.	Macro-porosity	18.	Beneficial nematode population	29.	Nitrate nitrogen
3.	Meso-porosity	19.	Parasitic nematode population	30.	Potassium
4.	Micro-porosity	20.	Potential mineralizable nitrogen	31.	pH
5.	Available water capacity	21.	Decomposition rate	32.	Magnesium
6.	Residual porosity	22.	Particulate organic matter	33.	Calcium
7.	Penetration resistance at 10 kPa	23.	Active carbon	34.	Iron
8.	Saturated hydraulic conductivity	24.	Weed seed bank	35.	Aluminum
9.	Dry aggregate size (<0.25 mm)	25.	Microbial respiration rate	36.	Manganese
10.	Dry aggregate size (0.25 - 2 mm)	26.	Glomalin	37.	Zinc
11.	Dry aggregate size (2 - 8 mm)	27.	Organic matter content	38.	Copper
12.	Wet aggregate stability (0.25 -2 mm)			39.	Exchangeable acidity
13.	Wet aggregate stability (2 - 8 mm)				
14.	Surface hardness with penetrometer				
15.	Subsurface hardness with penetrometer				
16.	Field infiltrability				

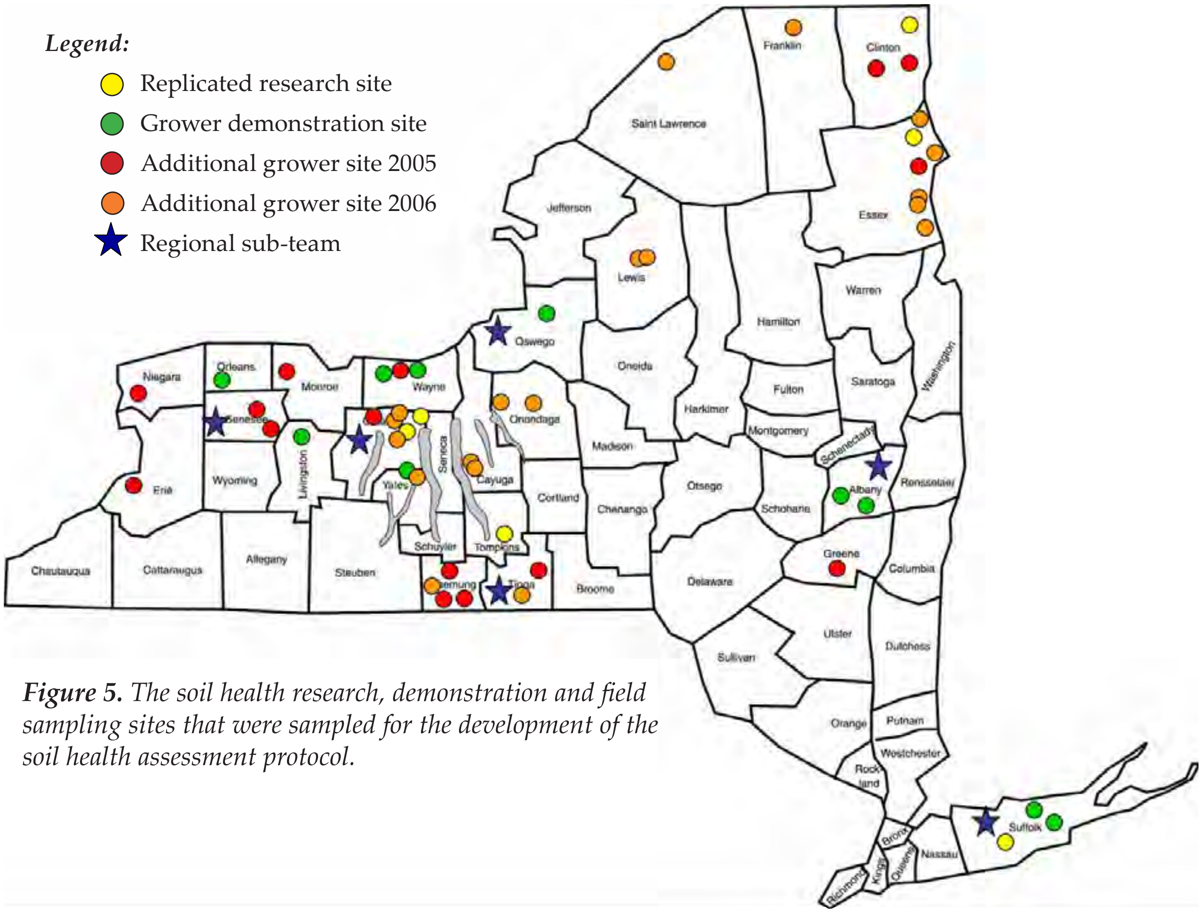


__Figure 5.__ The soil health research, demonstration and field sampling sites that were sampled for the development of the soil health assessment protocol.

In order to evaluate the thirty-nine soil health assessment indicators, soil samples were collected from replicated research trials, grower demonstration trials and from fields of interested growers from across New York State (Figure 5) and also Pennsylvania, Vermont and Maryland. The replicated research sites represent different vegetable and field crop production systems being managed using different practices in various combinations. For example, the Gates Farm in Geneva, NY is a 14-acre research site that consists of a total of 72 plots which represent three tillage (no-till/ridge-till, strip-till, and conventional tillage), three cover crop (no cover, rye, and vetch), and two rotation treatments. One rotation emphasizes continuous high-value vegetable production, while the second rotation includes season long soil-building crops (Figure 6). The grower demonstration sites are side-by-side comparisons of different management practices such as the use of a winter rye cover crop versus no cover crop or using strip tillage versus conventional moldboard plowing prior to planting sweet corn. Numerous individual fields of interested growers have been sampled in cooperation with county educators in order to build a database on the health status of New York soils. The selection of the sub-set of indicators used in the soil assessment protocol is described further on page 14.

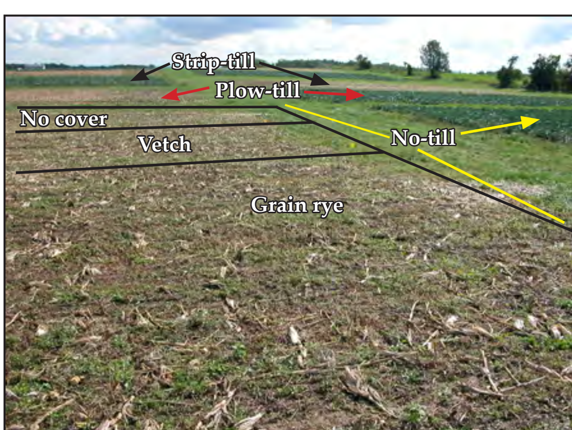


__Figure 6.__ The 14-acre long-term soil health research site at Gates Farm in Geneva, NY was established in 2003. The 72 plots represent three tillage systems, three cover crops and two rotation treatments replicated four times. One rotation (plots with green vegetation) emphasizes continuous high-value vegetable production and another rotation includes season long soil-building crops (plots with corn residue).

In-field soil health assessment

Qualitative on-farm, in-field measures of soil health involve no special analyses, only the informed scoring or rating of soil characteristics. This is usually done by visual assessment, but the smell and feel of soil may also be involved. While this approach is subjective and therefore can reflect user bias, when detailed guidelines and training have been provided the results can compare well to quantitative laboratory measurements. Some specific soil indicators, such as penetrometer resistance in the root zone, are always measured better directly in the field than in a laboratory.

Developing and using in-field assessments:

- A participatory process in developing qualitative soil health monitoring procedures locally has considerable educational value and opens up communication among farmers and between farmers and other agriculture professionals.

- Cards developed to date have utilized more than 30 physical indicators and more than 10 biological, chemical, and crop indicators of soil health. Soil physical characteristics might be scored for soil 'feel'; crusting; water infiltration, retention or drainage; and compaction. Soil biological properties might include soil smell (low score for sour, putrid or chemical odors vs. high score for 'earthy,' sweet, fresh aroma), soil color and mottling (which reflects balance of aerobic vs. anaerobic bacterial activity, among other things), and earthworm or overall biological activity.

- The rating scales used in soil health score cards vary from just a few categories ("poor, fair, or good") to scales of 1 to 10. The descriptions that define categories or rating scales are best based on local terminology and preferences. High quality photographs are an excellent way to train users and standardize scoring. See Figure 7 for an example.

POINTS TO REMEMBER:

- Training should include information on sampling, standardized verbal descriptions and/or photos that faciliate uniform scoring and keep users on track, and sufficient information regarding interpretation of results.
- To the extent possible, in-field measurements should be conducted at a similar time of year in relation to field operations, and at a similiar soil moisture and temperature.

Indicator Table

Indicator	Poor	Medium	Good
Earthworms	0-1 worms in shovelful of top foot of soil. No casts or holes.	2-10 in shovelful. Few casts, holes, or worms.	10+ in top foot of soil. Lots of casts and holes in tilled clods. Birds behind tillage.
Organic Matter Color	Topsoil color similar to subsoil color.	Surface color closer to subsoil color.	Topsoil clearly defined, darker than subsoil.
Organic Matter Roots/Residue	No visible residue or roots.	Some residue, few roots.	Noticeable roots and residue.
Subsurface Compaction	Wire breaks or bends when inserting flag.	Have to push hard, need fist to push flag in.	Flag goes in easily with fingers to twice the depth of plow layer.
Soil Tilth Mellowness Friability	Looks dead. Like brick or concrete, cloddy. Either blows apart or hard to pull drill through.	Somewhat cloddy, balls up, rough pulling seedbed	Soil crumbles well, can slice through, like cutting butter. Spongy when you walk on it.
Erosion	Large gullies over 2 inches deep joined to others, thin or no topsoil, rapid run-off the color of the soil.	Few rills or gullies, gullies up to two inches deep. Some swift runoff, colored water.	No gullies or rills, clear or no runoff.
Water Holding Capacity	Plant stress two days after a good rain.	Water runs out after a week or so.	Holds water for a long period of time without puddling.
Drainage Infiltration	Water lays for a long time, evaporates more than drains, always very wet ground.	Water lays for short period of time, eventually drains.	No ponding, no runoff, water moves through soil steadily. Soil not too wet, not too dry.
Crop Condition (How well it grows)	Problem growing throughout season, poor growth, yellow or purple color.	Fair growth, spots in field different, medium green color.	Normal healthy dark green color, excellent growth all season, across field.
pH	Hard to correct for desired crop.	Easily correctable.	Proper pH for crop.
Nutrient Holding Capacity	Soil tests dropping with more fertilizer applied than crops use.	Little change or slow down trend.	Soil tests trending up in relation to fertilizer applied and crop harvested.

Assessment Sheet

Date____________ **Crop**__________________
Farm/Field ID_______________________

Soil Quality	Poor			Medium			Good		
INDICATORS	1	2	3	4	5	6	7	8	9
Earthworms									
Organic Matter Color									
Organic Matter Roots/residue									
Subsurface Compaction									
Tilth/Friability Mellowness									
Erosion									
Water Holding Capacity									
Drainage Infiltration									
Crop Condition									
pH									
Nutrient Holding Capacity									
Other (write in)									
Other (write in)									

Assessment Guide

Indicator	Best Assessed
Earthworms	Spring/Fall Good soil moisture
Organic Matter Color	Moist soil
Organic Matter Roots/Residue	Anytime
Subsurface Compaction	Best pre-tillage or post harvest Good soil moisture
Soil Tilth Mellowness Friability	Good soil moisture
Erosion	After heavy rainfall
Water Holding Capacity	After rainfall During growing season
Drainage Infiltration	After rainfall
Crop Condition	Growing season Good soil moisture
pH	Anytime, but at same time of year each time
Nutrient Holding Capacity	Over a five year period, always at same time of year.

Figure 7. *Example score card from the Maryland Soil Quality Assessment Book (1997) published by the Natural Resource Conservation Service (available online as a pdf file at http://soils.usda.gov/sqi/assessment/state_sq_cards.html.*