Comprehensive Assessment of Soil Health

The Cornell Framework Manual

B.N. Moebius-Clune, D. J. Moebius-Clune, B.K. Gugino, O.J. Idowu, R.R. Schindelbeck, A.J. Ristow, H.M. van Es, J.E. Thies, H. A. Shayler, M. B. McBride, D.W. Wolfe, and G.S. Abawi

Third Edition

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Introduction

Soil health, or the capacity of the soil to function, is critical to human survival. Soil health constraints beyond nutrient limitations and excesses currently limit agroecosystem productivity and sustainability, resilience to drought and extreme rainfall, and progress in soil and water conservation. With mounting pressure to produce food, feed, fiber, and even fuel for an increasing population, soil health is gaining national and international attention. Research on both assessment and management of soil health, as well as farmers' innovations in soil health management approaches have matured over the decades. Multiple regional, national, and global efforts are now leveraging that work to reach new stakeholder audiences, so that soil health management is expanding into mainstream agriculture. Public recognition of the critical importance of maintaining and rebuilding healthy soils for long term sustainable agricultural production is growing. But while much progress has been made, there is much more to be done.

The more comprehensive assessment of soil health described in this manual is available to the public on a fee-for-service basis, and provides field-specific information on constraints in biological and physical processes, in addition to standard soil nutrient analysis (http://soilhealth.cals.cornell.edu/). In essence, the assessment expands on a well understood approach that has been foundational to high agricultural productivity. Just as standard soil testing has informed nutrient management based on identified deficiencies and excesses since the 1900s, the assessment developed here, similarly, identifies constraints to biological and physical soil functioning. This information then guides land managers in making targeted management decisions to plan and implement systems of soil health management practices to alleviate identified constraints and maintain healthier soils. The current (2016) version of the assessment and its interpretive scoring was developed for the Northeastern United States. However, the concepts, framework and indicators for soil health assessment

and management planning described here can be expanded and adapted for national and global applications. The most relevant components of the framework are 1) measurement of indicators that represent critical soil processes, 2) scoring of measured values that allows for interpretation, and 3) linkage of identified constraints with management practices. The main benefit of this approach is that the identification of physical biological and chemical constraints prompts farmers to seek improved and more sustainable soil and crop management practices. We hope that this framework will evolve and be used widely to measure and monitor soil health status. It is expected that a more comprehensive understanding of soil health status can lead to better, regenerative, and sustainable management of soils through holistic, adaptive, and data-driven approaches.

This manual is laid out in four parts:

I. Soil Health Concepts (1–18)

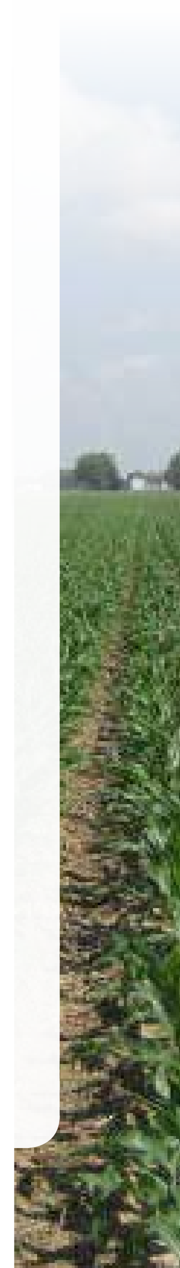
II. Soil Health Assessment (19–74)

III. Soil Health Management (75–104)

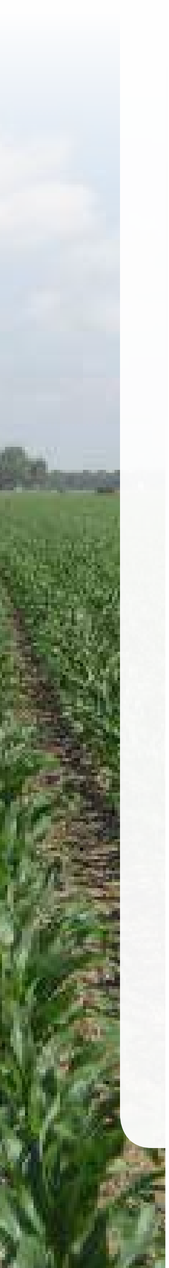
IV. Aditional Resources (105–110)

The purpose of this manual is to:

- Provide an overview of soil health concepts
- Provide an overview of Cornell University laboratory methods used to assess the health status of soil, the report generated from this more comprehensive assessment of soil health, and its interpretation
- Present a framework for soil health management planning and implementation based on information gained from soil health assessment that can be adapted for use in other land management systems, soils, and climates
- Provide a brief overview of in-field qualitative soil health assessment
- Provide a how-to guide for proper soil health sampling
- Describe soil constraints and soil health issues common to soils in the Northeast region, especially in vegetable and field crop production systems
- Identify management strategies for improving soil health based on measured constraints
- Provide guidelines for standardized and quantitative laboratory-based soil health assessment
- Provide links to additional soil health assessment and management resources



Part I
Soil Health Concepts



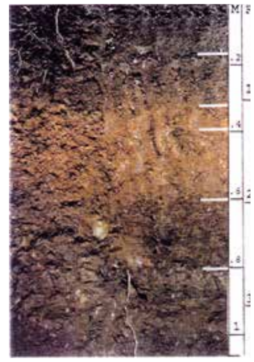
What is soil?

Representative and State Soils in the Northeast:

Soil types across the nation and the world are varied. They form with the diverse influences of local climate, organisms, topography, bedrock or underlying sediment type (parent material), and the effects of time. 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 political boundaries, therefore a given soil series does not necessarily occur within the confines of only one state. The soil map delineating the soil series informs the land manager of the soil's inherent quality, that cannot be changed through soil management.

According to the Natural Resources Conservation Service (NRCS), a state soil represents a soil series that has special significance to a particular state. Each state has selected a state soil (Figure 1.01). Of those, 20 have been legislatively established as "Official State Soils" and share the same level of distinction as official state flowers and birds.

Soil is at the foundation of everything that we and the other life on earth need to live, including food, fiber, habitat, shelter, recreational space, clean air and water, and more. But first, what is it?



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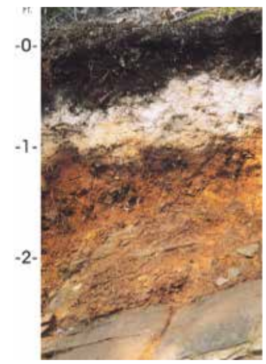

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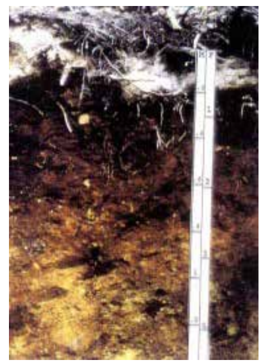
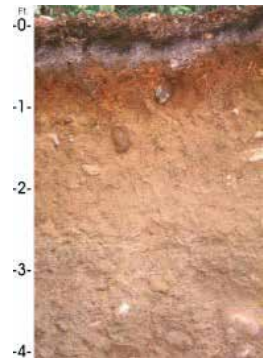
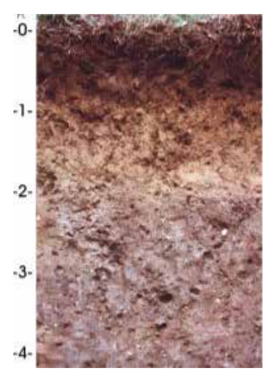


Marlow (NH)



Chesuncook (ME)

Hazleton (PA)



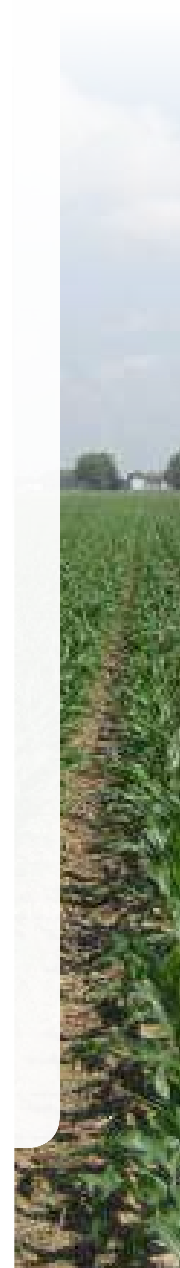
Paxton (MA)

Downer (NJ)

Windsor (CT)

Narragansett (RI)

FIGURE 1.01 Information and soil profile images from USDA-NRCS.



Soil is a dynamic interface between the lithosphere (rock), atmosphere (air), hydrosphere (water), and biosphere (living things). It is the zone in which rocks and organisms, and the air and water that move in and through and around them, interact. Soil is not just the physical parts that make it up, but also the active interactions between its various physical, biological, and chemical parts. A soil's characteristics determine how that soil functions as a foundation of the ecosystem it is part of, whether natural or managed by humans. When we discuss soil health, we are primarily concerned with the interactive processes involved with this functioning and how human management influences these processes.

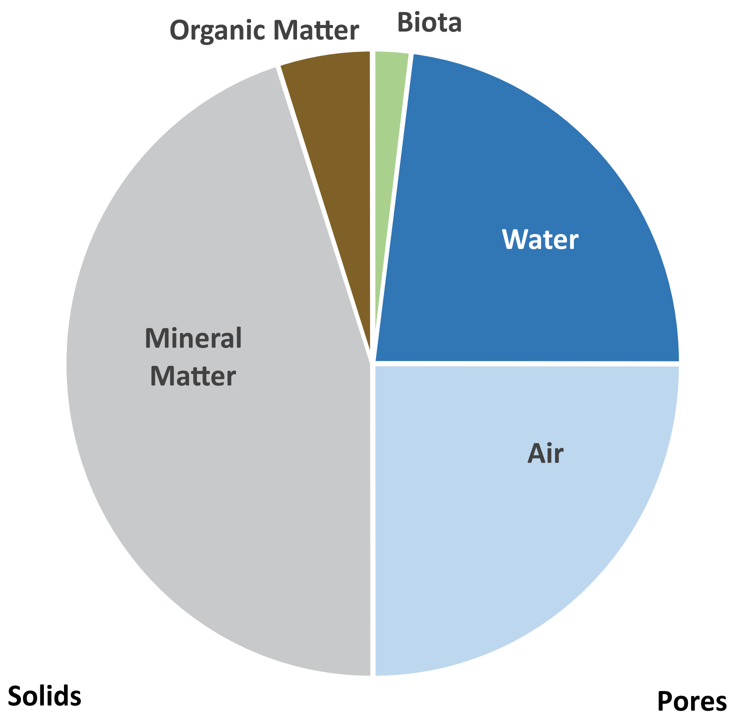


FIGURE 1.02 Distribution of solids and pores in soil. Solids are minerals, organic matter and living organisms, or biota. Pores are filled with water, air, and biota.

Physically, soil is made up of a mixture of materials, including various solids, air, and water in varying proportions (Figure 1.02). The solid components of soil include mineral and organic fractions (both living and non-living). This composition of soil strongly influences how it functions.

Mineral Solids: The large majority of the solids (in most soils) are the mineral parts, consisting of stone fragments, sand, silt, and clay. These particles are defined by their sizes, although they differ in the way they influence soil functioning beyond simply their size-related effects (Figure 1.03). The relative proportions of sand, silt and clay determine a soils texture and textural class (Figure1.04).

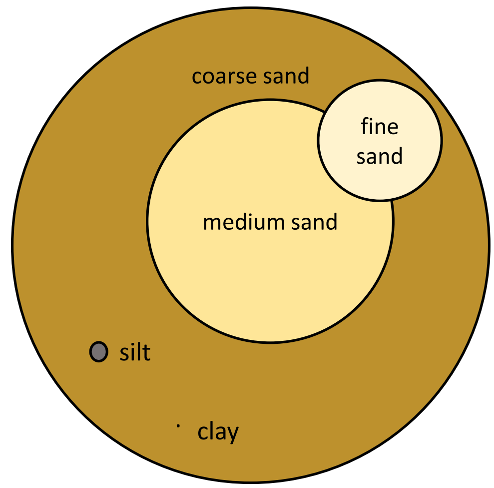


FIGURE 1.03. Reletive size of soil particles.

Texture is one of the fundamental characteristics important for quantifying how a soil is functioning. For example, the amount and type of clay, in particular, can greatly influence the ability of soils to hold and exchange nutrients, and to store organic matter. Clays have a lot of surface area because they are very small, layered, platy particles. The surfaces of most clays are negatively charged, so that positively charged nutrient ions can electrostatically 'stick' to them. This ability of soil particles to hold onto positively charged nutrient ions and exchange them with the soil water, or soil solution, is referred to as the soil's cation exchange capacity (CEC), and the surfaces to which the ions can 'stick' are the exchange complex.

Organic Matter: Soil Organic Matter (SOM or OM) is largely made up of carbon, and is any material that originated from living organisms. OM is of profound importance for soil function. It contributes to the soil's ability to hold onto nutrient ions, similarly to clay, but for an even greater range of ionic nutrients. It can also contain nutrients in its molecular structure. As soil biota (living things – see the following page on Life in the Soil) decompose the OM, nutrients can be released and become available to plants. Some of the very small particles of well decomposed organic materials become bound to fine soil mineral particles and can become protected from further biological activity inside very small soil aggregates. There it will remain more stable as part of the soil's structure. This process is known as carbon sequestration, an important process for mitigating climate change (also see page 94). Stabilized soil organic matter contributes to soil function in numerous ways, including those related to soil structure such as its capacity to store water and thus provide drought resilience.

Pores: The spaces between the solid soil particles, as mentioned previously, are called pores. These are filled with air, water, and biota. Water and air are essential for all life in the soil. Water is the medium that facilitates nutrient transport through the soil and enables plant nutrient uptake. It also allows microbes such as nematodes and bacteria to move through the soil. Air is constantly moving into and out of the soil, providing oxygen required for cell functioning in aerobic organisms including plant roots and most of the biota discussed in the following pages.

The balance of air and water depends on weather conditions, and also on the size of the pores. Pore sizes are determined in part by the sizes of the particles between

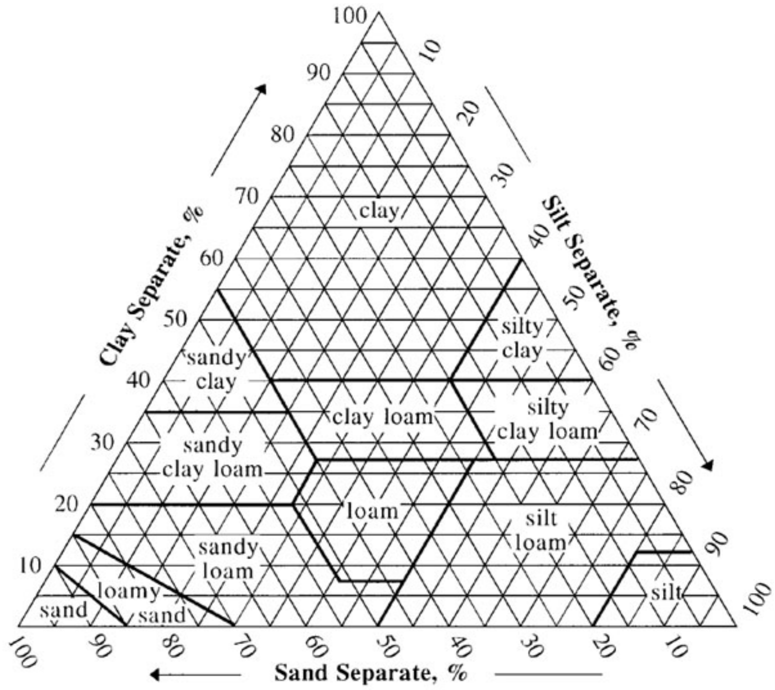


FIGURE 1.04. The soil textural triangle. For example, a soil with a texture of 70% silt, 20% sand, and 10% clay can be classified as a silt loam, one of the textural classes. *Source: USDA-NRCS*

which the spaces are formed: for example, clay soils tend to have smaller pores than sandy soils. But just as important as the sizes of the primary particles in this influence, is the aggregation, or 'clustering' of these particles into soil crumbs or aggregates, bound together by particle surface chemistry, fungal hyphae, and microbial and plant exudates (see Life in the Soil).

Just as the primary particles are of multiple sizes, soil aggregates can be of varying size, with larger aggregates made up in turn of smaller aggregates. This is referred to as soil structure, or popularly as 'tilth'. A healthy, well aggregated soil has a range of sizes of both stable crumbs and pores (Figure 1.05).

Pore sizes and their continuity determine how water moves in soil. For example, after a soil becomes wet, gravity will drain larger pores more readily than smaller ones. Due to the same forces responsible for capillary action, smaller pores will store a fraction of the water that infiltrates into the soil. Plants can access water from all but the smallest pores, which hold water too tightly to release it to plants. Thus, a well-structured soil with a range of pore sizes allows plant roots and soil dwelling organisms to have access to a good balance of air from the larger pores that drain readily through gravity, and water from the smaller pores that store water.

Life in the soil

The soil is teeming with life. Some soil scientists say that there are likely more species of organisms in a shovel full of garden soil than exist above ground in the entire Amazon rain forest (NRCS). There are many groups of soil-dwelling organisms, which range in size from those that are easy to see, such as earthworms and arthropods, to those that are microscopic, such as bacteria. Understanding these organisms and their needs, and how they influence soil functioning, can help us improve soil health. The initial source of food that drives the soil food web is organic material (e.g. leaves, roots, sticky substances called 'exudates', Figure 1.06). Just like us, biota need energy. Plants gather this energy from the sun as they fix CO_2 from the atmosphere into sugars via photosynthesis. Most other organisms need to consume energy rich materials that are directly or indirectly sourced from plants. Without plentiful plant-derived organic inputs, the soil food web cannot thrive. In essence, managers of healthy soils need to feed, and provide good habitat for, their "livestock" living underground.

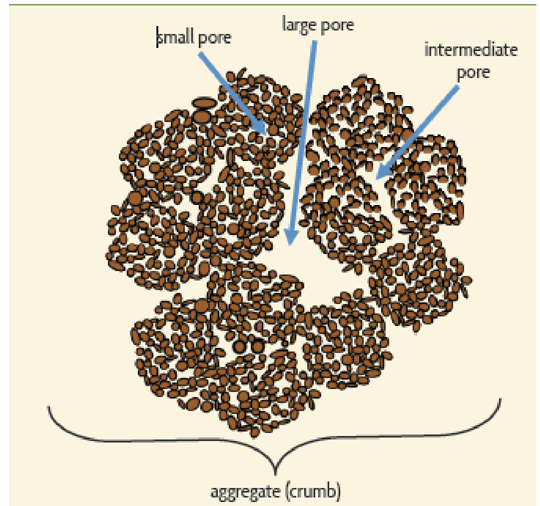


FIGURE 1.05. A healthy soil is well aggreated with a range of pore sizes. *Source: Building Soils for Better Crops*

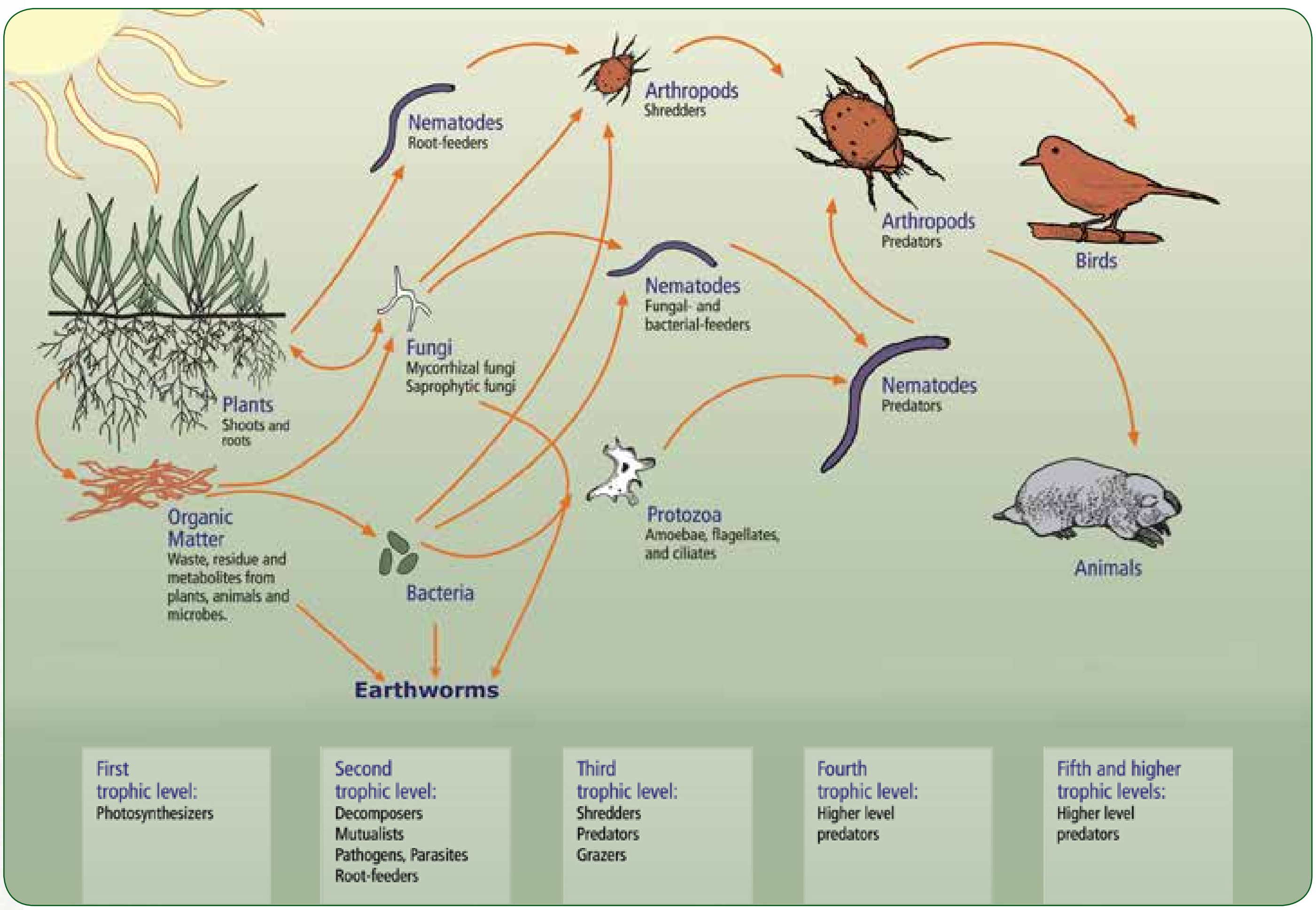


FIGURE 1.06. The soil food web. Relationship between the soil food web, plants, organic matter and animals. *Source: USDA- NRCS*

Earthworm. *Source: USDA-NRCS*

If we 'follow' a piece of plant residue into the soil, it will help organize a brief survey of some important soil biota. Picture a leaf falling to the soil surface... earthworms and arthropods are some of first organisms likely to interact with the leaf (Figure 1.07 and 1.08).

Earthworms physically drag organic material into the soil from the surface, exposing it to the activity of other soil biota. There are a number of different types of soil dwelling earthworms (or annelids, that differ from roundworms or nematodes, and will be discussed shortly). While many of these would be considered invasive exotic species in forested systems, their presence and activity are generally considered quite welcome and a sign of a healthy system in agricultural soils. Earthworms burrow through the soil, consuming the solids (including both mineral and organic matter). They digest some of the nutritious material and 'egest' the remainder as 'casts'. These worm castings are coated with microbial cultures from the worm's gut, which can contribute to both building stable aggregates and suppressing plant disease, depending on the type of worm. They help break down organic matter, mix materials in the soil profile, alleviate compaction, and develop soil pores. Earthworms support the microbial community, and in addition are often considered to be themselves good indicators of the health status of the soil, as they tend to be both easily visible and sensitive to management. Their numbers decline when conditions and management negatively impact a variety of soil processes.

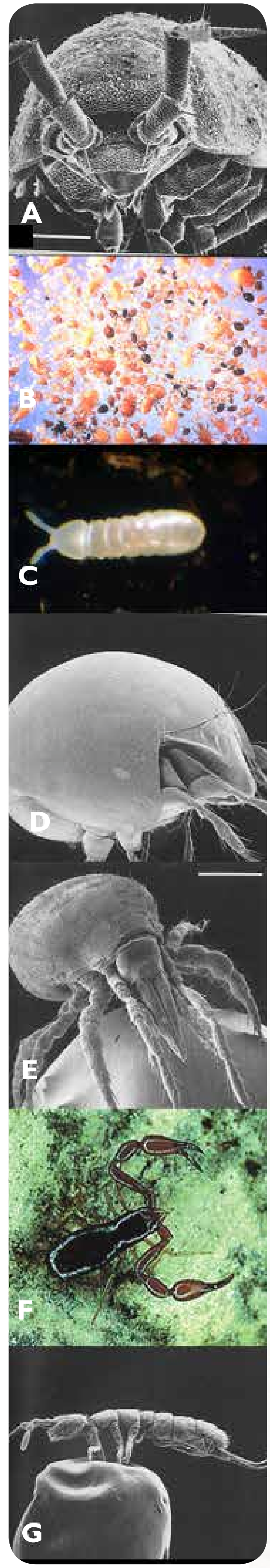


FIGURE 1.07. Various Arthropods feed on decaying OM and break larger pieces down into smaller ones: A) Sowbug, B) 200 species of mites, C & G) springtail, D) Oribatid turtle-mite, E) Predatory Pergamasus mite, F) Pseudoscorpion. Photos credit: Soil and Water Conservation Society

Arthropods, including spiders, mites, and other insects, also interact early with organic matter added to a system. These animals are small from our perspective but immense compared with many of the other soil biota. Among their more important activities with regard to soil functioning, they break larger organic matter pieces down into smaller pieces (shredding), expose the organic matter to microbial cultures (inoculation), and mix the soil materials (bioturbation).

Bacteria and Fungi: Some of the organic material we are following into the soil is directly digested by the annelids and arthropods, although material inoculated with bacteria and fungi is ultimately broken down by them more thoroughly. This is due to both bacteria and fungi producing digestive enzymes that they release into their surroundings. They then absorb the breakdown products and release nutrient ions for plant uptake in the process. This activity is important for carbon and nutrient cycling, and of course for residue management as well. It would be quite inconvenient for management if plant residues and roots continued to accumulate in the soil environment.

Protozoa: As the bacterial colonies grow on and around the degrading organic matter, larger mobile organisms such as ciliates, flagellates, and amoebae (which, informally, may be collectively referred to as protozoans) may consume them. These organisms are single-celled, yet larger than the bacterial cells, and generally live and move about in the thin films of water that can be found on the surfaces of most of the soil solids. These protozoans may also consume algal cells and cyanobacterial cells that grow in habitats with access to sunlight, where they get their energy through photosynthesis, as plants do.

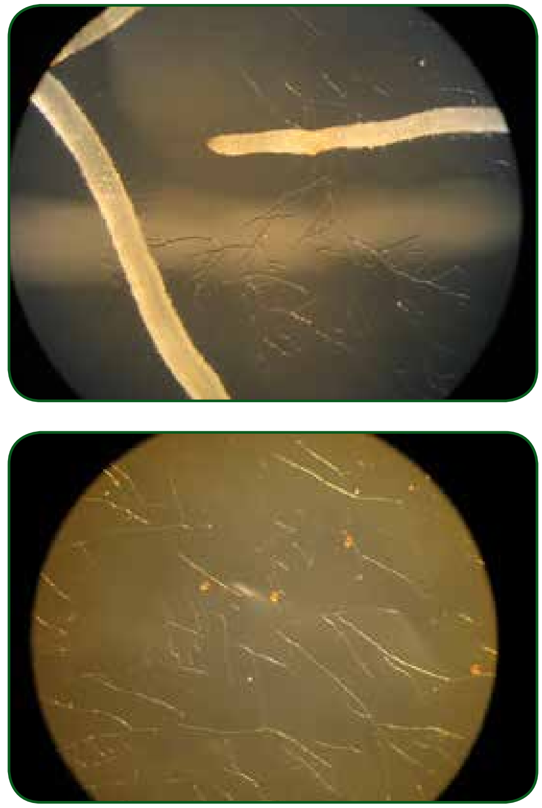


FIGURE 1.08. Arbuscular mycorrhizal fungi, growing out of carrot roots (top), and showing network of hyphae and spores (bottom).

Enzymatic breakdown of cellulose:

Cellulose is the main component of plant cell walls, and therefore a large bulk of plant material. It is a large, or high molecular weight compound that has to be broken apart by the enzymes that microbes release, before the smaller breakdown products can be taken up and used as an energy source. Bacteria and fungi produce different and complementary kinds of cellulose degrading enzymes. As the cellulose in the cell wall materials is broken down, other compounds become more exposed and therefore available for uptake by the microbial community. Smaller compounds like amino acids or sugars, or salts can then be taken up directly. Larger compounds, such as proteins, need further breakdown first. Some of these enzymes in fact are the very same enzymes that are being explored for use in cellulosic ethanol production, where cellulose from biomass crops is broken down by enzymes into sugars. Sugars are then fermented by bacterial culture to produce alcohol, which we can use as a liquid fuel.

Nematodes: Larger, yet still microscopic, multicellular animals called nematodes (or roundworms, Figure 1.09) similarly live and move about in the water films, and may consume the bacteria, fungi, and protozoa. There are numerous groups of nematodes, including those that feed on bacteria, fungi, or even other nematodes. Some parasitic nematodes feed on plants or animals – including several agricultural pest. There have been reports of nematodes which contribute to suppression of plant disease by consuming plant pathogens. Some researchers have characterized nematode diversity as an index to represent soil biological and functional diversity, and therefore soil health.

Nutrient Benefits from Decomposition: As organisms feed on organic matter, or on each other, they respire or 'burn off' much of the carbon present in the food (this respiration is representative of general biological activity, and is measured as a soil health indicator). As they do so, they accumulate a small portion of the total carbon, as well as nitrogen and

FIGURE 1.09. Nematodes.

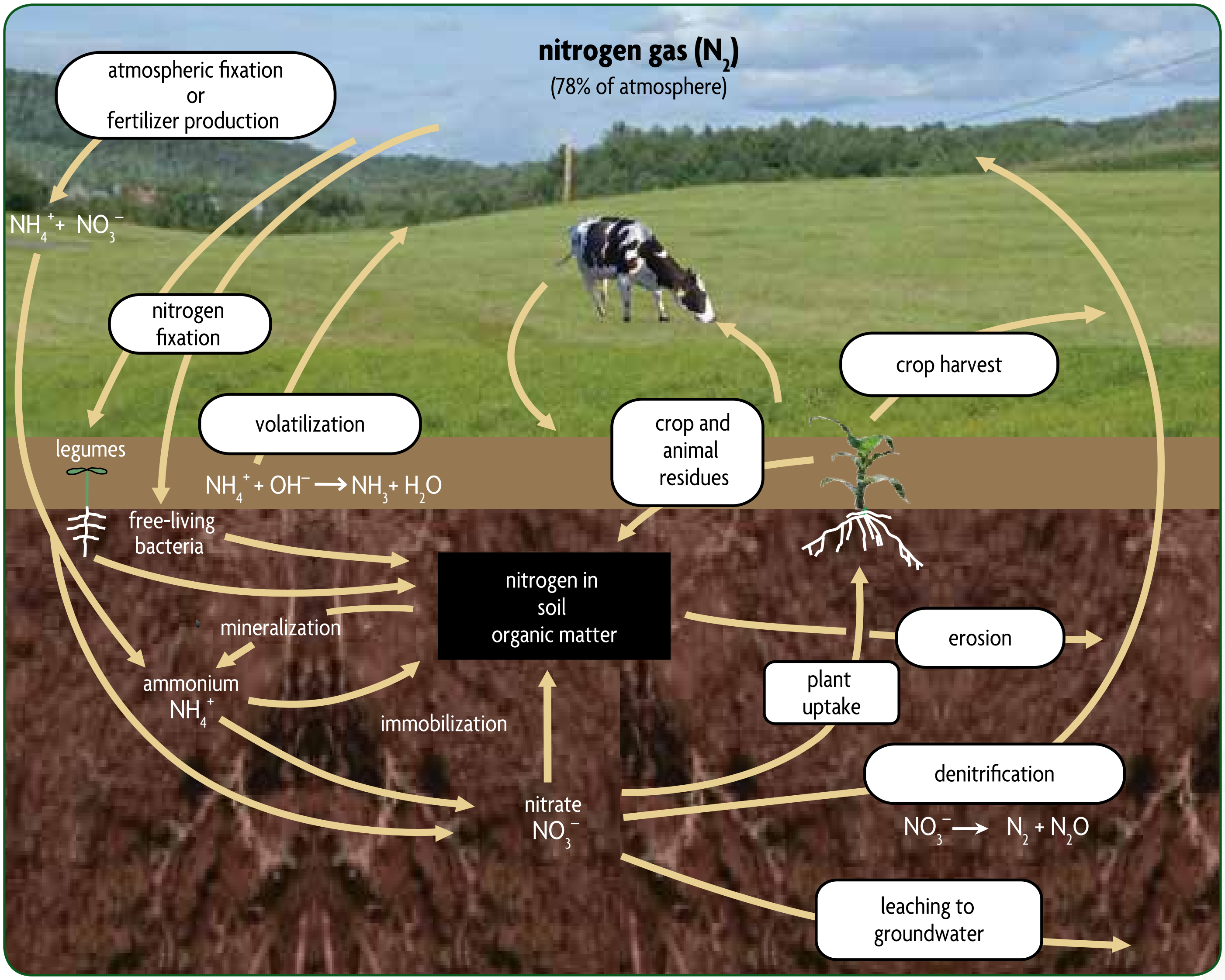


FIGURE 1.10. Nitrogen cycle demonstrating nutrient benefits from decomposition..

other nutrients, in their biomass. Nutrients stored in soil biota are not immediately available to plants (they are 'immobilized'), but also are protected from environmental loss (such as nitrogen leaching or volatilization), because they are in solid form or within living cells.

An organism's need for carbon as energy source and for nitrogen or other nutrients usually differs in magnitude and in proportion from what it consumes. To consume enough carbon, biota often consume more nitrogen than necessary, so that they excrete excess N. This is part of the important process called mineralization. In mineralization, nitrogen that has been bound to carbon in relatively large molecules ('organic nitrogen') is released in 'mineral' form as smaller, more soluble, nitrogen containing ions such as ammonium (NH_4^+) or nitrate (NO_3^+). These can then be taken up by plants. Mineralization is thus a process of great importance in nutrient cycling and availability (Figure 1.10). The opposite effect, immobilization, may occur as well, when the materials that the soil biota consume contain a very high ratio of carbon to nitrogen. For example, when decomposing plant materials such as straw or wood, bacteria and fungi may take up free nitrogen from their surroundings and make it less available, as little is available to them from the same material that is their carbon-rich energy source.

Much of current fertility management for agriculture relies on supplying nutrients in soluble forms as amendments. However, in some agricultural management systems, an increased emphasis is placed on maintaining soil organic matter, soil microbial diversity and activity. In these systems, as in natural or less managed systems, a significant fraction of plants' nutrient needs can be stored in and supplied from organic materials.

Soil Structure Benefits: Aggregates are built and stabilized by the soil biota through the growth of fine roots, fungi, and the soil microbial culture, as well as by the periodic wetting and drying of the soil (Figure 1.11). Fine plant roots and the thread-like fungal 'hyphae' enmesh primary soil particles, soil organic matter in various states of decomposition, and already formed small aggregates into clumps, or macroaggregates. As these are held together, the roots and hyphae

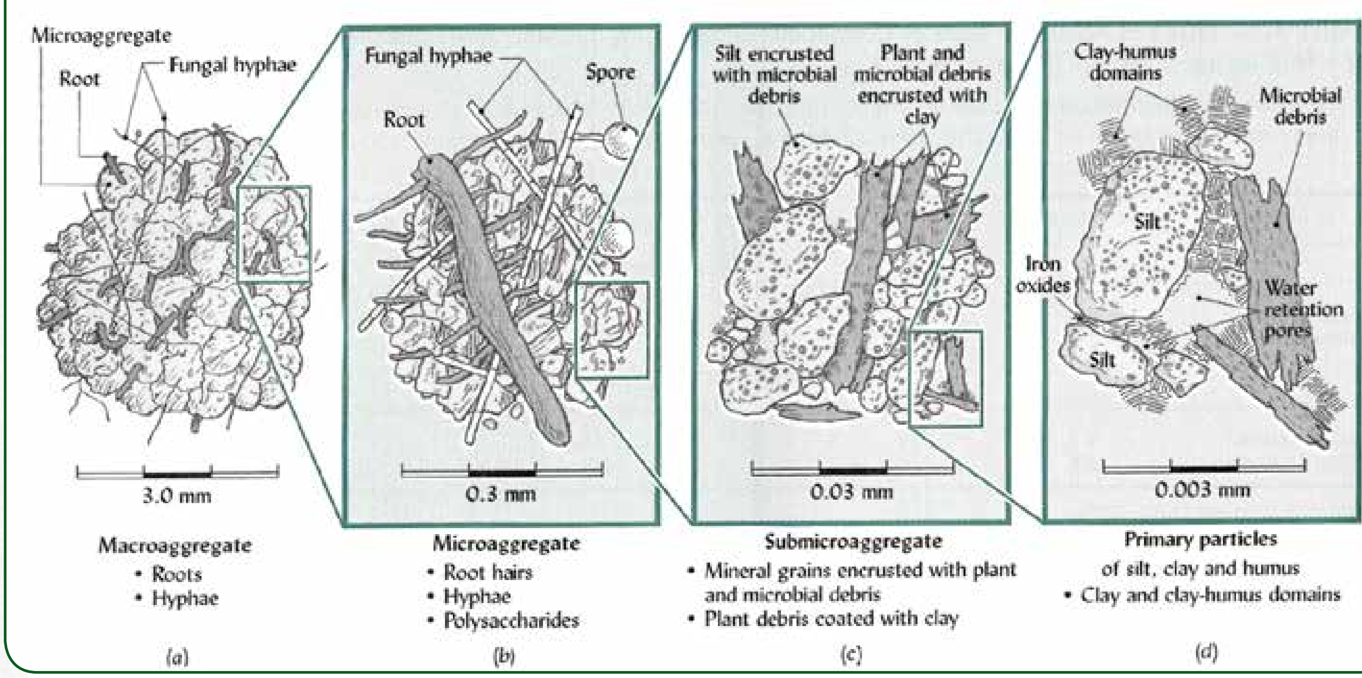
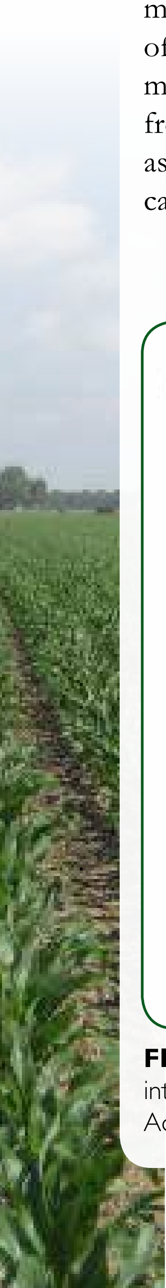


FIGURE 1.11. Aggregate size and composition. An active microbal population will build and stabalize soil through production and interaction with adhesive byproducts. Each step (a–d) demonstrates the bonding agents and aggregation of soil as size decreases. Adapted from *The Nature and Properties of Soils*, 12th ed., Brady and Weil (1999) Fig. 4.26 from p 150.



release exudates that can bind the parts of the aggregates together, and also serve as food for other organisms such as bacteria, colonial unicellular yeasts, and protozoa. Microaggregates form within the macro-aggregates as soil microbes release sticky compounds that further bind soil particles together, and form gels that hold water and slowly release it as the soil dries. At the finest scales, microbial cells and debris stick to fine clay particles, and chemical bonds may form between organic matter and mineral particles as they are held close together to make very small micro-aggregates. For the biota to effectively carry out these processes, it is important for soil disturbance (such as tillage) to be minimized, and of course for there to be a carbon supply for the biota, as well as both air and water availability.

Stable soil aggregates are important for maintaining good (crumbly) soil structure or 'tilth', enabling adequate air exchange and water infiltration, storage, and drainage. Stable soil aggregation minimizes erosion and flooding. These processes are also critical in sequestering, or stabilizing carbon, in the form of well-decomposed organic materials protected within small pores, and tightly bound to soil mineral particles.

Symbiotic Organisms: The organisms discussed so far are free-living in the soil, and decompose and consume plant materials, exudates or secretions that plants release. Two other key groups of soil organisms are not directly involved in decomposition, but are important in soil functioning. These are important symbiotic bacteria and fungi that associate with plant roots. They include nodule-inducing nitrogen fixing bacteria (rhizobia) and mycorrhizal fungi and they live in close association with plant roots, and interact with living plants in a mutually supportive manner.

FIGURE 1.12 Nodules on pea roots.

N fixing bacteria: Gaseous nitrogen (N_2) is a major component of atmospheric air, but plants cannot use it directly. The nodule-inducing nitrogen fixing bacteria (Rhizobium, Bradyrhizobium, and Sinorhizobium, among others) interact with legumes, such as beans, peas, soybeans, clover and vetch. The legume roots develop nodules, which house the bacterial colonies inside (Figure 1.12). Plant tissues provide sugars to the bacteria, while the bacteria convert atmospheric nitrogen into ammonia (NH_3), in a process called nitrogen fixation. Ammonia is quickly converted to ammonium (NH_4^+) in solution and incorporated by the plant into amino acids and other nitrogenous molecules. Sometimes more nitrogen is 'fixed' than is required by the plant,

Soil Microbes Drive Many Soil Processes:

- Decompose organic matter (plant residues)
- Sequester carbon
- Recycle, store (immobilize), and release (mineralize) nutrients for sustained availability to plants
- Increase access to nutrients
- Fix nitrogen
- Stabilize and maintain soil structure
- Biologically suppress plant pests
- Parasitize and damage plants (see "Nematodes" on page 8)
- Promote plant growth
- Detoxify pollutants and clean water

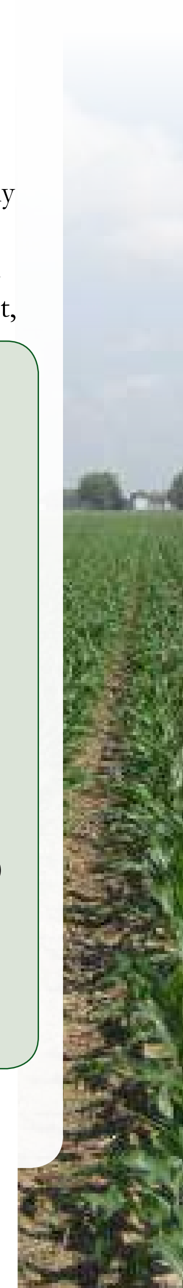


FIGURE 1.13. Mycorrhizal fungi's close association with plant roots form symbotic relationships.

and so excess is released into the surrounding soil. The fixed nitrogen can also become available for other plants in the system as parts of the legume die and decompose, either through root turnover, or as residues or whole plant biomass is incorporated by biota or human management. Some free-living (not plant associated) and associative (close to roots but not in nodules) nitrogen fixation is known to occur in both natural and managed systems. However, it is the nodule-associated nitrogen fixation that is managed intentionally by inoculating the host plants (legumes) with the appropriate rhizobia, and by maintaining a legume phase in rotations and cover cropping.

Mycorrhizal fungi: Most plant roots associate with symbiotic fungi (Figure 1.13). One major group of these are called arbuscular mycorrhizal fungi. Together with plants, these fungi form joint structures called mycorrhizae (from the Greek words for fungus and root). The plant host provides sugars to the fungus, used for growth and metabolism, in exchange for nutrients. Outside of the root, the fungus grows extensively through the soil, and can reach more spaces and absorb more nutrients (especially phosphorus, which is poorly soluble) than the plant roots alone could. In addition to providing a nutrient benefit to the plant host, these fungi contribute to both plant and soil health in multiple ways. They can help the plant resist disease, and tolerate drought and saline (salty) conditions. The arbuscular mycorrhizal fungi also contribute substantially to the accumulation of soil organic matter and to the formation and stabilization of soil aggregates.

Soil organisms are critical to numerous biological, physical, and chemical soil processes. They interact with the plants we generally manage in agricultural systems, and with the physical soil environment that these plants grow in. They are essential parts of the functioning healthy ecosystems that soils supports, and are key contributors to the health of the soil itself.

What is soil health?

The terms 'soil health' and 'soil quality' are becoming increasingly familiar worldwide. A modern consensus definition of soil health is **"the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals and humans"** (Natural Resources Conservation Service – USDA-NRCS, 2012; Soil Renaissance, 2014). Doran and Parkin, in 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, with one key distinction conceptualized by scientists and practitioners over the last decades: soil quality includes both inherent and dynamic quality. Inherent soil quality refers to the aspects of soil quality relating to a soil's natural composition and properties (soil type, as delineated by the NRCS Soil Survey) influenced by the natural long-term factors and processes of soil formation. These generally cannot be influenced by human management. Dynamic soil quality, which is equivalent to soil health, refers to soil properties that change as a result of soil use and management over the human time scale. (See example, Figure 1.14, on the following page).

Soil health invokes the idea that soil is an ecosystem full of life that needs to be carefully managed to regain and maintain our soil's ability to function optimally. The term 'soil health' has been generally preferred by farmers, while scientists have generally preferred 'soil quality'.

Harvesting soybeans. Photo credit: Jenn Thomas-Murphy

FIGURE 1.14. Dynamic soil quality- Left: long-term pasture/hay with occasional annual crops at Tuckaway Farm, NH; Right: long-term annual tillage and vegetable production without cover crops or other organic inputs. Both of these photos are have the same inherent soil quality and therefore they are the same soil type – they are both Buxton Silt Loam. However, due to management differences, soil health has diverged significantly.

Important soil functions related to crop production and environmental quality include:

- Retaining and cycling nutrients
- Supporting plant growth
- Sequestering carbon
- Allow infiltration, and facilitate storage and filtration of water
- Suppressing pests, diseases, and weeds
- Detoxifying harmful chemicals
- Supporting the production of food, feed, fiber, and fuel

When the soil is not functioning to its full capacity, sustainable productivity, environmental quality, and net farmer profits are jeopardized over the long term. Impaired function may result from constraints to specific and interacting soil processes (see pages 15-17). Below are some examples of the economic benefits of maintaining and improving soil health:

- Better plant growth, quality, and yield
- Reduced risk of yield loss during periods of environmental stress (e.g., heavy rain, drought, pest or disease outbreak)
- Better field access during wet periods
- Reduced fuel costs by requiring less tillage
- Reduced input costs by decreasing losses, and improving use efficiency of fertilizer, pesticide, herbicide, and irrigation applications.

Characteristics of a healthy soil

Good soil tilth

Soil tilth refers to the overall physical character of the soil in the context of its suitability for crop production. Soil with good tilth is crumbly, well structured, dark with organic matter, and has no large and hard clods (Figure 1.15).

Sufficient depth

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

Good water storage and good drainage

During a heavy rain, a healthy soil will take in (allow infiltration) and store more water in medium and small pores, but will also drain water more rapidly from large pores, as a result of good soil structure and an adequate distribution of different sizes of pore spaces. Thus, the soil will retain more water for plant uptake during dry times, but will also allow air to rapidly move back in after rainfall, so that organisms can continue to thrive.

Sufficient supply, but not excess 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. An excess of 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.

Characteristics of a healthy soil (continued)

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 or is less active. This could result from direct competition from other soil organisms for nutrients or habitat, hyperparasitism, etc. In addition, healthy plants are better able to defend themselves against a variety of pests (somewhat analogous to the human immune system).

Large population of beneficial organisms

Soil organisms are important to the functioning of the soil. They help with cycling nutrients, decomposing organic matter, maintaining soil structure, biologically suppressing plant pests, etc. A healthy soil will have a large and diverse population of beneficial organisms to carry out these functions and thus help maintain a healthy soil status.

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 block sunlight, interfere with stand establishment and harvest and cultivation operations, and harbor disease causing pathogens and pests.

Free of chemicals and toxins that may harm the crop

Healthy soils are either devoid of excess amounts of harmful chemicals and toxins, or can detoxify or bind such chemicals. These processes make these harmful compounds unavailable for plant uptake, due to the soil's richness in stable organic matter and diverse microbial communities.

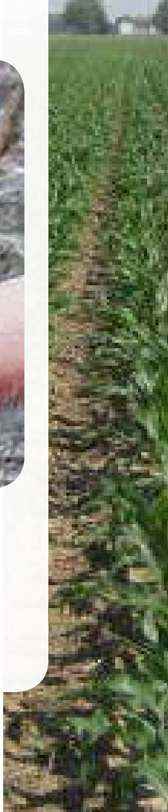
Resistant to degradation

A healthy, well aggregated soil full of a diverse community of living organisms is more resistant to adverse events including erosion by wind and rain, excess rainfall, extreme drought, vehicle compaction, disease outbreak, and other potentially degrading influences.

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 1.15. The effect of organic matter (OM) on the same soil type managed using conventional plow tillage (left) or zone tillage for 10 years (right). Soil with good tilth is crumbly, well structured, dark with OM and has no large and hard clods..



Common soil constraints

It is important to recognize soil constraints that limit crop productivity, farm sustainability, and environmental quality. In this way management practices can be adjusted to alleviate these problems. Below is a listing of soil constraints commonly observed in the Northeast region of the U.S., along with some contributing factors and resulting soil conditions.

Soil Compaction

Contributing factors

- Traffic or tillage when soil is wet ('plastic')
- Heavy equipment and loads
- Uncontrolled traffic patterns

Can result in

- Reduced root growth in surface and subsurface soils
- Limited water infiltration, resulting in runoff, erosion, ponding and poor aeration
- Drought sensitivity due to reduced water storage and reduced rooting
- Reduced nutrient access due to poor root growth and restricted water flow
- Increased pathogen pressure due to poor drainage and to plant stress
- Increased cost of tillage and lower yields

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

Ruts resulting from late fall harvest when soils are wet.

Poor Aggregation

Contributing factors

- Intensive tillage
- Limited use of soil building crops and soil cover
- Low active rooting density
- Limited duration of root presence during the year
- Limited organic additions
- Low biological activity to stabilize aggregates

Can result in

- Crusting and cracking
- Poor seedling emergence and stand establishment
- Poor water infiltration and storage
- Increased occurrence of erosion and runoff
- Reduced root growth
- Less active microbial communities
- Reduced aeration
- Reduced drought resistance due to decreased water intake during rainfall events

Surface crusting in mid-spring.

Weed Pressure

Weedy beet field..

Contributing factors

- Poor crop rotations and omission of cover crops
- Resistance to herbicides
- Poor weed management, poor 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 Pathogen Pressure

Contributing factors

- Poorly planned crop rotations and low rotational diversity
- Ineffective residue management
- Poor sanitary practices (equipment, tools, vehicles not cleaned between operations)
- Low microbial diversity, resulting in reduced suppressiveness
- Poor physical soil functioning, particularly waterlogging, or other plant stress inducing conditions

Symptoms of root rot diseases on pea roots.

Can result in

- Damaged and diseased roots
- Uneven and poor growth
- Reduced yields, crop quality, and profits

Low Water and Nutrient Retention

Contributing factors

- Low organic matter and resulting poor structure, water holding capacity, and exchange capacity
- Poor retention and biological recycling of nutrients in biomass and soil organic matter
- Excessive tillage
- Insufficient use of soil building crops

Application of liquid manure to increase water and nutrient retention.

Can result in

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

Salinity and Sodicity

Contributing factors

- Frequently found in semi-arid and arid climates, especially under irrigated systems
- Common in the Northeast only in high tunnels and greenhouses, which could be considered to be artificial "irrigated deserts"

Can result in

- Loss of crop yield and quality
- Loss of aggregation and thus infiltration and drainage functions if sodicity is the problem

Saline/sodic soil.

Heavy Metal Contamination[1]

Contributing factors

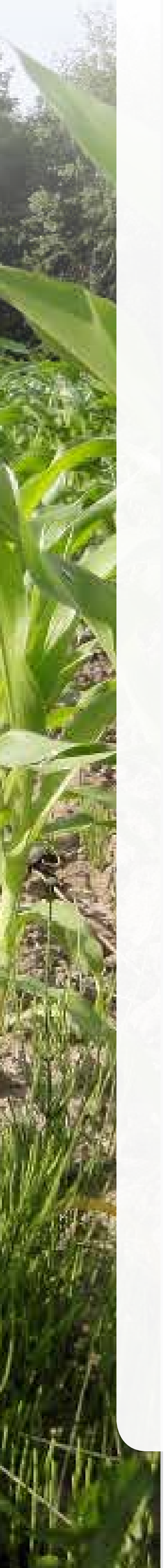
- Common in urban areas and other sites with past use of contaminant sources such as lead paint, fertilizers, pesticides (e.g., lead arsenate use on orchard land)
- Past activities such as high traffic, industrial or commercial activity, treated lumber, petroleum spills, automobile or machine repair, junk vehicles, furniture refinishing, fires, landfills, or garbage dumps
- Naturally occurring high heavy metal concentrations are generally rare in the Northeast

Can result in

- Higher risks of human exposure when children or adults swallow or breathe in soil particles or eat food raised in or on contaminated soil
- Inhibition of soil biological activity
- Plant toxicity, and reduced yield and/or crop quality

Growth inhibition in soil contaminated with copper and zinc..

1 Content adapted from resources developed by the Cornell Waste Management Institute (http://cwmi.css.cornell.edu/soilquality.htm) and the Healthy Soils, Healthy Communities Project (http://cwmi.css.cornell.edu/healthysoils.htm)



Part II
Soil Health Assessment

In-field soil health assessment

Qualitative, on-farm, in-field assessment of soil health does not need to involve special analyses, only the informed observation and interpretation of soil characteristics. This is usually done by visual assessment, but the smell and feel of soil may also be involved. Field test kits for measuring several indicators are also available (e.g. NRCS soil quality test kit). While this approach is more subjective and therefore can reflect user bias, when detailed guidelines and training have been provided the results can be very informative in making management decisions. Guided, in-field assessment can also be particularly effective to increase awareness and understanding of how important it is to maintain healthy soils, and the importance of key soil processes. Some specific soil indicators, such as compaction measured using a penetrometer in the root zone, are always measured better directly in the field than in a laboratory.

Developing and using in-field assessments:

- Participatory processes in developing qualitative soil health monitoring procedures locally have had significant educational value and opened up communication among farmers and between farmers and other agriculture professionals.
- A number of score cards and kits for measuring soil health in the field have been developed (Figure 2.01, following page). These have used more than 30 physical indicators and more than 10 biological, chemical, and crop observation based indicators of soil health. In this approach, 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 by in-field respiration measures. Crop indicators of soil functioning such as root proliferation and health, signs of compaction (such as thick angular roots), legume nodulation, and signs of residue decomposition can also provide useful information.
- 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 achieve somewhat standardized scoring (Figure 2.02.).

POINTS TO REMEMBER:

- Training should include information on sampling, standardized verbal descriptions and, if possible, photos that facilitate uniform scoring and keep users on track. Sufficient information regarding interpretation of results is essential
- To the extent possible, comparisons of measurements should be made between samples taken at a similar time of year in relation to field operations, and at a similar soil moisture content and soil temperature

Crusting at the soil surface.

A subsoil plow pan restricts root growth and decreases resilience during extreme weather.

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)									

Field Notes/Inputs

Farm I.D. ______________

Field I.D. ______________ Date __________

Crop ______________ Acres __________

Inputs

	Type	*Quantity*	*Price*
Fertilizer			
Lime			
Manure			
Cover Crops			
Pesticides			
Other			
Equipment Used			

Problems, Comments, Weather Conditions

____

Yields

Amount ______________

Units ______________

Moisture ______________

Price ______________

FIGURE 2.01. 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://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/assessment/?cid=nrcs142p2_053871).

FIGURE 2.02. While the corn root in a compacted soil (left) cannot access water and nutrients from most of the soil volume, dense rooting (right) allows for full access. High quality photographs like these are an excellent way to train users and acheive standarized scoring. *Source: Building Soils for Better Crops*

Development of Cornell 's Comprehensive Assessment of Soil Health

Soil health is a concept that deals with the integration and optimization of the chemical, physical, and biological processes of soil that are important for sustained productivity and environmental quality (Figure 2.03). Over the years the concepts and understanding of the importance of the soils' chemical and even physical properties have been well accepted in the agricultural community as a whole. However, it has not been until more recently that the importance of understanding and managing the soil's biological properties has moved beyond a few leading innovative producers and scientists, to become a focus in broader circles. Scientific research and a larger group of producers are now making significant progress on assessing and managing soil biological functioning in diverse agricultural production systems.

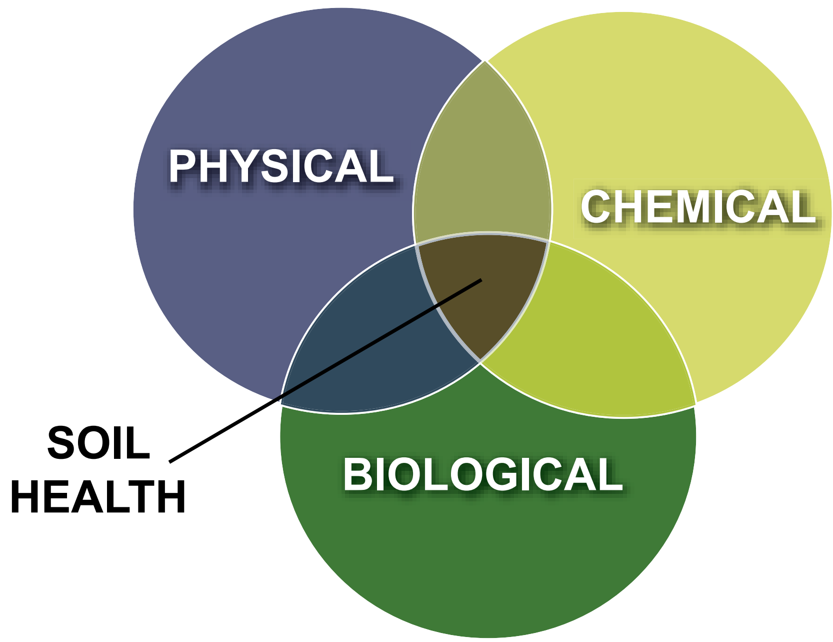


FIGURE 2.03. The concept of soil health deals with integrating the physical, biological and chemical components of the soil (Adapted from the Rodale Institute).

While soil nutrient (chemical) testing has long been available to farmers, physical and especially biological testing had largely remained only in research labs until the first version of the Cornell Soil Health Assessment was made publicly available in 2006. As the stakeholder community converges on standards for more comprehensive assessment of soil health, and national awareness is bringing about wide adoption, we hope that public and private labs integrate more comprehensive soil health testing, and management suggestions, into their offerings. This can lead to a future where soil testing will involve a more comprehensive testing of soil health for the average land manager.

Our approach...

The Cornell Soil Health Team has been working to address soil degradation issues that have resulted in reduced soil health, 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 abundance, activity, and diversity of beneficial organisms. To address these issues, a group of interested growers, extension educators, researchers and private consultants and funders established a Program Work Team with support from Cornell Cooperative Extension in the early 2000s. One of the major accomplishments was the development of an initial cost-effective protocol for assessing the health status of soils in New York and the Northeast region.

The protocol has been revised over the years, and is the outcome of a process where many potential indicators were evaluated for their use in standardized, rapid, quantitative assessment of soil health based on relevance to key soil processes, response to management, complexity of measurement, and cost (Table 2.01).

In order to evaluate the many indicators for soil health assessment, soil samples were collected from replicated research trials, grower demonstration trials and from fields of interested growers from across New York State (Figure 2.04, following page) and later also Pennsylvania, Vermont, Maryland, New Hampshire, and other parts of the Northeast. The replicated research sites represent different vegetable and field crop production systems being managed using different practices in various combinations.

TABLE 2.01. Many potential indicators that were initially evaluated for use in the soil health assessment protocol.

Physical	Biological	Chemical
Texture	Root pathogen pressure assessment	Phosphorus
Bulk density	Beneficial nematode population	Nitrate nitrogen
Macro-porosity	Parasitic nematode population	Potassium
Meso-porosity	Potentially mineralizable nitrogen	pH
Micro-porosity	Cellulose decomposition rate	Magnesium
Available water capacity	Particulate organic matter	Calcium
Residual porosity	Active carbon	Iron
Penetration resistance at 10 kPa	Weed seed bank	Aluminum
Saturated hydraulic conductivity	Microbial respiration rate	Manganese
Dry aggregate size (<0.25 mm)	Soil proteins	Zinc
Dry aggregate size (0.25 - 2 mm)	Organic matter content	Copper
Dry aggregate size (2 - 8 mm)		Exchangeable acidity
Wet aggregate stability (0.25 -2 mm)		Salinity
Wet aggregate stability (2 - 8 mm)		Sodicity
Surface hardness with penetrometer		Heavy metals
Subsurface hardness with penetrometer		
Field infiltrability		

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 crops (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. 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 (Figure 2.05). Numerous individual fields of interested growers were also initially sampled in cooperation with county educators in order to build a database on the health status of Northeast soils. The selection of the subset of indicators used in the soil assessment protocol is described further on pages 25-26.

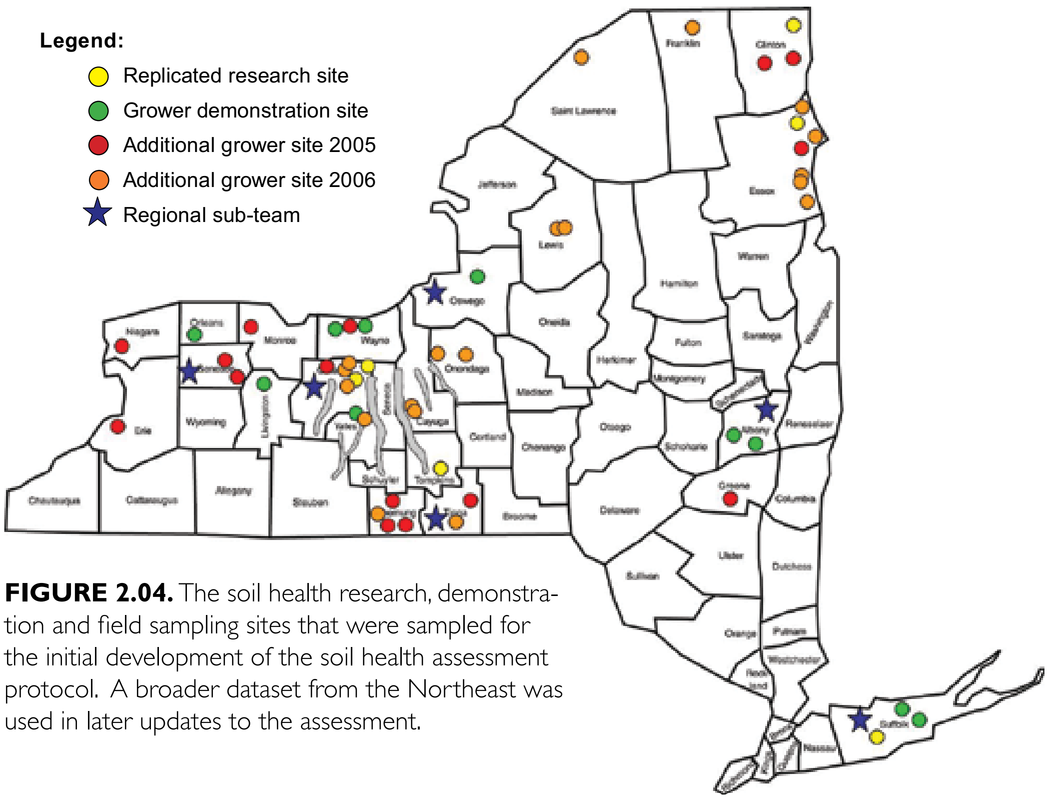


FIGURE 2.04. The soil health research, demonstration and field sampling sites that were sampled for the initial development of the soil health assessment protocol. A broader dataset from the Northeast was used in later updates to the assessment.

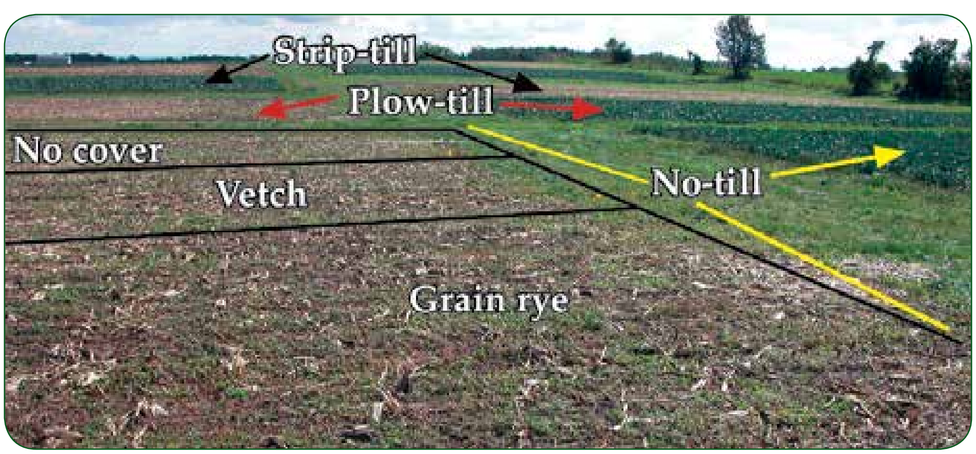
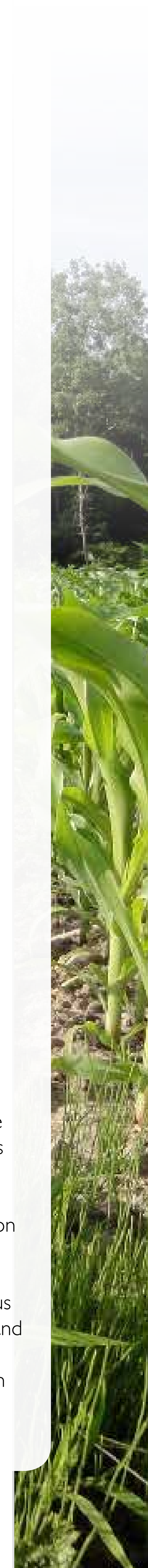
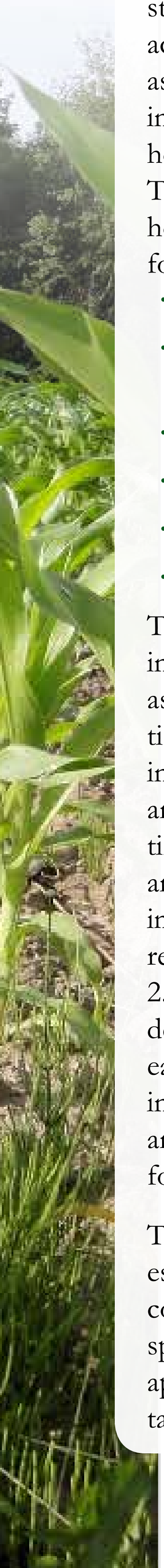


FIGURE 2.05. The 14-acre long-term soil health research site at Gates Farm in Geneva, NY was established in 2003. The 72 plots represent three tillage systems, three cover crops and two rotation treatments replicated four times. One rotation (plots with green vegetation) emphasizes continuous high-value vegetable production and another rotation includes season long soil-building crops (plots with corn residue).





Comprehensive Assessment of Soil Health Overview

The Cornell Soil Health Assessment protocol emphasizes the integration of soil biological, physical, and chemical measurements. These measurements include soil texture (to help interpret other measured indicators), available water capacity, field penetrometer resistance, wet aggregate stability, organic matter content, soil proteins, respiration, active carbon, and macro- and micro-nutrient content assessment. Additional indicators are available as add-ons, including root pathogen pressure, salinity and sodicity, heavy metals, boron and potentially mineralizable nitrogen. These measurements were selected from 42 potential soil health indicators (page 23, Table 2.01) that were evaluated for:

- sensitivity to changes in soil management practices
- ability to represent agronomically and environmentally important soil processes
- consistency and reproducibility
- ease and cost of sampling
- cost of analysis
- ease of interpretation for users

The results of these measurements have been synthesized into a grower-friendly comprehensive soil health assessment report with indicator scores, constraint identification, and management suggestions. This report can initially be used by agricultural service providers, consulants and growers as a baseline assessment and guide to prioritization of management focus. Subsequent sampling and analysis of the same field can help determine the impact of implemented soil management practices on soil health. The report is explained in further detail on pages 70-74. Table 2.02 provides a brief description of each indicator. More detailed descriptions, as well as the basic methodology, how each indicator relates to the functioning of the soil, the interpretive scoring function used to assign a rating score, and comments on managing identified constraints can be found on pages 35–69.

This framework facilitates expansion with future indicators, especially biological assessments, as these become more cost effective and interpretable. It also allows for region-specific or crop-specific indicators or revised scoring approaches for individual indicators, as further implementations of the framework are established.

Scoring Functions **27**
Soil Sampling Protocol **31**
Planning field sampling design 31
Materials needed for one sample 31
Steps for soil sampling 31
Soil sample storage requirements:... 33
Soil sample shipping to lab:.. 33
Indicator Lab Protocols **35**
Soil Health Assessment Report...........**70**

Why assess soil health?

- Increase awareness of soil health
- Understand constraints beyond nutrient deficiencies and excesses
- Target management practices to alleviate soil constraints
- Monitor soil improvement or degradation resulting from management practices
- Facilitate applied research – compare management practices to develop recommendations for farm and field specific soil health management planning
- Land valuation – facilitate the realization of equity embodied in healthier soils
- Enable assessment of farming system risk

See the Cornell Assesment of Soil health website for the most up-to-date package offerings and pricing: http://soilhealth.cals.cornell.edu

TABLE 2.02. Indicators of the Comprehensive Assesment of Soil Health and what they mean.

PHYSICAL	Available Water Capacity: reflects the quantity of water that a disturbed sample of soil can store for plant use. It is the difference between water stored at field capacity and at the wilting point, and is measured using pressure chambers.
	Surface Hardness: is a measure of the maximum soil surface (0 to 6 inch depth) penetration resistance (psi), or compaction, determined using a field penetrometer.
	Subsurface Hardness: is a measure of the maximum resistance (psi) encountered in the soil between 6 to 18 inch depths using a field penetrometer.
	Aggregate Stability: is a measure of how well soil aggregates resist disintegration when hit by rain drops. It is measured using a standardized simulated rainfall event on a sieve containing 0.25mm and 2.0mm soil aggregates. The fraction of soil that remains on the sieve determines the percent aggregate stability.
BIOLOGICAL	Organic Matter: is a measure of all carbonaceous material that is derived from living organisms. The percent OM is determined by the mass of oven dried soil lost on combustion in a 500°C furnace.
	Soil Protein: is a measure of the fraction of the soil organic matter which contains much of the organically bound N. Microbial activity can mineralize this N and make it available for plant uptake. This is measured by extraction with a citrate buffer under high temperature and pressure.
	Soil Respiration: is a measure of the metabolic activity of the soil microbial community. It is measured by rewetting air dried soil, and capturing and quantifying carbon dioxide (CO_2) produced.
	Active Carbon: is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping fuel and maintain a healthy soil food web. It is measured by quantifying potassium permanganate oxidation with a spectrophotometer.
	Add-on Indicators: Root Pathogen Pressure Rating: is a measure of the degree to which sensitive test-plant roots show symptoms of disease when grown in standardized conditions in assayed soil. Assessed by rating washed roots through visual inspection for disease symptoms. Potentially Mineralizable Nitrogen: is a combined measure of soil biological activity and substrate available to mineralize nitrogen to make it available to the plant. It is measured as the change in mineralized plant-available nitrogen present after a seven day anaerobic incubation.
CHEMICAL	Soil Chemical Composition: a standard soil test analysis package measures levels of pH and plant nutrients. Measured levels are interpreted in this assessment's framework of sufficiency and excess but no crop specific recommendations are provided.
	Add-on Indicators: Salinity and Sodicity: Salinity is a measure of the soluble salt concentration in soil, and is measured via electrical conductivity. Sodicity is a calculation of the sodium absorption ratio (SAR) and is measured using ICP spectrometry to determine Na^+, Ca^{2+}, Mg^{2+} concentrations and using an equation to calculate the absorpation ratio. Heavy Metals: is a measure of levels of metals of possible concern to human or plant health. They are measured by digesting the soil with concentrated acid at high temperature.

Scoring Functions

To interpret our soil health measurements, scoring functions were developed for each indicator, by adapting work of Andrews et al. (2004)[1] at NRCS and ARS in the 1990s and early 2000s. The scoring functions are used to convert a value for a specific indicator to an interpretive rating. A color (red, yellow, green) is also assigned in the soil health assessment report summary (page 30). In the context of our soil health assessment, a scoring function is a curve that assigns specific scores between 0 and 100 to the values measured for individual indicators. A score of 100 is the best (highest) while a score of 0 is the worst (poorest). For most of the indicators, scoring functions were developed separately for the major soil textural groups (coarse, medium, fine) based on the observed distribution of measured values for the indicators in regional soils of similar texture.

We used data collected across the Northeastern United States to establish these scoring curves, so scores are relative to measured values in this region. Several scoring functions have been updated in 2014 and 2015, and now are based on data sampled from an expanded geographic range, including the mid-Atlantic and Midwest, along with near-border regions in southeastern Canada. The scoring functions for most of the soil health indicators consist of cumulative normal distribution (CND) curves scaled to give scores ranging from 0 to 100, while the remainder are scored, likewise on a scale of 0 to 100, based on established outcome-based thresholds, or linearly. Some indicators are given higher scores for higher measured values, some the reverse. Others are given lower scores for measured values that are further in either direction from an optimum range. This is illustrated further in the section following the illustrated examples below. Specific scoring function information for each indicator is presented graphically with the more detailed descriptions of each indicator in following sections.

For illustration, Figure 2.06 shows the observed distribution of active carbon measurement values from samples of medium textured soils in the scoring calibration set. For this dataset, the height of the bars show the frequency of measurements falling within each bin (range) represented by the bars. For example, approximately 20% of the soil samples in this set had measured active carbon concentrations falling between 550 and 650 parts per million (ppm). A normal distribution curve (bell curve) with the same mean (561 ppm) and standard deviation (180 ppm) as the calibration set is shown superimposed over the frequency bars.

The resulting scoring function (for active carbon in medium textured soils) is shown as a cumulative normal distribution, in Figure 2.07 on the following page. In this graph, the horizontal (X) axis represents the measured value, and the vertical (Y) axis represents the score, as a percentile, ranging from 0 to 100.

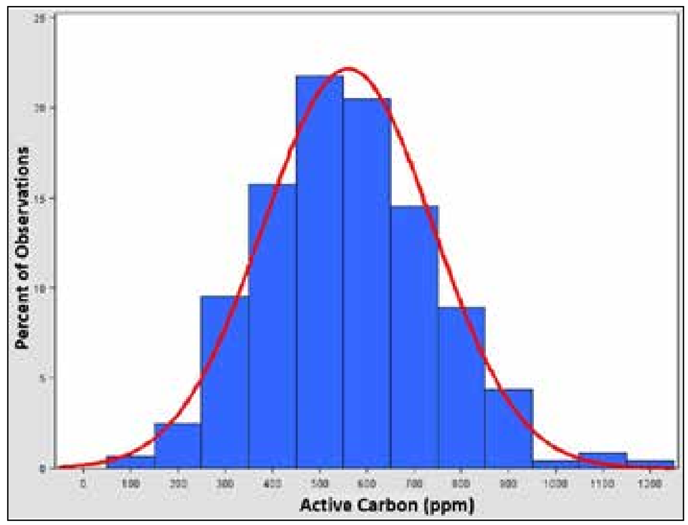


FIGURE 2.06. Distribution of active carbon data in medium textured soils.

For example, a sample of a medium textured soil with a measured active carbon content of 700 ppm would be given a score of 80, as shown by the arrows superimposed on the scoring function graph. In practical terms, this means that 80% of medium textured soil samples in the calibration set had active carbon contents lower than or equal to the sample being scored. This approach can be used to adapt the framework presented here to regions with different soils and climate. Scoring functions should be adjusted

1 Andrews, S.S., D.L. Karlen, and C.A. Cambardella. 2004. The soil management assessment framework: A quantitative soil quality evaluation method. Soil Science of America Journal 68: 1945-1962 .

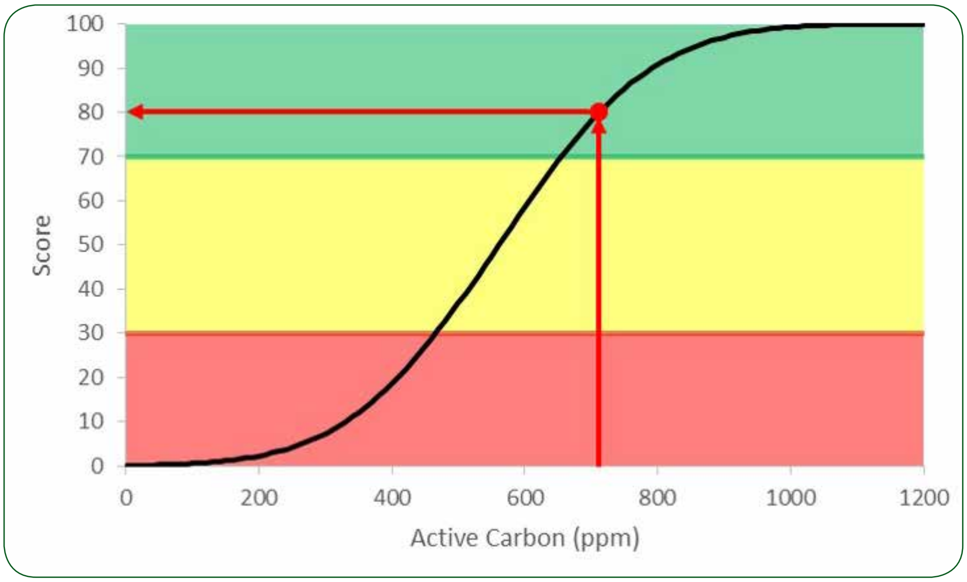


FIGURE 2.07. Cumulative normal distribution for scoring active carbon in silt soils. In this example, 80% of medium textured soil samples in the calibration set had active carbon contents lower than or equal to the sample being scored.

to different conditions for more appropriate interpretation (see for example work that was done to develop scoring functions for a region in Western Kenya, Moebius-Clune et al., 2010). Future work to score measured values based on outcomes such as yield, crop quality, risk, and environmental considerations (as available for standard nutrient testing) is needed.

We used the following values to set the thresholds for rating soil health indicators: i) scores between 0 and 30 are considered low, suggesting a constraint in the proper functioning of processes represented by the low scoring indicator. Priority should therefore be given in management planning to ameliorating this condition; ii) scores between 30 and 70 are considered medium or intermediate, worthy of consideration in management planning but not necessarily representing a constraint to proper functioning; and iii) scores between 70 and 100 are considered high, suggesting that the processes represented by the high scoring indicator are likely functioning well. Management should be geared toward maintaining this condition. In the assessment report summary, low scoring indicators are color coded red (in the Rating column), intermediate scores yellow, and high scores green. Likewise, in the management suggestions tables within the assessment report, constraints identified by low scoring indicators for the assessed sample are emphasized by red colored text (Part III, pages 79-81).

Three general types of scoring are used, whether the curve shape is normal, linear, or otherwise. These are described below:

A. More is Better:

In this situation, the higher the value of the indicator, the higher the score until a maximum level is attained (Figure 2.08 A, following page). Indicators falling in this class include aggregate stability, available water capacity, organic matter content, soil proteins, respiration, active carbon, and potentially mineralizable nitrogen (possible environmental impacts of excessive N mineralization are currently not scored).

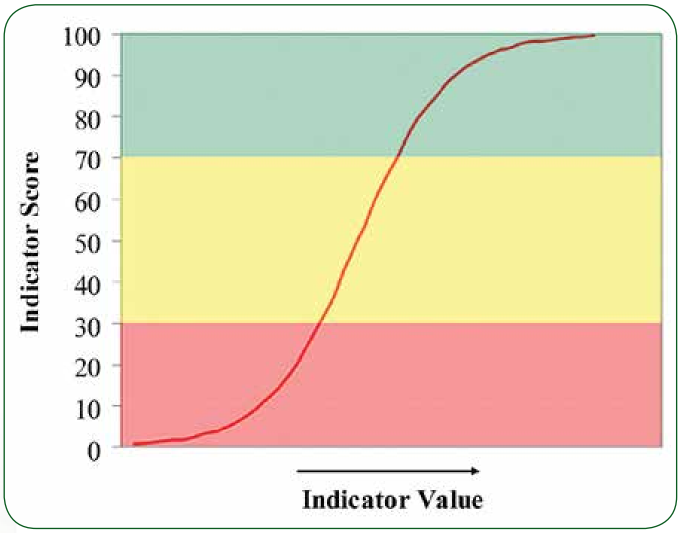
Potassium content is scored in a 'more is better' fashion as well, dependent on established outcome-based thresholds, as are minor elements (Magnesium and Zinc) for which there is a risk of deficiency. These contribute to the minor element score depending on whether they are deficient or sufficient.

B. Less is Better:

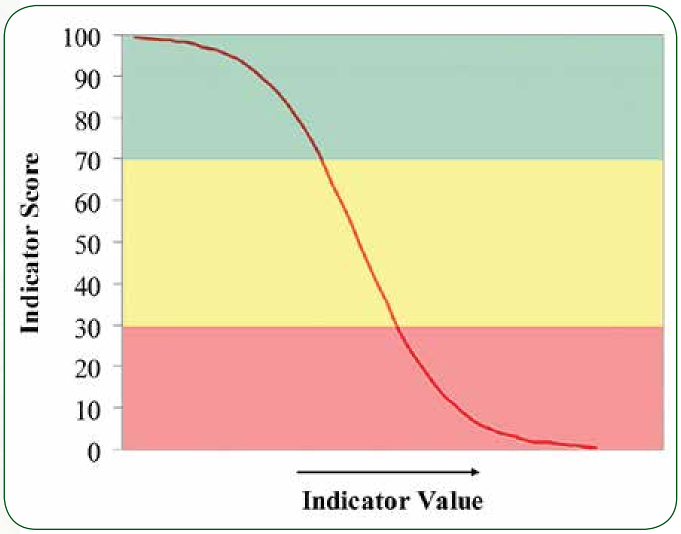
The scoring curve in this case gives higher scores to lower values of the indicator (Figure 2.08 B). Soil measurements in this group include surface hardness, subsurface hardness and root pathogen pressure assessment. Minor elements (Manganese and Iron) for which there is a risk of toxicity from excess contribute to the minor element score depending on whether they are excessive or not excessive.

C. Optimum Curve:

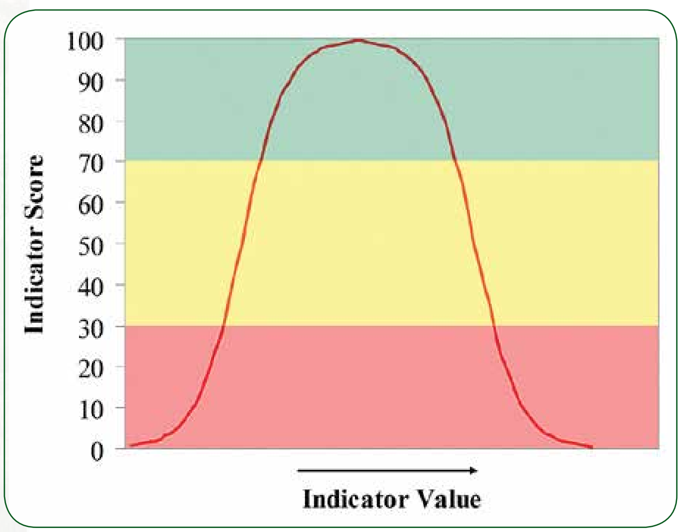
In this case, the curve rises to the highest level with increasing indicator values from the low side, flattens out within an optimum range, and then decreases as indicator values increase beyond the high end of the optimum range (Figure 2.08 C). Indicators that were scored this way are pH and extractable phosphorus.



A. More is better graph



B. Less is better graph



C. Optimum graph

FIGURE 2.08. Three general scoring curve types, depending on the indicator that is evaluated.

In the end, an overall quality score is computed from the average of all the individual indicator scores and summarized in a single report page (Figure 2.09). It is generally advised to give more priority to individual indicators' ratings and to identification of constraints to proper functioning of important processes, rather than a single overall score, although this average score may be useful in some cases for comparison.

The overall rating of the soil sample based on this score is given as:

i. >85 Very High

ii. 70-85 High

iii. 55-70 Medium

iv. 40-55 Low

v. <40 Very Low

A more detailed description of the summary report is given starting on page 70.

Plant root growing down a worm channel in the soil profile.

Cornell Soil Health Assessment

Jane Cabbage
45 Sauerkraut Lane
Brassica, NY, 14103

Agricultural Service Provider:
Doe, John
Assessments Inc.
john@doe.com

Sample ID:	S_2
Field/Treatment:	Veg B
Tillage:	7-9 inches
Crops Crown:	CBP, SPF, LET
Date Sampled:	5/15/2015
Given Soil Type:	Honeoye
Given Soil Texture:	Silt Loam
Coordinates:	42.44790 °N; 76.47570 °W

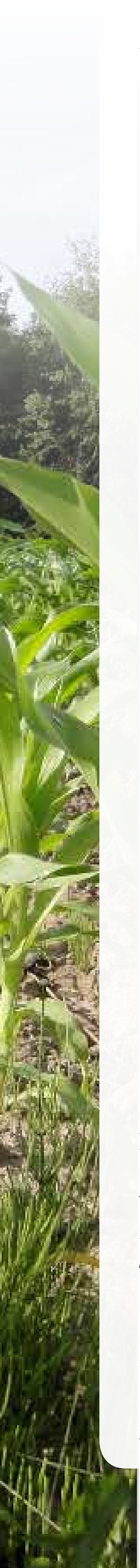
Measured Soil Textural Class: Silt Loam **Sand: 20%** **Silt: 65%** **Clay: 15%**

Test Results

	Indicator	Value	Rating	Constraint
Physical	Available Water Capacity	0.12	22	Water Retention and Availability
Physical	Surface Hardness	425	0	Rooting, Water Transmission
Physical	Subsurface Hardness	477	3	Subsurface Pan/Deep Compaction, Deep Rooting, Water and Nutrient Access
Physical	Aggregate Stability	24.0	24	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
Biological	Organic Matter	2.0	13	Nutrient and Energy Storage, Ion Exchange, C Sequestration, Water Retention
Biological	ACE Soil Protein Index	3.0	13	Organic Matter Quality, Organic N Storage, N Mineralization
Biological	Respiration	0.44	29	Soil Microbial Abundance and Activity
Biological	Active Carbon	400	19	Energy Source for Soil Biota
Chemical	pH	6.8	100	
Chemical	Phosphorus	17.8	100	
Chemical	Potassium	140.0	100	
Chemical	Minor Elements Mg: 300 Fe: 1.0 Mn: 10.0 Zn: 2.0		100	

Overall Quality Score 44 Low

FIGURE 2.09. Example summary report page for a conventional cabbage operation. The report is described further on page 70, and a full report including interpretive text is included in Appendix A. Because producers generally manage soil nutrient levels and pH carefully, using standard soil testing, chemical soil health is often found to be in the optimal range (100 rating and green in example above). Constraints are more frequently found in physical and biological health, because these aspects of soil health have not previously been tested and explicitly managed (< 30 rating and in red in example above).



Soil Sampling Protocol

Planning field sampling design

Prior to sampling a field, it is important to determine:

- The goals of sampling, such as assessing current status for a management unit, identifying constraints in a particular problem area, or comparing between different areas on a farm.
- Whether one sample will adequately represent an entire field or management unit, or whether a unit should be divided up for gathering multiple samples.

Materials needed for one sample

- 2 Five-gallon buckets or similar containers (one for soil, one for supplies)
- 1 sturdy, re-closable plastic freezer storage bag (large 1-gallon) for each sample
- Clipboard and Submission Form (soilhealth.cals.cornell.edu, example page 34)
- Permanent marker for labeling sample bags
- Pen for data entry in submission form
- Straight shovel (sharpshooter or trenching spade style)
- Penetrometer (if available)
- Cooler for sample storage

Steps for soil sampling

Sampling should be done when soils are at field capacity. This ensures appropriate interpretation of field penetration resistance measurements, facilitates proper mixing of subsamples, and prevents soils from smearing during sampling and transport. In general, identify 10 locations within the area you would like to test that are representative of the field or plot (Figure 2.10).

The following recommended guidelines are similar to sampling for nutrient analysis. Irregular areas in a field, such as the low spot in Example 2 to the right, should be avoided, unless a sample is specifically being collected from a problem area to identify constraints.

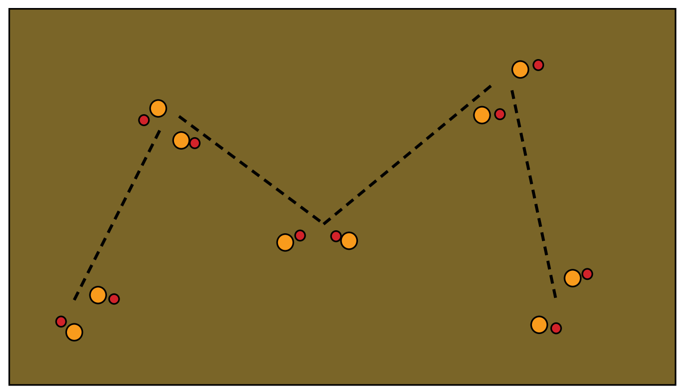
Whenever possible, fields should be divided into sampling units when there are differences in key characteristics such as:

- soil type or slope
- management practices
- observed crop growth and yield.

At each of at least five stops, collect two bulk soil samples at least 15 feet apart. Also take a penetrometer reading for each of two depth ranges (0 to 6 inches, 6 to 18 inches), at each bulk sample location (see field diagrams below).

Sample portions :
- Bulk soil sample (placed in bucket)
- Penetrometer readings (at 2 depths)

Example 1: Uniform field (1 sample)



Example 2: Uneven field - 2 soil types (2 samples)

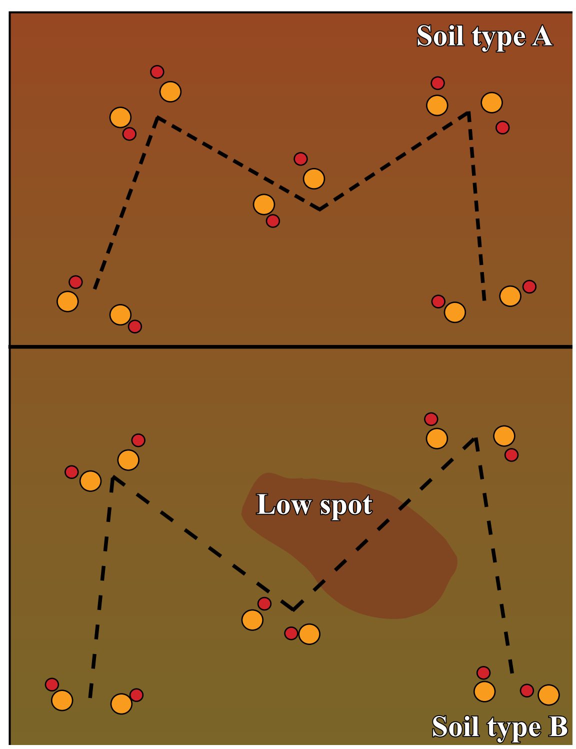


FIGURE 2.10. Examples of different field characteristics and how they may affect sampling.

NOTE: We do not recommend using a standard soil probe as more cores will need to be collected than a spade to obtain the necessary amount of soil for analysis, and more physical smearing will result, impairing physical indicator measurements.

At each location:

A. See previous page for sampling design. Remove surface debris (Figure 2.11 A)

B. Use a spade to dig a small hole about 8" deep (B). From the side of the hole take a vertical, rectangular slice of soil 6" deep and about 2" thick. Ensure that the sample is the same width at the top and bottom of the slice. It is important to collect the same amount of soil from all soil depths so the sample is not biased with more soil from the top compared to the bottom, especially since soil biological properties vary with depth.

C. Manually remove any extra soil to ensure an even, rectangular 6" deep x 2" thick slice of soil, the width of the shovel (C1). Place into clean pail (C2).

D. At each sub-sample location collect soil hardness information with a penetrometer (D). Record maximum hardness (in psi) from the 0-6" and the 6-18" depth ranges in the sample Submission Form. For additional information on measuring penetration resistance see page 37.

E. Repeat steps A – C to collect the remainder of the subsamples from at least 10 representative locations in the sampling area. Mix thoroughly and place at least 4 full cups of soil (more if root pathogen pressure assay is desired) into a clearly labeled one-gallon re-closable freezer bag (Figure 2.12).

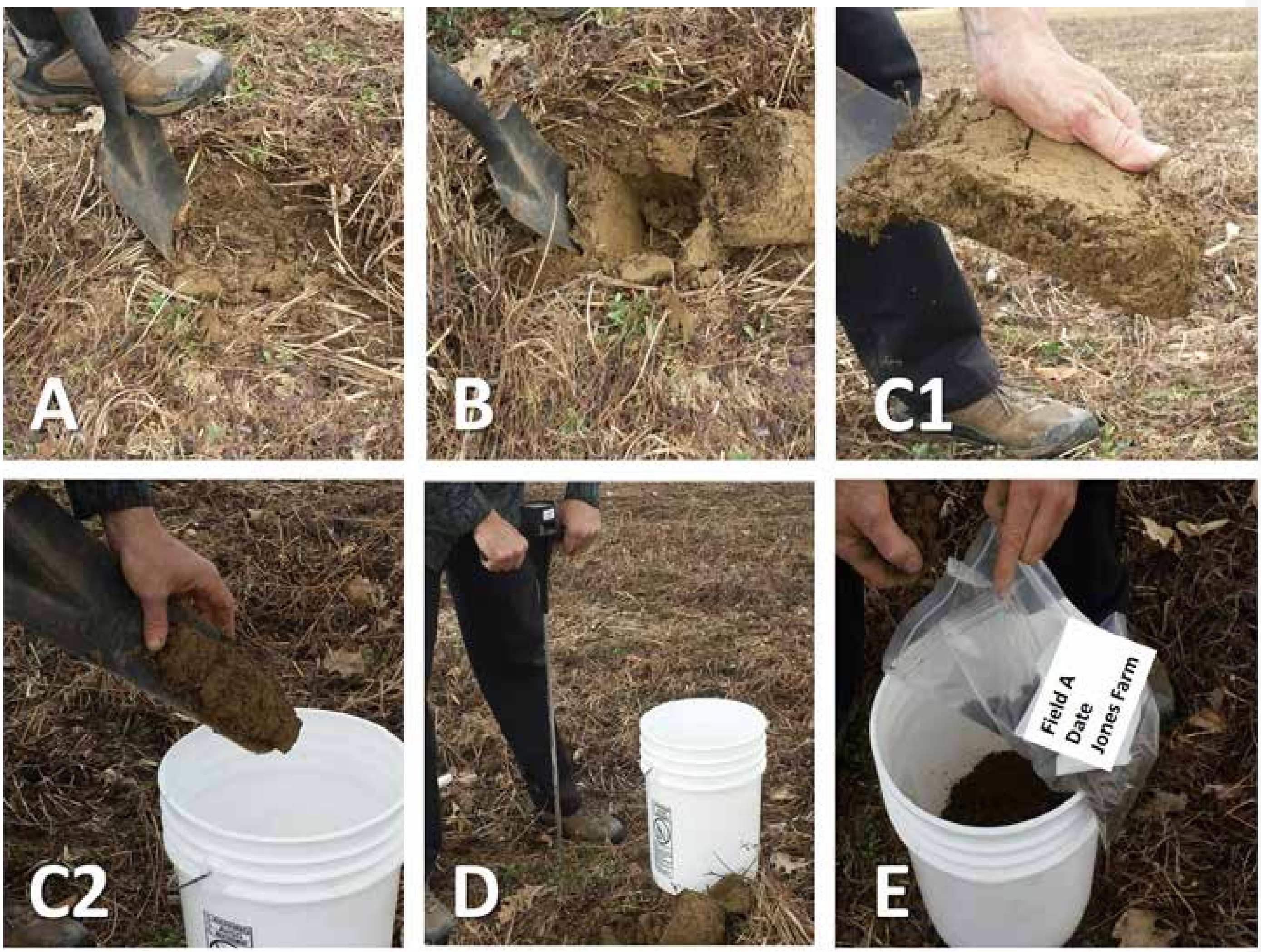
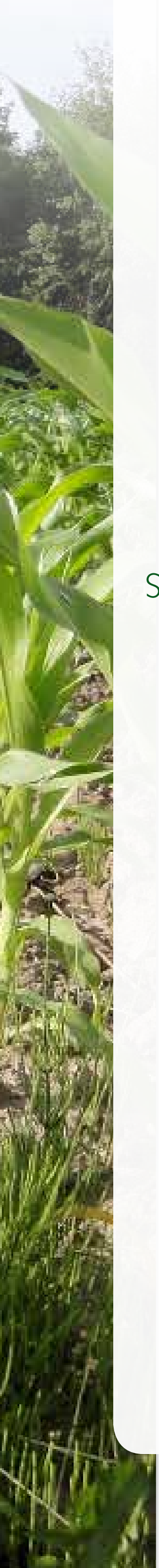


FIGURE 2.11. The steps of taking a soil health sample. The mircoorganisms in the soil are sensitive to heat. Keep sampes out of the direct sunlight and keep as cool as possible during the sampling. Store samples in a refrigerator or cold room after returning from the field and ship to Cornell as soon as possible. Photo credit: Kirsten Kurtz



Soil sample storage requirements:

- Always keep samples out of direct sunlight, and if possible, in a cooler in the field. High temperatures in a bag of soil sitting in the sun will have a detrimental impact on biological indicator measurements.
- Upon returning from the field, store samples in refrigerator or cold room as soon as possible, cool overnight, and ship for analysis as soon as possible (see further details below).
- Do not freeze the samples.
- Do not dry the samples.
- **IMPORTANT:** If you are planning on submitting a batch of numerous samples, and have particular sampling considerations to discuss regarding storage or pre-processing, such as for a larger research project, please contact Soil Health Lab personnel prior to sampling using the contact information on the soil health lab website.

Soil sample shipping to the lab

- Recommended shipping guidelines:
- Visit our website and download the submission form: soilhealth.cals.cornell.edu. Download and save the file (Figure 2.13). Open and fill in the necessary information.
- Save the submission form file for your records and email it as an attachment to: soilhealth@cornell.edu
- **Use a rapid shipping method**
- Print one copy of the submission form and insert into the shipping box with soil samples. There is a PDF version of the form on the website if you don't have Excel
- Make sure to include your penetrometer measurements for each correctly labeled sample
- Use a small USPS Flat Rate Box ($5.95 in 2016) or send up to six 4-cup samples, using USPS Priority Mail Medium Flat Rate box ($12.65)

A complete sample will consist of:

- a clearly labeled bag containing at least 4 full cups of composited soil
- a completed submission form with penetrometer readings clearly recorded

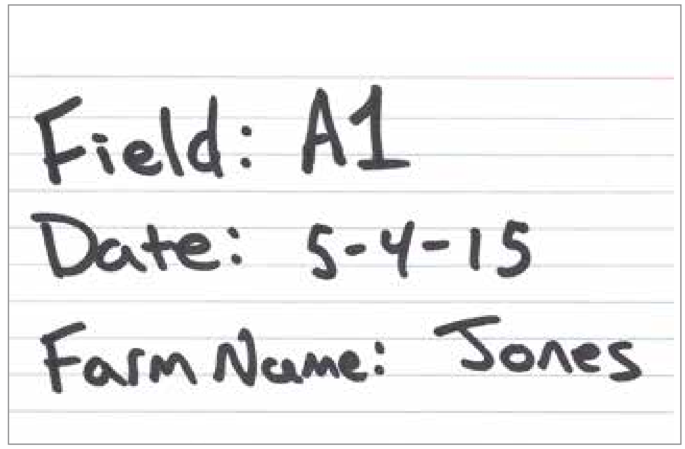


FIGURE 2.12. Sample label for individual field samples. Label should include field name or ID, date sampled and farm name. Correct labeling is critical to ensure that you receive the correct information for your field.

Send samples and completed submission forms to:

Cornell Nutrient Analysis Lab
c/o Soil Health Lab
G01 Bradfield Hall
306 Tower Rd.
Ithaca, NY 14853

soilhealth@cornell.edu
607-227-6055

2015 Cornell Assessment of Soil Health Submission Form - EXCEL spreadsheet **page 1**

EXCEL users: Complete this form, print the 2 sheets and insert into the shipping box with soil samples. Also 1) save the file for your records and 2) attach the EXCEL file to an email to the lab.

No EXCEL?: Print this form from any format, enter your iunformation, place in the box with your samples. OR see website for pdf version of form.

You will be contacted upon receipt of this form with the amount due for the soil sample analyses. NOTE: Quarantined samples are subject to an additional 15% surcharge.

Cornell Nutrient Analysis Lab, G01 Bradfield Hall, 306 Tower Rd, Ithaca, NY 14853 607-227-6055

email: soilhealth@cornell.edu

http://soilhealth.cals.cornell.edu

You can enter more than one ASP here

Grower First Name	Grower Last Name	Grower Address	Grower Email Address	Who is paying for the sample? (name or email)	Quarantine samples?	Ag Service Provider (or leave blank)	Ag Service Provider Email Address	Ag Service Provider Phone Number

number your samples	Field I.D./Sample Name WRITTEN ON SAMPLE BAG	Date sampled 2015	Testing Package Basic, Standard or Comprehensive (see page 2)	Any Additional Testing? Choose: Soluble Salts; Heavy Metal digestion; Bean Root Bioassay; Hot-water Soluble Boron	GPS Coordinates for Field or Sample (online help at http://itouchmap.com/latlong.html)		soil name (if known)	Tillage Depth 2015 1 = notill 2 = 1-7 inch 3 = 7-9 inch 4 = > 9 inch	Crop Information* *Find the Crop Codes at http://dairyone.com/analytical-services/agronomy-services/soil-testing/ 2013	2014	2015

page 2

BASIC Soil Health Analysis Package $50/sample (sample size 3 cups)
Recommended applications: field crops, dairy, lawns
> Soil pH, Organic Matter, Modified Morgan Extractable P, K, micronutrients
> Wet Aggregate Stability
> Soil Respiration
> Surface , sub-surface Hardness interpretation (optional- *you provide the penetrometer readings*)

STANDARD Soil Health Analysis Package $95/sample (sample size 4 cups)
Recommended applications: organic production, veg crops, problem diagnosis, home gardens
> Soil pH, Organic Matter, Modified Morgan Extractable P, K, micronutrients
> Soil Texture
> Wet Aggregate Stability
> Available Water Capacity
> Active Carbon
> Soil Respiration
> Soil Protein
> Surface and sub-surface Hardness (optional- *you provide the penetrometer readings*)

EXTENDED Soil Health Analysis Package $150/sample (sample size 6 cups)
Recommended applications: urban/ suburban gardens, problem diagnosis, soil health initializing, home gardens, landscaped areas, corner lots, brownfields
> Includes the **STANDARD Soil Health Analysis Package PLUS**
> Add-on Soluble Salts
> Add-on Heavy Metal Screening
> Add-on Bean Root Bioassay

Useful Add-on Tests for the BASIC and STANDARD Package

Soluble Salts $10/sample
Recommended applications: high tunnels, lawns and urban areas, heavily composted areas, home gardens, landscaped areas

Heavy Metal Screening $30/sample
Recommended applications: urban areas, home gardens, playgrounds, brownfields

Bean Root Bioassay $15/sample
Recommended applications: home gardens, vegetables, problem areas

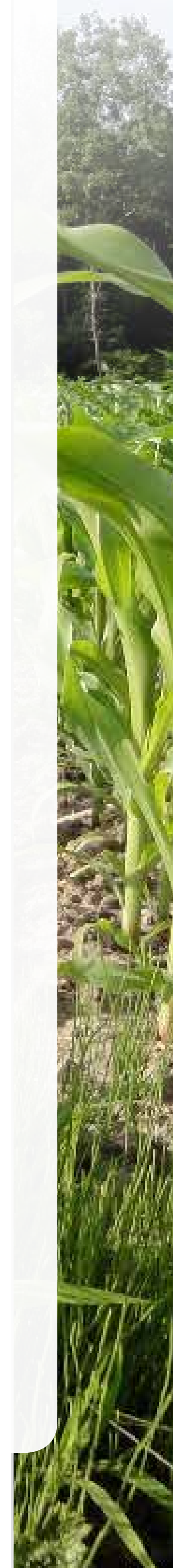
Hot Water-soluble Boron $15/sample
Recommended applications: small fruits, vegetables, home gardens

Soil penetrometer data- record the highest number encountered in the 0-6" and the 6-18" depth for each subsample location

location 1		location 2	0-	location 3	0-	location 4	0-	location 5	0-	location 6	0-	location 7	0-	location 8	0-
0-6"	6-18"	6"	6-18"	6"	6-18"	6"	6-18"	6"	6-18"	6"	6-18"	6"	6-18"	6"	6-18"

All of the soil analyses found in the Packages or the Add-ons are available from the Cornell Nutrient Analysis Lab. Use the Submission form S at this link: http://cnal.cals.cornell.edu/forms/pdfs/CNAL_Form_S.pdf

FIGURE 2.13. Sample submission form. Go to soilhealth.cals.cornell.edu to download form.



Soil Health Indicator Protocols and Scoring

Soil Health indicators were selected for the assessment using criteria discussed on page 25, such as their sensitivity to management changes, in measurement consistency and reproducibility, ease and cost of sampling and cost of analysis. The following pages provide a detailed desription of each indicator, how it is measured, how it relates to soil functioning and the interpretive scoring function used to assign a rating score.

Soil Texture

Most of a soil's solid material is made up of a mixture of variously sized mineral particles, the relative amounts of which determine a soil's texture. The textural class is defined by the relative amounts of sand (0.05 to 2 mm particle size), silt (0.002 to 0.05 mm), and clay (less than 0.002 mm), as seen in the textural triangle (following page). Particles that are larger than 2 mm are called coarse fragments (pebbles, cobbles, stones, and boulders), and are not considered in the textural class, although they may help define a soil type. Organic matter is also not considered in the determination of soil texture, although it is very important for soil functioning, as we will further discuss. A soil's textural class—such as a clay, clay loam, loam, sandy loam, or sand—is perhaps its most fundamental inherent characteristic. It affects many of the important physical, biological, and chemical processes in a soil, but is not easily altered by management, and changes little over time. Thus, while texture is not a soil health indicator per se, it informs the interpretation of most soil health indicators.

Basic Protocol[2]:

- Air dry a portion of the soil sample and sieve past 2mm.
- Approximately 14g (+/- 0.1g) of sieved soil is added to a 50ml centrifuge tube containing 42ml of a dispersant solution (3% sodium hexametaphosphate, a detergent).
- Shake vigorously on reciprocating shaker for 2 hours to fully disperse soil into suspension.
- Wash entire contents of centrifuge tube onto a sieve assembly (Figure 2.14 A). Sieve assembly consists of 0.053mm sieve on top of a plastic funnel above a 1L beaker. Rinse all material through the sieve. Sand captured on top of the sieve is washed into a tared metal can and set aside (B).
- Silt and clay particles collected in the 1L beaker are re-suspended by stirring and allowed to settle for 2 hours (C). The clay in suspension is then carefully decanted. The settled silt is washed into a second tared can. Both tared cans (one containing the sand fraction and the other the silt fraction) are dried at 105^{O} C to constant weight before recording the dry weight.
- Calculate percent sand, silt clay from:
  Sand (%) = dry wt sand (g)/dry wt (g) soil added to centrifuge tube.
  Silt (%) = dry wt silt (g)/dry wt (g) soil added to centrifuge tube.
  Clay (%) = 100% - Sand (%) - Silt (%).

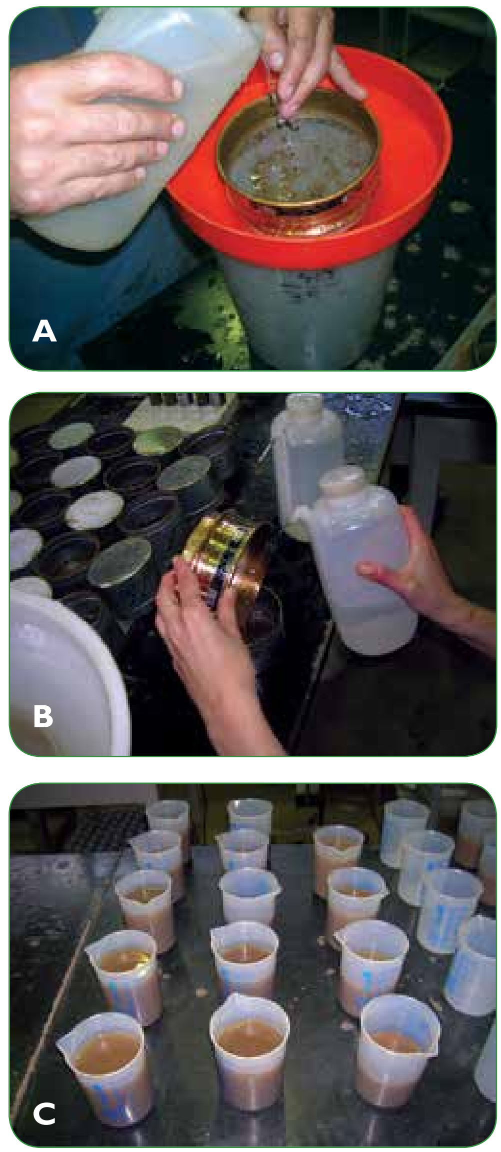


FIGURE 2.14. Determining soil textural class in the lab.

[2]Kettler ,T. A., J.W. Doran, and T. L. Gilbert. 2001. Simplified method for soil particle-size determination to accompany soil-quality analyses. Soil Science Society of America Journal 65:849–852.

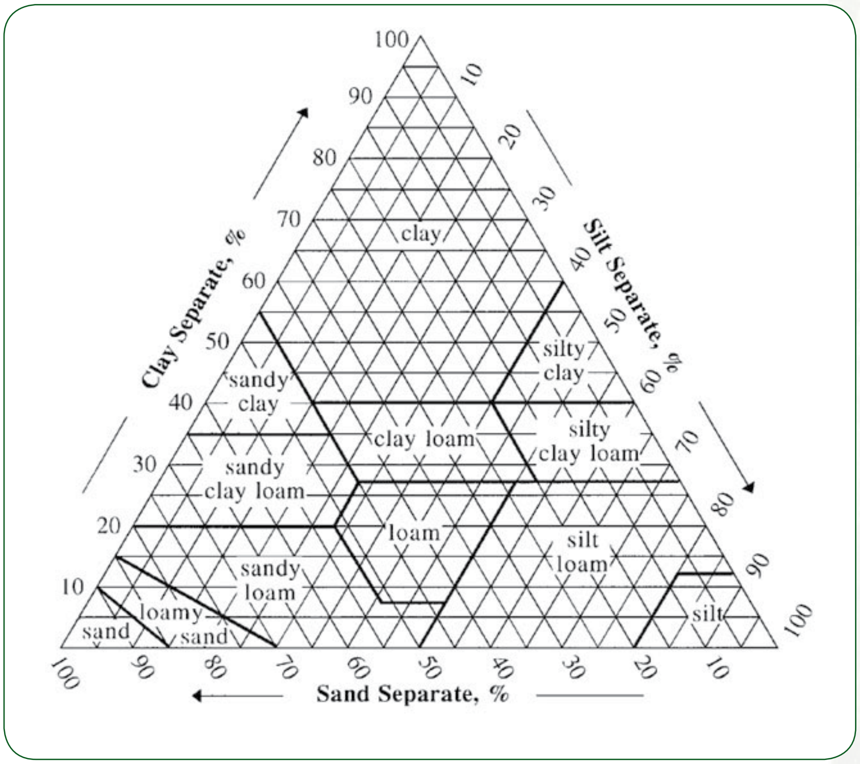
How soil texture relates to soil function:

Texture affects many important soil processes due to the total amount of pore space and how varied pore space is within aggregates. Soils with higher clay contents generally have higher ability to retain nutrients (more cation exchange capacity, or CEC, discussed previously) and can accumulate, or sequester, more organic matter. The size distribution of the particles strongly influences the size of the pore spaces between the particles, the formation and stabilization of soil aggregates, and the spaces between these aggregates. These aggregates and inter-aggregate spaces are as important as the sizes of the particles themselves, because the relative quantities of variously sized pores—large, medium, small, and very small—govern the important processes of water and air movement. These in turn affect processes like water infiltration, permeability, water storage, aeration, nutrient leaching, and denitrification. In addition, soil organisms and plant roots live and function in the pores. When the soil loses porosity (generally due to management), roots cannot grow as well, and many organisms have more difficulty surviving. Most pores in a clay are small (generally less than 0.002 mm), whereas most pores in a sand are large (but generally still smaller than 2 mm).

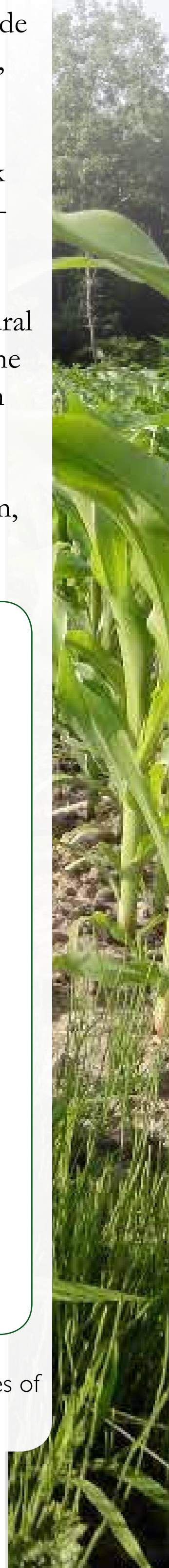
On the one extreme of the texture and aggregation spectrum, we see that beach sands have large particles (in relative terms) and very poor aggregation due to a lack of organic matter or clay to help bind the sand grains. A good loam or clay soil, on the other hand, has smaller particles, but they tend to be aggregated into crumbs that have larger pores between them and small pores within. Although soil texture doesn't generally change over time, the total amount of pore space and the relative amount of variously sized pores are strongly affected by management practices.

Using texture in developing scoring functions

Soil texture contributes to inherent soil quality, the characteristics of the soil that result from soil forming processes. It is virtually unchangable through soil management for a particular soil and is therefore not scored as part of a soil health assessment. Information on soil texture, however, is very valuable by itself for planning management practices. Moreover, soil textural information is used to score most of the other soil health indicators, because interpretations are best made in light of interactions with soil texture. For example, given the same management, coarse textured soils like loamy sands generally have lower organic matter levels than fine-textured clay loams, because they lack the ability to stabilize organic matter through organo-mineral bonds. Measured organic matter contents, along with other indicators, are scored relative to an appropriate distribution for soils of a particular textural grouping, to account for this type of difference. In the soil health assessment scoring process, we distinguish between coarse-textured (sand, loamy sand, sandy loam), medium-textured (loam, silt loam, silt, sandy clay loam) and fine-textured (clay loam, silty clay loam, sandy clay, silty clay, clay) soils.



Textural triangle used in determining soil texture. Soils with different properties of sand, silt and clay are assigned different classes. *Source: USDA-NRCS*



Available Water Capacity

Available water capacity is an indicator of the range of plant avaiable water the soil can store. In the field, a soil is at the upper end of soil wetness when water that it can't hold against gravity has drained - this is called field capacity. The lower end the range is called the 'permanent wilting point', when only water unavailable to plants, also called hygroscopic water, is left. The water stored in the soil against gravity is plant available until it decreases to the permanent wilting point. Available water capacity is determined from measuring water content at field capacity and permanent wilting point in the lab, and calculating the difference.

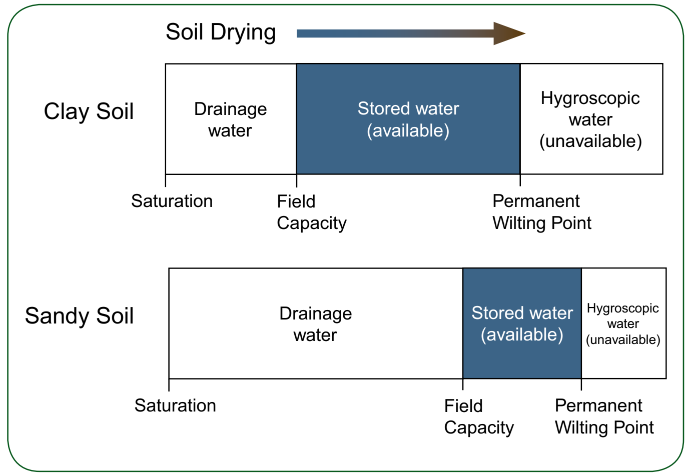


FIGURE 2.16. Water storage for two soil textural groups. The blue shaded area represents water that is available for plant use.

Basic Protocol

- Soil is placed on two ceramic plates with known porosity, and wetted to saturation (Figure 2.15 A).
- The ceramic plates are inserted into two high pressure chambers to extract the water to field capacity (10 kPa), and to the permanent wilting point (1500 kPa) (B).
- After the sample equilibrates at the target pressure, the sample is weighed (C), then oven-dried at 105° C overnight, and then weighed again once dry.
- The soil water content at each pressure is calculated, and the available water capacity can then be calculated as the soil water loss between the 10 and 1500 kPa pressures.

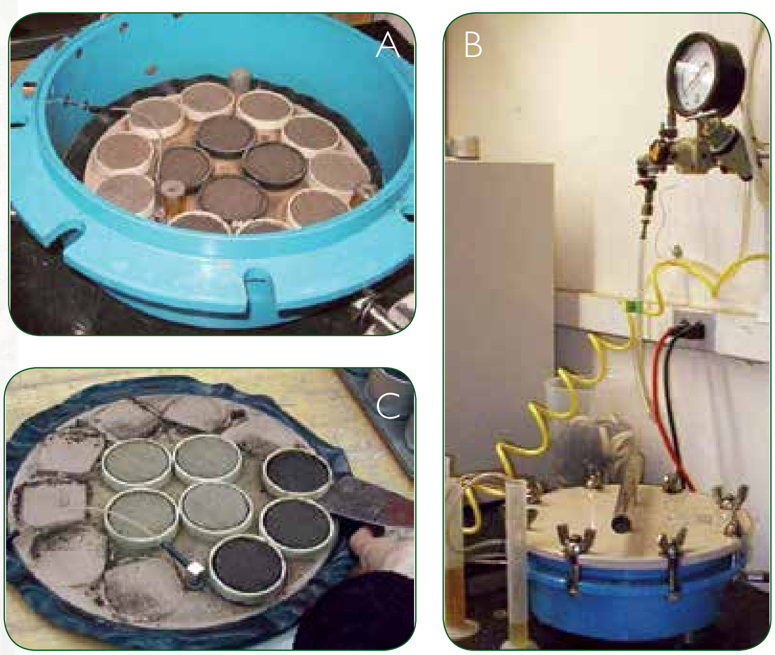


FIGURE 2.15 A-C Ceramic plates with soil (A) are inserted into high pressure chambers (B). Equilabrated samples at target pressure (C). Samples are weighed and then oven dried overnight.

How AWC relates to soil function

Available water capacity is an indicator of how much water per weight of soil can be stored in the field, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. Water is stored in medium and small sized soil pores and in organic matter. Sandy soils, which tend to store less organic matter and have larger pores, tend to lose more water to gravity than clayey and loamy soils (see Figure 2.16).

A common constraint of sandy (coarse textured) soils is their lower ability to store water for crops between rains, which is especially a concern during droughty periods, and in areas where irrigation is costly or not available. In heavier (fine textured) soils, the available water capacity is generally less constraining, because they naturally have high water retention ability. Instead, they are typically more limited in their ability to supply air to plant roots during wet periods, and to allow for enough infiltration to store water if rains come infrequently in heavy events. Note that total crop water availability is also dependent on rooting depth, which is considered in separate indicators, surface and subsurface hardness.

Managing constraints and maintaining optimal available water capacity

Available water capacity can be improved in the short term by large additions of stable organic materials, such as composts, or possibly biochar, that themselves can store larger amounts of water. Mulches may be used to prevent limited water from evaporating. In the long term, building organic matter and aggregation will build porosity for storing water. This can be accomplished by reducing tillage, long-term cover cropping, mulching, rotating annual crops with diverse perennials, and generally keeping actively growing roots in the system to build and maintain soil pores (Part III). In coarse textured soils building higher water storage is more challenging than in finer textured soils that inherently store more water. Therefore, managing for relatively high water storage capacity, and also for decreased evaporation through surface cover, is particularly important in coarse textured soils. While the inherent textural effect cannot be influenced by management, management decisions can be, in part, based on an understanding of inherent soil characteristics.

Scoring function

Below is the scoring function graph for Available Water Capacity for coarse, medium, and fine textured soils (Figure 2.17). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report summary page (see page 71).

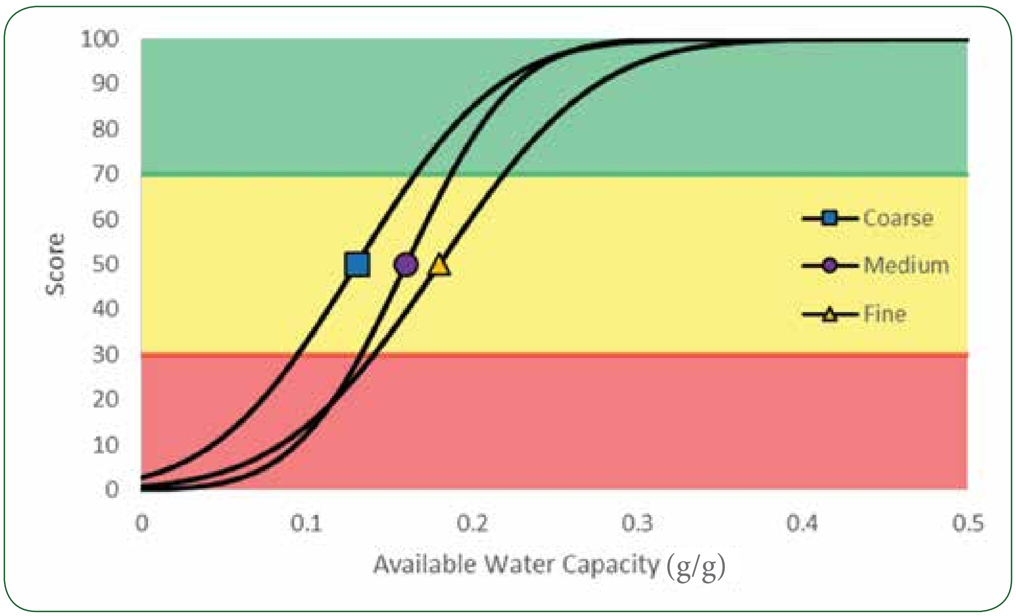


FIGURE 2.17. Scoring function graph for Available Water Capacity (AWC) for three textural categories. In this case, more is better. The higher the AWC (g/g), the higher the score until a maximum amount is attained.

Surface and Subsurface Hardness

Surface and subsurface hardness are indicators of the soil compaction status, measured as field penetration resistance in pounds per square inch (psi) using a field penetrometer pushed through the soil profile. It is measured in the field with a penetrometer or soil compaction tester for two depth increments (surface: 0 – 6”, and subsurface: 6 – 18”). Measurements should be taken when the soil is near field capacity, since moisture content influences the measurement. The reading in psi can be converted to kilogram-force per square centimeter (kgf/cm^2).

Basic Protocol (guidelines for field user):

- Surface and subsurface hardness are measured using a penetrometer, an instrument that measures the soil’s resistance to penetration. It consists of a cone-tip, a metal shaft, and a pressure gauge that measures resistance in psi (Figure 2.18 A).
- Most penetrometers come with two different sized tips which correspond to two different gauge scales. The outer and inner scales correspond to the larger ¾ inch and the smaller ½ inch diameter tips, respectively (B). For most instances, the ½” tip should be used. The ¾” tip is for very soft soil. Be sure to use the scale appropriate for the tip size.
- The level of soil moisture can greatly affect the ease with which the probe penetrates the soil, and therefore the measured values. <u>It is recommended that penetration readings be taken when the soil is at field capacity</u> (2-3 days after free drainage). If the soil conditions are not ideal, it is important to note conditions at the time so that proper interpretation of the reading can be made.

FIGURE 2.18 A and B. Measuring suface and subsurface hardness with a pentrometer.

- Apply slow even pressure so penetrometer advances into the soil at a rate of 4 seconds per 6 inches or less. Record the highest pressure reading measured for each of the two depths in the sample intake form. If you detect a hard layer, make sure to note its depth – this is important information for management decisions.
- Field profiles of penetration resistance can be created by recording the measured psi every inch through the soil profile and then plotting them on a chart (Figures 2.19 and 2.20). These charts can be used to identify various layers of compaction, if present. For the soil health test, however, we only target two depths.

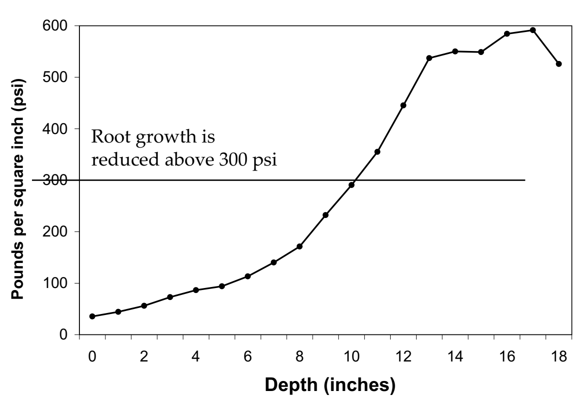


FIGURE 2.19. Soil compaction graph for a field in intensive vegetable production in 2005 (Courtesy of C.R. MacNeil).

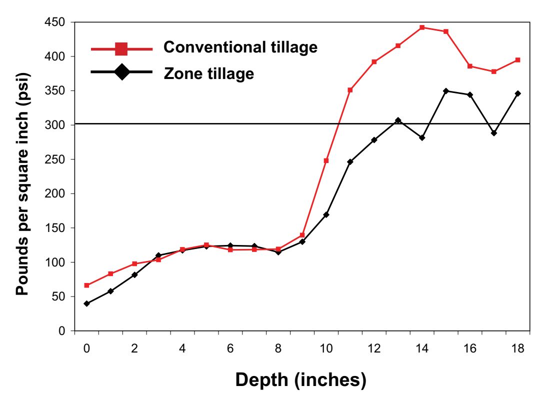


FIGURE 2.20. Soil compaction graph for a conventionally plow tilled field and zone-till field with deep ripping on the same farm in spring of 2005 (Courtesy of C.R. MacNeil).

How soil hardness relates to soil function:

Large pores are necessary for water and air movement and to allow roots and organisms to explore the soil. Field penetration resistance measures whether the soil is compacted. Compaction occurs when large pores are lost as solid soil materials are packed closer together through tillage or traffic with heavy equipment, particularly on wet soils. When surface soils are compacted, runoff, erosion, slow infiltration, and poor water storage result.

Subsurface hardness prevents deep rooting and causes poor drainage and poor deep water storage (Figures 2.21 below and 2.22 on the following page). After heavy rain events, water can build up over a hard pan, causing poor aeration both at depth and at the surface, as well as ponding, poor infiltration, runoff and erosion. Impaired water movement and storage create greater risk during heavy rainfall events, as well as greater risk of drought stress between rainfall events.

Most crop roots cannot easily penetrate soil with penetrometer readings above about 300 psi. Similarly, growth of mycorrhizal fungal hyphae and mobility of other beneficial soil organisms may be severely restricted by excessively hard soil. Since plant roots must be actively growing and exploring the root zone to access water and nutrients, crop quality and yield decline with compaction. Low growth increases weed pressure, and stressful conditions make crops more susceptible to pathogen pressure.

Managing and preventing surface and subsurface hardness constraints

Compaction in surface and subsurface soil occurs very rapidly when the soil is worked or trafficked while it is too wet, and compaction can be transferred deep into the soil even from surface pressure. Thus avoiding soil disturbance, especially when the soil is wet, can prevent compaction. Maintaining aggregation is particularly critical for preventing surface compaction (pages 15,44). Compaction can be alleviated by targeted management (Part III). Subsoil compaction can be addressed by deep tillage or by deep rooting crops. Surface compaction can be alleviated by targeted mechanical surface loosening of the soil, followed by fresh organic matter additions and vigorously rooting cover/rotation crops to strengthen and rebuild aggregates (pages 84-93). In the long term, reduced, well-timed tillage and controlled traffic with minimized loads, soil cover, rotations, and active rooting will maintain non-compacted soils.

Compaction from wet soil conditions: wheel traffic.

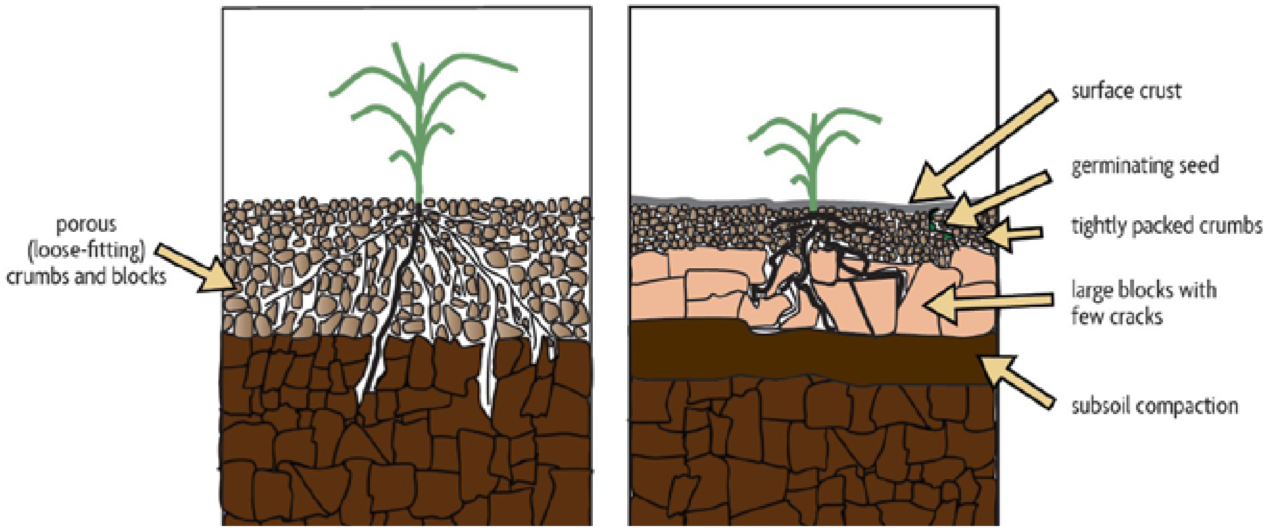


FIGURE 2.21. Plants growing is soil with good soil structure (left). Soil with three types of compaction: surface crusting, plow layer/surface compaction, and subsoil compaction (right). *Source: Building Soils for Better Crops, 3rd Edition*

Scoring function:

Below are the scoring function graphs for surface and subsurface resistance in coarse, medium, and fine textured soils (Figure 2.23). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71).

FIGURE 2.22. Dense rooting allows for full soil exploration (left). Surface compaction prevents root from acessing water and nutrients (right). *Source: Building Soils For Better Crops, 3rd Edition*

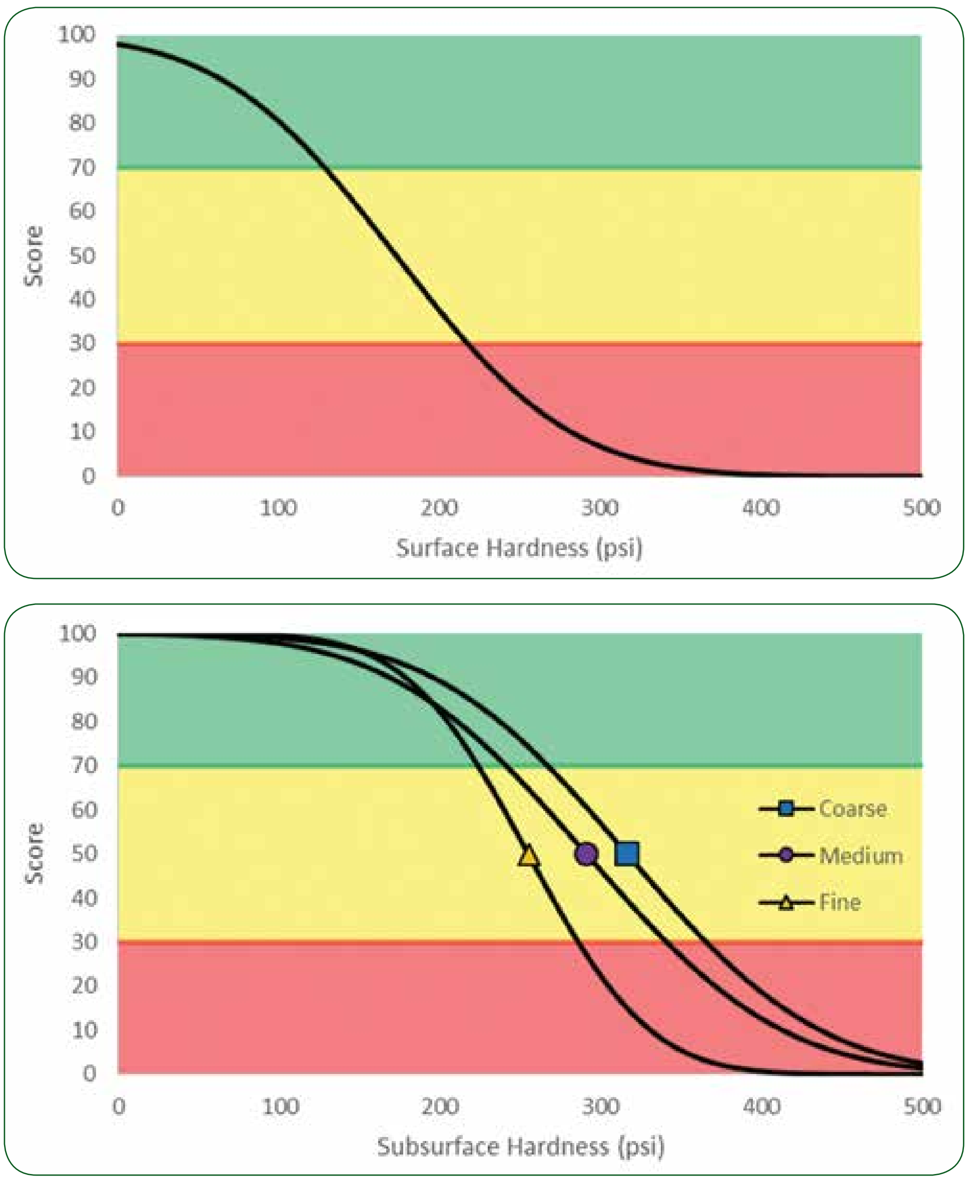


FIGURE 2.23. Scoring function graphs for Surface and Subsurface Hardness for three textural categories. In this case less is better. Higher scores are given to lower values of the indicator.

Aggregate Stability

Aggregate stability is a measure of the extent to which soil aggregates resist falling apart when wetted and hit by rain drops. It is measured using a Cornell Sprinkle Infiltrometer that steadily rains on a sieve containing a known weight of soil aggregates sized between 0.25 mm and 2 mm. The unstable aggregates slake (fall apart) and pass through the sieve. The fraction of soil that remains on the sieve is used to calculate the percent aggregate stability (Figure 2.24 A-C). For details on the Sprinke Infiltrometer visit soilhealth.cals.cornell.edu.

Basic Protocol

- Soil is air-dried and placed on stacked sieves of 2.0 mm, 0.25 mm and a catch pan. The dried soil is shaken for 15 seconds on a Tyler Coarse Sieve Shaker to separate out aggregates of 0.25 - 2.0 mm size for analysis.
- A single layer of aggregates from 0.25 - 2.0 mm in size (about 30g) is spread on a 0.25 mm sieve (diameter is 200 mm, or about 8 inches) (A).
- Sieves are placed at a distance of 500 mm (20 inches) below a rainfall simulator, which delivers individual drops of 4.0 mm diameter (B).
- The test is run for 5 minutes and delivers 12.5 mm of water (approximately 0.5 inches) as drops to each sieve. See soils starting to wet in (C). A total of 0.74 J of energy thus impact each sieve over this 5 minute rainfall period. Since 0.164 mJ of energy is delivered for each 4.0 mm diameter drop, it can be calculated that 15 drops per second impact each sieve. This is equivalent to a heavy thunderstorm.
- The slaked soil material that falls through during the simulated rainfall event, and any stones remaining on the sieve are collected, dried and weighed, and the fraction of stable soil aggregates (WSA) is calculated using the following equation:

  $$WSA = W_{stable} / W_{total},$$

  where

  $$W_{stable} = W_{total} - (W_{slaked} + W_{stones})$$

  where W = weight (g) of stable soil aggregates (stable), total aggregates tested (total), aggregates slaked out of sieve (slaked), and stones retained in sieve after test (stones). Corrections are made for stones.

FIGURE 2.24 A-C. Aggregate Stability test. A rain simulator is used for 5 minutes on a sieve containing soil aggregates.

How aggregate stability relates to soil function

This method tests the soil's physical ability to hold together and sustain its aggregation, or structure, during most impactful conditions: a heavy rain storm or other rapid wetting event, such as irrigation, after surface drying weather (Figure 2.25). This is a good indicator of both physical and biological health (Part I, page 9). Soils with low aggregate stability tend to form surface crusts and compacted surface soils. This can reduce air exchange and seed germination, increase plant stress and susceptibility to pathogen attack, and reduce water infiltration and thus storage of water received as rainfall. This leads to runoff, erosion and flooding risk downstream during heavy rainfall, and higher risk of drought stress later. Poor soil aggregation also makes the soil more difficult to manage, as it reduces its ability to drain excess water, so that it takes longer before field operations are possible after rain events. In heavy (fine textured) soils, enhanced friability and crumbliness from good aggregation makes the soil less dense, so that it is lighter, and is easier to work with less fuel. A well aggregated clay soil allows for excess water to drain through the cracks and fissures between crumbs, while storing water for plant use within the stable aggregates. Good aggregation is critical for resilience to extreme weather.

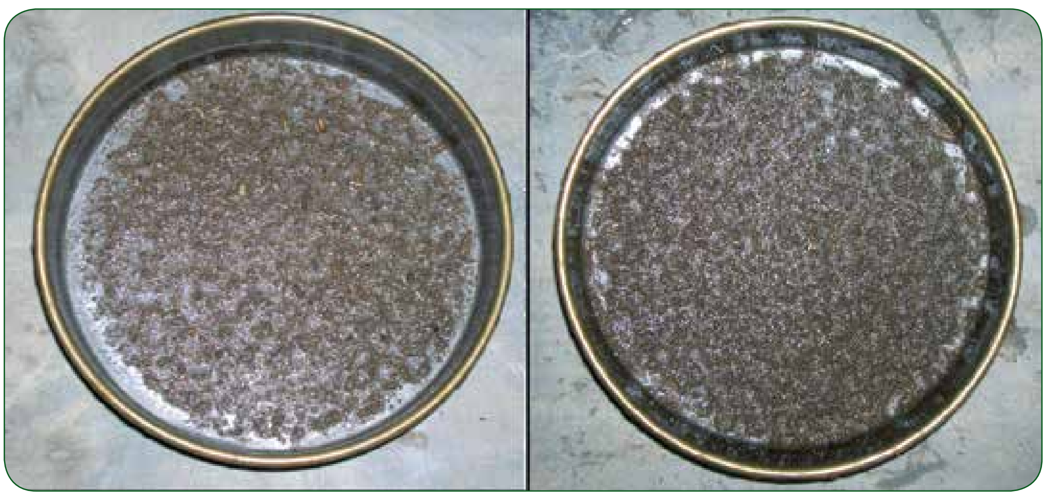


FIGURE 2.25. Pictures of different soil aggregate test results: A Lima silt loam soil from a long-term tillage experiment. The moldboard plow treatment on the left has 34% water stable aggregates while the soil under zone-till management on the right has 56% water stable aggregates (0.25 mm sieve).

Managing constraints and maintaining optimal aggregate stability

Stable aggregates are built by biological activity, as aggregates are largely "stuck" together by fungal hyphae, microbial colonies, and plant and microbial exudates. This means plentiful fresh and diverse organic materials (such as green manures, cover crops with vigorous fine roots, animal manures, and mulches) are needed to sustain soil biota, so that they can stabilize soil aggregates. Repeated tillage breaks down stable soil aggregates, especially when organic additions are too low. Such soils can be so degraded that they become addicted to tillage, where crop establishment then requires a soil loosening operation. A successful transition to reduced tillage usually requires focused tillage for crop establishment, and significant organic additions or rotation with a perennial forage or cover crop, to build the soil for minimized disturbance. Reduced tillage, soil cover, and diverse species and rotations with active living roots will maintain stable aggregates in the long term (Part III).

Scoring function

Below is the scoring functions graph for aggregate stability for coarse, medium, and fine textured soils (Figure 2.26). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71).

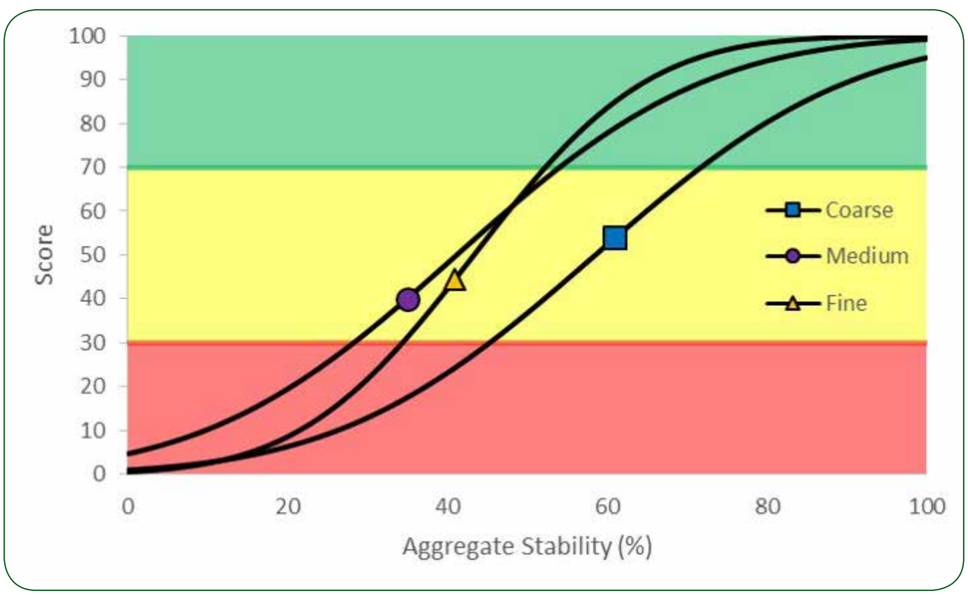


FIGURE 2.26. Scoring function graphs for Aggregate Stability for three textural categories. In this case more is better. The higher the percent stability of aggregates, the higher the score of the indicator.

Organic Matter

Organic matter is a measure of carbon-containing material that is, or is derived from, living organisms, including plants and other soil dwelling organisms. Total soil organic matter consists of both living and dead material, including well decomposed, more stabilized materials. Percent organic matter is determined by loss on ignition, based on the change in mass after a soil is exposed to high temperature (500 °C or 932°F) in a furnace. At these temperatures, carbonaceous materials are burned off (oxidized to CO_2), while other materials remain. Organic matter content is often provided by soil analysis laboratories along with major and minor nutrient contents, using a variety of methods.

Basic Protocol:

- A sample is dried at 105°C to remove all water.
- The sample is weighed (Figure 2.27).
- The sample is then ashed (for weight loss on ignition) for two hours at 500°C, and the percent of mass lost is calculated.
- The % loss on ignition (LOI) is converted to % organic matter (OM) using the following equation:

$$\% \text{ OM} = (\% \text{ LOI} * 0.7) - 0.23$$

FIGURE 2.27 Soil mass is determined prior to being exposed to high temperature. Soil is weighed after being ashed to calculate the percentage of mass lost.

FIGURE 2.28. Corn residue on the soil surface is a source of organic matter. *Source: USDA-NRCS*

How organic matter relates to soil function:

Soil organic matter (OM) is where soil carbon is stored, and is directly derived from biomass of microbial communities in the soil (bacterial, fungal, and protozoan), as well as from plant roots and detritus, and biomass-containing amendments like manure, green manures, mulches, composts, and crop residues (Figure 2.28). As discussed earlier, OM in its various forms greatly impacts the physical, chemical and biological properties of the soil. OM acts as a long-term carbon sink, and as a slow-release pool for nutrients. It contributes to ion exchange capacity (nutrient storage), nutrient cycling, soil aggregation, and water holding capacity, and it provides nutrients and energy to the plant and soil microbial communities (Figure 2.29). Soils with high organic matter tend to require lower farm inputs, and be more resilient to drought and extreme rainfall. It has been argued that organic matter management is soil health management.

Managing constraints and maintaining optimal organic matter content

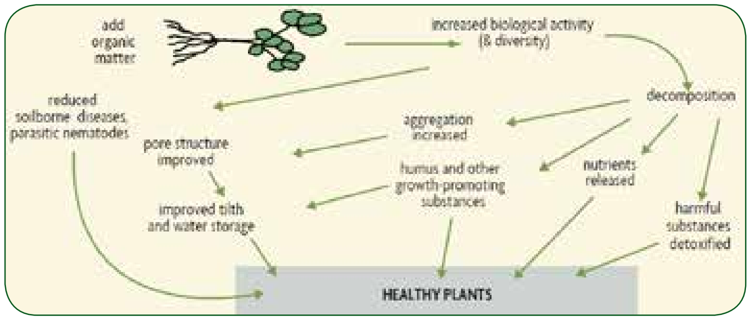


FIGURE 2.29. Adding organic matter results in a cascade of changes within the soil. *Source: Building Soils for Better Crops, 2nd Edition*

Intensive tillage and lack of carbon inputs decrease organic matter content and overall soil health with time. Increasing organic matter in the soil takes time and patience. It is unlikely that a single incorporation of a green manure will noticeably increase the percent organic matter. Adding more stable organic matter such as compost, or possibly biochar, can improve water infiltration and retention in the short term. Retention and accumulation of OM in the long term is improved by reducing tillage intensity and frequency (as much as is feasible within the constraints of the production system), and repeated use of diverse organic matter additions from various sources (amendments, residues, and the active growth of crops, forages, or cover crops, particularly their roots) which all stimulate both microbial community growth and the stabilization (sequestration) of carbon in aggregates. The appropriate selection of organic matter input will depend on the management goal(s) and other microbial activity and food source related constraints identified. Additional information on organic matter amendments and other resources can be found in Part III, page 92.

Scoring function:

Below is the scoring function graph for total Organic Matter content in coarse, medium, and fine textured soils (Figure 2.30). The red, yellow and green shading reflects the color coding used for the ratings on the soil health assessment report (see page 71).

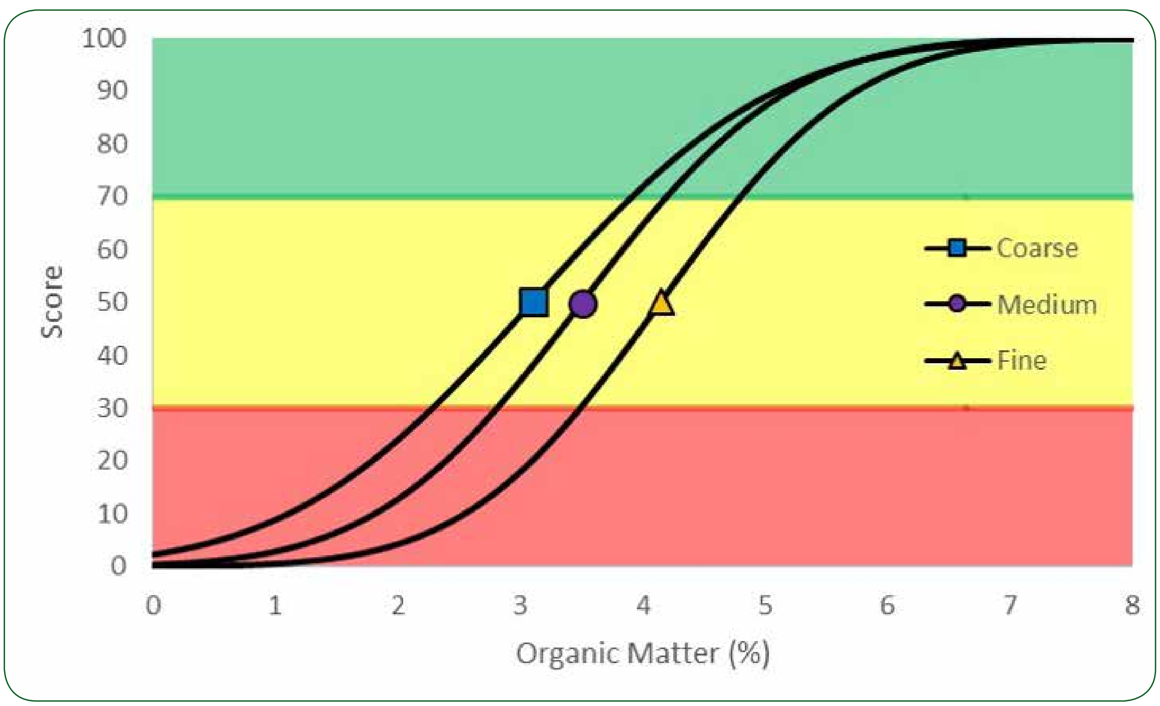
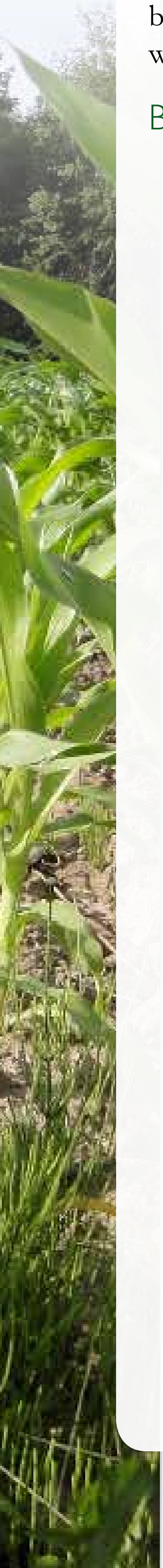


FIGURE 2.30. Scoring function graphs for total Organic Matter (OM) for three textural categories. In this case more is better. The higher the percent of OM, the higher the score of the indicator.



Soil Protein Index

The Autoclaved Citrate Extractable (ACE) Protein Index is an indicator of the fraction of the soil organic matter that is present as proteins or protein-like substances. This represents the large pool of organically bound nitrogen (N) in the SOM, which microbial activity can mineralize, and make available for plant uptake. Protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status.

Basic Protocol

- Proteins are extracted from sieved, well-mixed, air-dried soil, using a protocol modified from Wright and Upadhyaya (1996) and Clune (2008).
- 3.00 g of soil are weighed into a pressure- and heat- stable glass screw-top tube, with 24.00 ml of sodium citrate buffer (20 mM, pH 7.0), and the mixture is shaken to disperse aggregates and mix well (5 min at 180 rpm) (Figure 2.31 A).
- The tubes are autoclaved for 30 min (121° C, 15 psi) and then cooled (B).
- 2 ml of the slurry is withdrawn to a smaller micro-centrifuge tube (top of C), and centrifuged at 10,000 x gravity to remove soil particles.
- A small subsample of this clarified extract is used in a standard colorimetric protein quantification assay (BCA; demonstrated in tubes at bottom of C), to determine total protein content of the extract.
- The Cornell Soil Health Lab uses the Thermo Pierce BCA protein assay, miniaturized for use in 96-well microplates, incubated at 60° C for uniform response to different protein types, and read color development in a BioTek spectrophotometric plate reader (D).
- Extractable protein content of the soil is calculated by multiplying the protein concentration of the extract by the volume of extractant used, and dividing by number of grams of soil used.

How soil protein relates to soil function

Plant residues are ultimately the source of much of the soil organic matter. These are made up of several types of compounds, and of these, protein contains the largest fraction of N (Figure 2.32). Microbial biomass secondarily builds up as these residues and other organic matter amendments decompose, and this biomass is largely similar in composition, although it contains a few additional compound types. Some of these contain N, but not in as great a proportion as in protein.

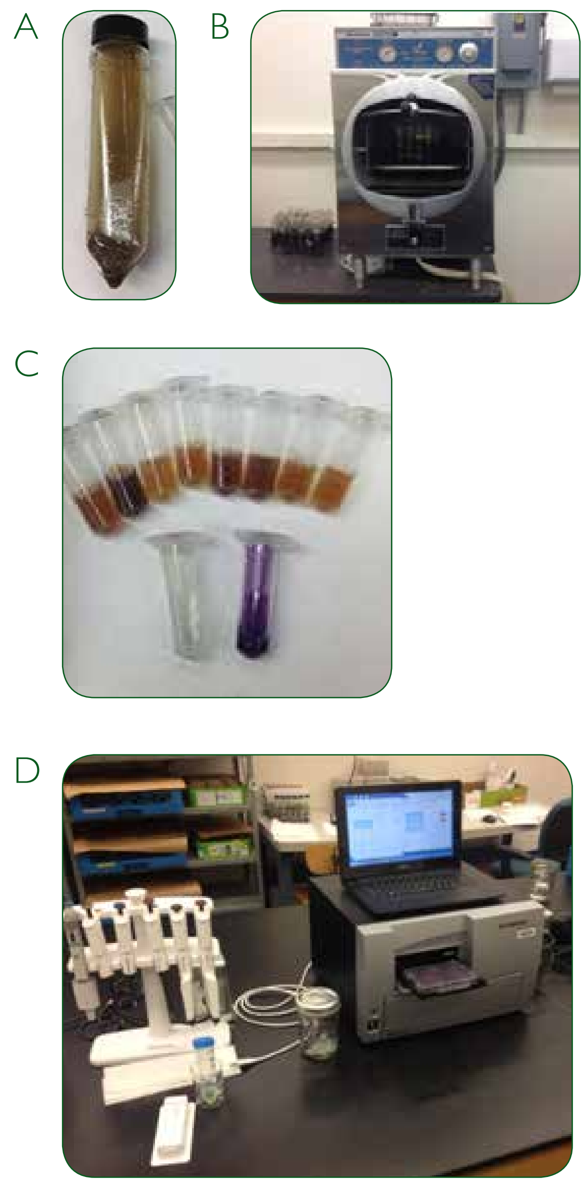


FIGURE 2.31 A-D. Lab procedure for the Autoclaved Citrate Extractable (ACE) Protein Index.

Protein content, as organically bound N, influences the ability of the soil to store N, and make it available by mineralization during the growing season. Soil protein content has also been associated with soil aggregation and thus water storage and movement.

Managing constraints and maintaining optimal soil protein content

To store and maintain N in the soil organic matter, we need to accumulate compounds that are relatively stable, rich in N (low C:N ratio), microbially degradable, and potentially abundant in amendments, crops, cover crops, or residues (Part III). Protein content can be increased by adding biomass such as manure, fresh green biomass, and high-N well finished compost, and by growing biomass in place by maintaining the presence of living, actively growing roots – particularly legumes that are well nodulated – and soil microbes. Protein content tends to decrease with increasing soil disturbance such as tillage.

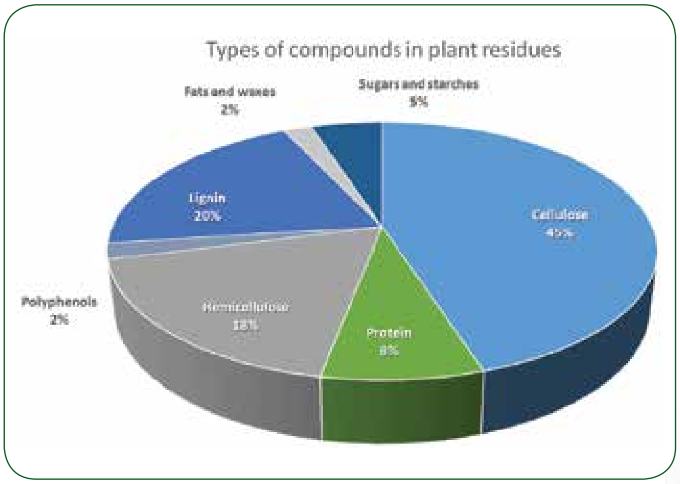


FIGURE 2.32. Types of compounds in plant residues. Protein are found in high abundance and contain the largest fraction of N. Modified from Brady and Weil (2002)

Scoring Function

Below is the scoring function graph for the ACE Soil Protein Index in coarse, medium, and fine textured soils (Figure 2.33). The red, yellow and green shading reflects the color coding used for the ratings on the soil health assessment report (see page 71). It should be noted that while none of the scoring functions for indicators related to nitrogen mineralization currently are calibrated to decline with very high values, extremely high N mineralization could increase losses of N to the environment, and thus harm air and water quality.

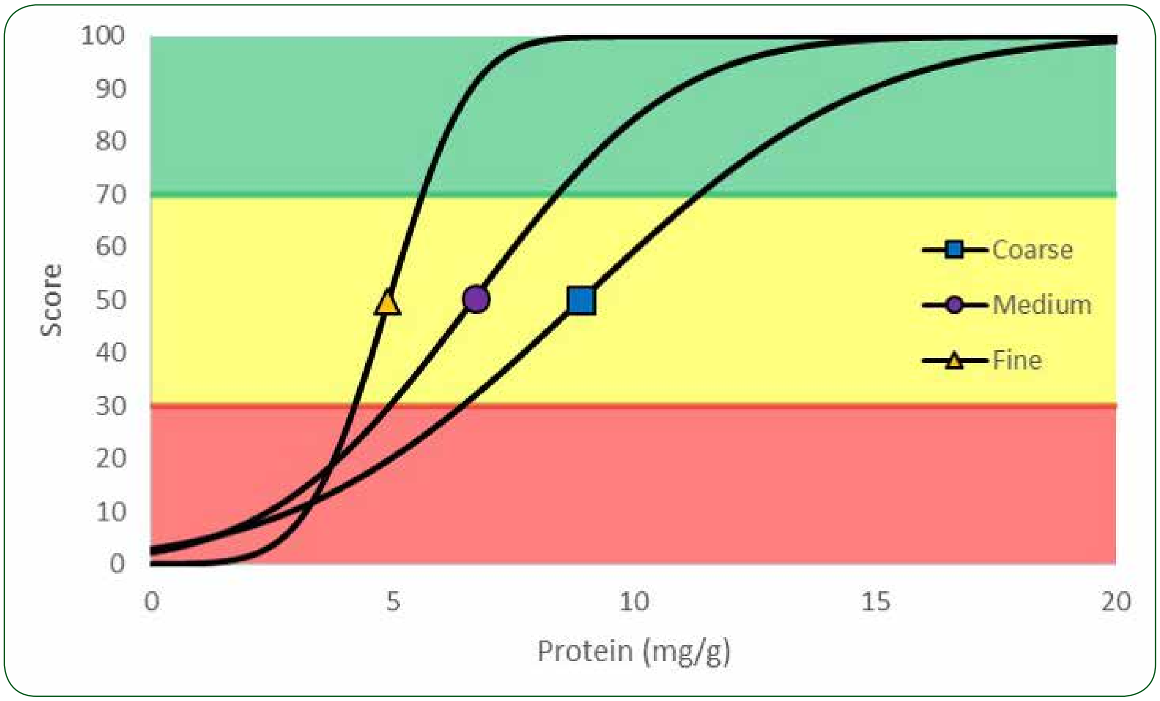


FIGURE 2.33. Scoring function graphs for the ACE Soil Protein Index for three textural categories. In this case more is better. The higher the protein content, the higher the score of the indicator.

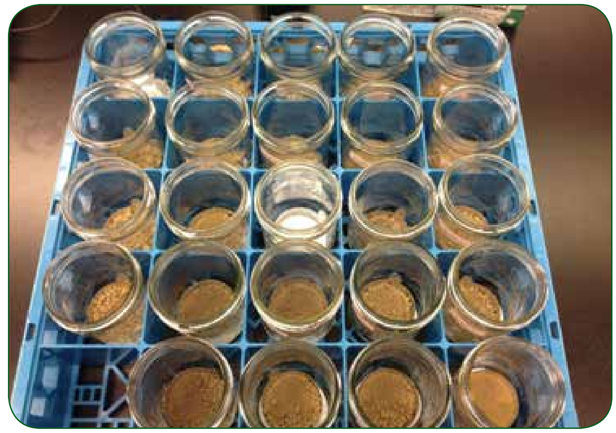
Soil Respiration

Respiration is a measure of the metabolic activity of the soil microbial community. It is measured by capturing and quantifying carbon dioxide (CO_2) released from a rewetted sample of air dried soil held in an airtight jar for 4 days. Greater CO_2 release is indicative of a larger, more active soil microbial community.

Basic Protocol

- 20.00 g of air-dried, sieved soil are weighed into an aluminum weighing boat, which is pre-perforated with 9 pin-holes through the bottom.
- The weighing boat with soil is placed on top of two staggered filter papers in the bottom of a standard 1 pint wide-mouth mason jar (Figure 2.34 A).
- A trap assembly (a 10 ml glass beaker secured to a plastic tripod 'pizza stool') is placed in the jar, and the beaker filled with an alkaline CO_2 - trapping solution (9 ml of 0.5 M KOH) (B).
- 7 ml of distilled, deionized water is pipetted into the jar onto the side, so that the water runs down and is wicked up into the soil through the filter paper.
- The jar is sealed tightly and incubated undisturbed for 4 days.
- Trap electrical conductivity declines linearly with increasing CO_2 absorption, as OH^- concentration in the trap declines and CO_3^{2-} concentration in the trap increases.
- After incubation, the jar is opened and the conductivity of the trap solution is measured (C).
- CO_2 respired is calculated by comparison with the conductivities of the original trap solution, and a solution representing the trap if saturated with CO_2 (0.25 M K_2CO_3).

A



B

C

FIGURE 2.34 A-C. Soil Respiration is measured by capturing and quantifying CO_2 released from samples.

How soil respiration relates to soil function

Respiration is a direct biological activity measurement, integrating abundance and activity of microbial life. It thus is an indicator of the biological status of the soil community, which can give insight into the ability of the soil's microbial community to accept and use residues or amendments, to mineralize and make nutrients available from them to plants and other organisms, to store nutrients and thus buffer their availability over time, and to develop good soil structure, among other important functions (Part I, page 5). Soil biological activity thus influences key physical, biological, and chemical soil processes, and is also influenced by constraints in physical and chemical soil functioning. Several individual enzyme and process activity assays are possible, as is quantification of microbial biomass size. However, measuring respiration by trapping of evolved CO_2 gives a rapid, low cost, integrative measure of general microbial activity level.

Managing constraints and maintaining optimal soil biological activity

The soil's biological activity is improved by keeping the soil covered with plants or residues throughout the season, adding fresh, microbially degradable amendments, growing biomass in place by maintaining living roots for as much of the year as possible, increasing diversity of species in the system through rotations, interseeding, or intercropping, and by reducing the use of biocides such as pesticides, fungicides, and herbicides (Part III). Beneficial soil biological activity tends to decrease with increasing soil disturbance such as tillage, heavy traffic, and compaction, as well as with extremes in low or high pH, or contamination by heavy metals or salts.

Scoring function

Below is the scoring function graph for soil respiration in coarse, medium, and fine textured soils (Figure 2.35). The red, yellow and green shading reflects the color coding used for the ratings on the soil health assessment report (see page 71).

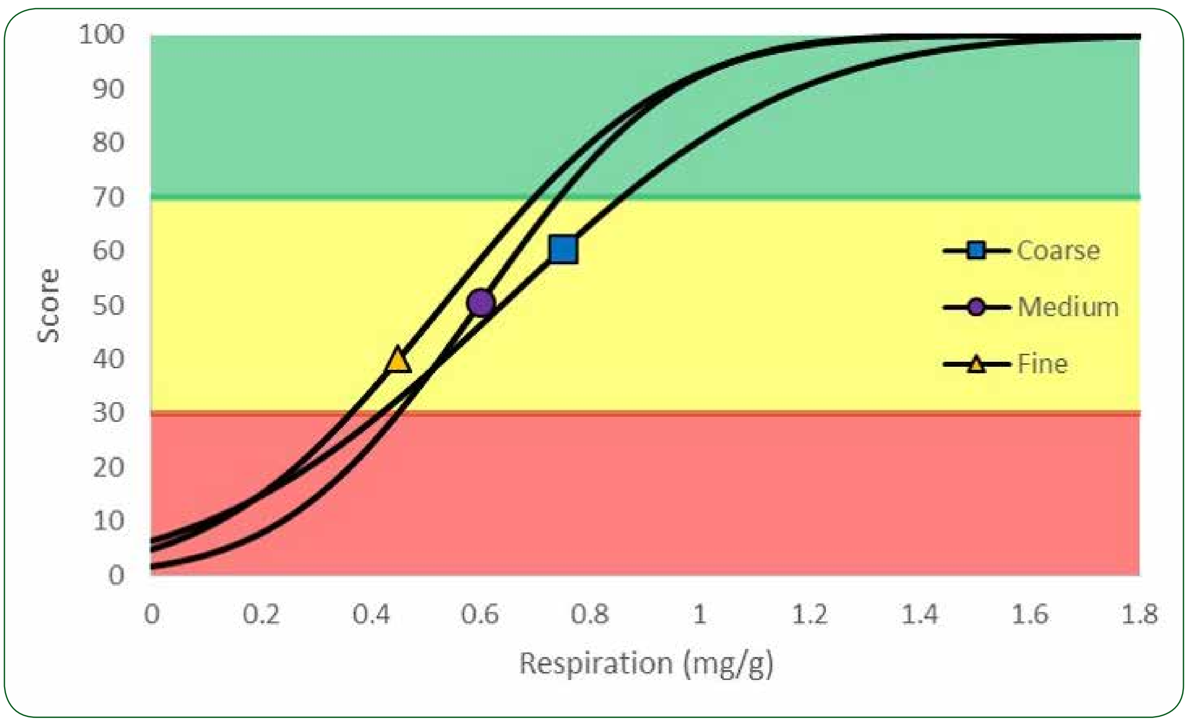


FIGURE 2.35. Scoring function graphs for Soil Respiration for three textural categories. In this case more is better. The higher the respiration, the higher the score and indication of a larger, more active soil community.

Active Carbon

Active carbon is an indicator of the small portion of soil organic matter that can serve as a readily available food and energy source for the soil microbial community, thus helping to maintain a healthy soil food web. To begin the process of measuring active carbon, soil is mixed with a potassium permanganate solution, which starts off deep purple in color. The permanganate oxidizes the active carbon and loses some of its color. The more active carbon found in the soil, the more the purple color declines. This color change is measured with a spectrophotometer or colorimeter.

Basic Protocol:

- Soil is air-dried and sieved to 2 mm.
- A 2.5 g sample of air-dried soil is placed in a 50 ml centrifuge tube filled with 20 ml of a 0.02 M potassium permanganate ($KMnO_4$) solution, which is deep purple in color (Figure 2.36 A).
- The soil and $KMnO_4$ are shaken for exactly 2 minutes to oxidize the active carbon in the sample. The purple color becomes lighter as a result of this oxidation reaction.
- The sample tube is then allowed to settle for 8 minutes, decanted off to another tube, and diluted with distilled water.
- Absorbance is measured at 550 nm (B).
- The absorbance of a standard dilution series of the $KMnO_4$ is also measured to create a calibration curve for interpreting the sample absorbance data.
- A simple formula is used to convert sample absorbance value to active C in units of mg carbon per kg of soil.

How active carbon relates to soil function:

Research has shown that active carbon is highly correlated with and similar to particulate organic matter (POM), which is determined with a more complex and labor-intensive wet-sieving and/or chemical extraction procedure. Due to its role in providing available food and energy sources for the soil microbial community, active carbon is positively correlated with percent organic matter, aggregate stability, and with measures of biological activity (such as respiration) and microbial biomass. Research has shown that active carbon is a good "leading indicator" of soil health response to changes in crop and soil management, usually responding to management much sooner (often years sooner) than total organic matter percent. This is likely because when a large population of soil microbes is fed plentifully over an extended period of time, well decomposed organic matter builds up. Thus, monitoring the changes in active carbon can be particularly useful to farmers who are changing practices with the goal of building up soil organic matter.

FIGURE 2.36 A and B. A 2.5g sample of soil is placed in a centrifuge tube filled with $KMnO_4$ solution (A). Absorbance is measured at 550 nm (B).The more active carbon found in the soil sample, the lighter the color of the solution.

Managing constraints and maintaining optimal soil biological activity

Reducing tillage and increasing organic matter additions from various sources will increase active carbon, and will feed, expand, and balance the microbial community, thus increasing total organic matter over the long term. Various sources include amendments, residues, and active and diverse forage, crop, or cover crop growth, with living roots providing labile carbon to soil microbes for as much of the year as possible (Part III).

Scoring function:

Below is the scoring function graph for active carbon in coarse, medium, and fine textured soils (Figure 2.37). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71).

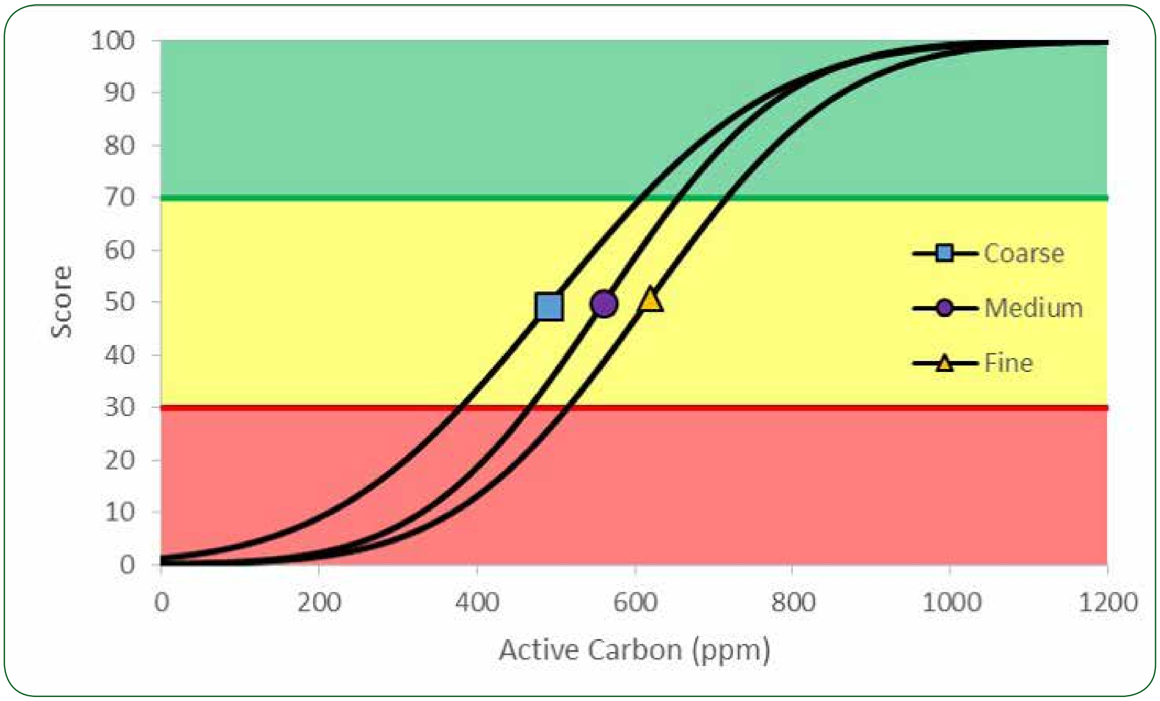
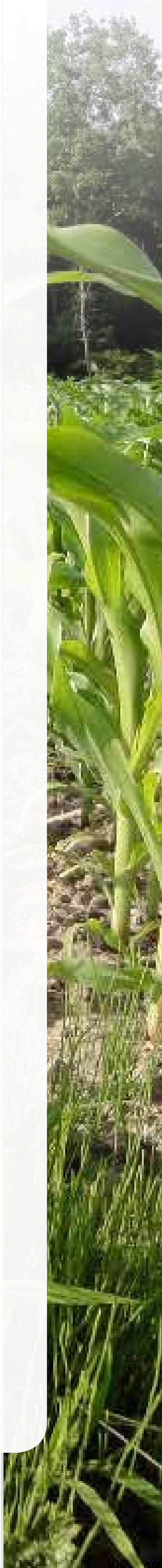
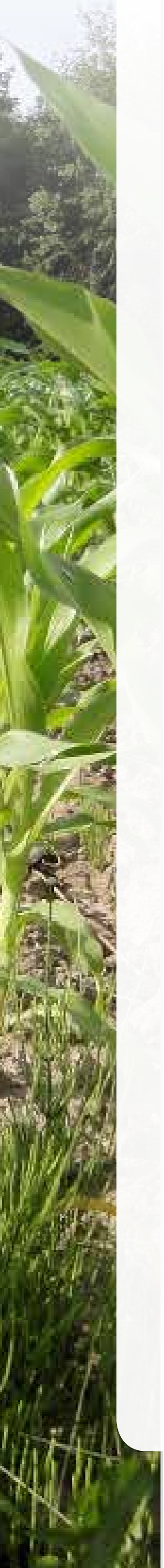


FIGURE 2.37. Scoring function graphs for Active Carbon for three textural categories. In this case more is better. The higher the Active Carbon, the higher the score indicating a trend toward more Organic Matter building up in the soil through biological activity.





Standard Nutrient Analysis

As part of the Cornell Assessment of Soil Health, a traditional soil fertility test analysis package for the Northeastern US is used, that measures pH and extracts plant macro- and micronutrients to estimate plant nutrient availability. Measured levels are interpreted in the framework for sufficiency and excess but are not crop specific. The analysis results for pH, extractable phosphorus and potassium are scored and integrated into the Cornell Assessment of Soil Health Report (see page 71). Selected secondary nutrients and micronutrient analyses are combined into one rating for the report.

Basic Protocols

Plant Available Nutrients:	**Analysis Method:**
Extractable Phosphorus Extractable Potassium Magnesium Iron Manganese Zinc	Nutrients are extracted from soil by shaking with Modified Morgan's solution, which is an ammonium acetate plus acetic acid solution buffered at pH 4.8. After shaking, the extraction slurry is filtered through a paper filter, and the filtrate is analyzed on an inductively coupled plasma emission spectrometer (ICP, Spectro Arcos) for the elements Al, As, B, Ba, Be, Ca, Cd, Co, Cu, Fe, Li, Mg, Na, P, Pb, S, Se, Sr, Ti, V, Zn and Cl. As part of the soil health assessment, P, K, Mg, Fe, Mn, and Zn are scored and included in the report.
pH:	The pH of a suspension of one part water to one part soil is determined by pH electrode probe, using a Lignin pH robot.

How nutrient analysis results relate to soil function

Adequate nutrient availability is of course critical to crop production. Chemical analysis – standard soil nutrient and pH testing – has been foundational for maintaining agricultural productivity. By identifying which nutrients need to be added through amendments, or whether pH needs to be adjusted for improved nutrient availability from the soil, these tests have guided farmers since the 1900s in alleviating constraints in the availability of specific nutrients to their crops, and thus increasing yields. This critical component of soil health assessment is the one that is the most accepted and adopted by land managers to date.

Standard Nutrient Analysis (continued)

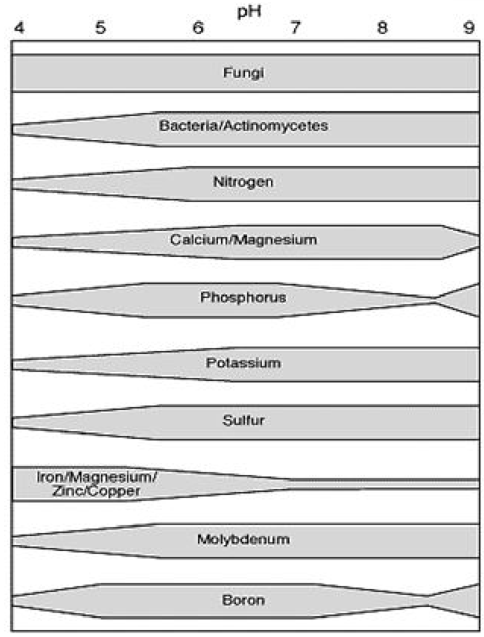


FIGURE 2.38. Relationship between soil pH and plant nutrient availability in soil solution. Modified from Brady and Weil (1999)

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable (Figure 2.38). Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil organic matter (OM) increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. P is an essential plant macronutrient, as it plays a role in photosynthesis, respiration, energy storage and transfer, cell division, cell enlargement, and several other process in plants. Its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants. Excessively high P values indicate a risk of adverse environmental impact. P can be considered a contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

Extractable Potassium is a measure of potassium (K) availability to the crop. K is an essential plant macronutrient as it plays a role in photosynthesis, respiration, energy storage and transfer, regulation of water uptake and loss, protein synthesis, activation of growth related enzymes, and other processes. Plants with higher potassium tend to be more tolerant of frost and cold. Thus, good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased OM, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

Minor Elements, also called secondary nutrients (calcium, magnesium and sulfur) and micronutrients (iron, manganese, zinc, copper, boron, molybdenum, etc.) are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P, and K. If any minor elements are deficient, decreased yield and crop quality may result. Toxicities can also occur when concentrations are too high. The Cornell Assessment of Soil Health's minor elements rating indicates whether four measured nutrients (magnesium, iron, manganese, and zinc) are deficient or excessive (Table 2.03, page 56). Micronutrient availability is strongly influenced by pH and OM. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of others (see Figure 2.38 above). High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

Managing constraints and maintaining optimal nutrient availability

Management of fertilizers and liming amendments has been well researched and communicated by numerous authors worldwide. Much has been written about this topic elsewhere, so that we will only briefly summarize some important concepts.

Nutrient balances:

Once adequate nutrient levels are present in the soil, nutrients still have to continue to be imported to a farm and added to the soil. The amounts added must be adequate to replace nutrients that leave the farm in products that are harvested and sold, or that leave through environmental losses, or else these nutrients are essentially mined by plant uptake until they become deficient. Maintaining optimal pH through lime or wood ash applications, and adding organic matter, will help immobilize aluminum and heavy metals, and contribute to maintaining proper nutrient availability.

Soil Health: biological and physical influences on nutrient availability:

Nitrogen is the only nutrient that can be biologically "produced" on farm. Legumes and their symbiotically associated rhizobia can fix unavailable, but plentiful N_2 from the air, transforming it to plant available forms. Nitrogen is also the most dynamic of the nutrients – which is to say its availability in soil changes rapidly as influenced by weather, physical soil condition, microbial activity, and the availability of organic materials. This is why it is not extracted in this analysis– its availability can differ by the time test results are returned. While in season N tests are in use, using models along with soil tests (e.g. Adapt-N, http://adapt-n.cals.cornell.edu) to estimate the impact of weather on fertilizer needs is likely the future of nitrogen management.

Cover crops planted between rows of corn.

Other nutrients can only come from soil minerals, organic matter, and external sources of fertility, although biota can help in making these more available to plants. Availability of nutrients present in the root zone is very much influenced by soil microbes and plant roots. For example, some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. The influence of such biological and physical processes is generally not taken into account by standard extractants such as the one used here. There is active research ongoing to adjust fertility recommendations by using additional physical and biological information, such as indicators of microbial species presence and activity.

Scoring functions

Scoring function graphs are shown below for pH, extractable phosphorus (P) and potassium (K) on coarse, medium, and fine textured soils (Figure 2.39). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71).

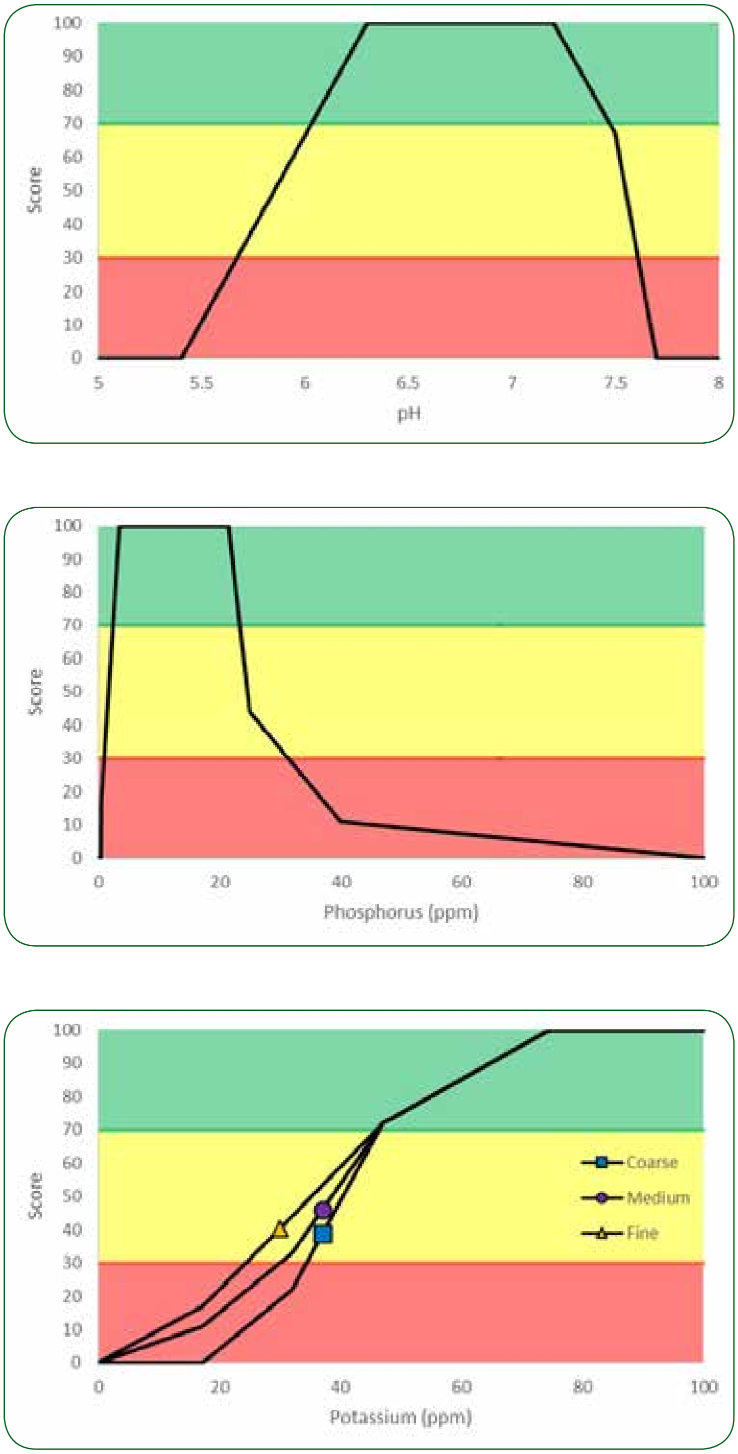


FIGURE 2.39. Scoring function graphs for pH, micro and macro nutrients for three textural categories. If all nutrients are adequate then a score of 100 (good) is given on the report. If one nutrient is deficient or excessive a score of 56 (moderate) is given. If two or more nutrients are deficient or excessive a score of 11 (poor) is given.

TABLE 2.03. The optimal ranges for secondary nutrients and micronutrients.

Nutrient	PPM
Magnesium	> 33
Iron	< 25
Manganese	< 50
Zinc	> 0.25

Add-on Test: Potentially Mineralizable Nitrogen

Potentially mineralizable nitrogen (PMN) is an indicator of the capacity of the soil microbial community to convert (mineralize) nitrogen tied up in complex organic residues into the plant available form of ammonium. Soil samples are anaerobically incubated for 7 days, and the amount of ammonium produced in that period is measured as an indicator of nitrogen mineralization. This indicator has been replaced with soil protein and respiration measurements in the soil health assessment package, as those two separately indicate the activity of the microbial community in aerobic conditions, and the availability of N containing organic residues. PMN is now available as an add-on test.

Basic Protocol

- As soon as possible after sampling, the fresh soil sample (stored at 40°F) is sieved.
- Two 8g soil samples are placed into 50 ml centrifuge tubes.
- 40 ml of 2.0 M potassium chloride (KCl) solution is added to one of the tubes, which is shaken on a mechanical shaker for 1 hour, and filtered
- 20 ml of the filtrate is collected from this tube and analyzed for ammonium concentration, as a measure of pre-incubation ammonium.
- 10 ml of distilled water is added to the second tube, which is hand shaken, capped with a nitrogen gas (N_2) atmosphere, and incubated for 7 days at 30°C (86°F).
- After the 7 day anaerobic incubation, 30 ml of 2.67 M KCl is added to the second tube (creating a 2.0 M solution). The tube is shaken, filtered, and the filtrate is collected and analyzed for ammonium concentration (Figure 2.40).
- The difference between the pre-incubation and post-incubation measurements is used as an indicator of N mineralization.

How PMN relates to soil function

Nitrogen is the most limiting nutrient for plant growth and yield in most agricultural situations (Figure 2.41). Almost all of the nitrogen stored in crop residues, soil organic matter, manures and composts, is in the form of complex organic molecules (e.g., proteins) that are not available to plants (i.e., cannot be taken up by plant roots). We rely on several microbial species to convert this organic nitrogen into the ammonium and nitrate forms that plant roots can utilize (Part I, Figure 1.10). The PMN test provides us with one indication of the capacity of the soil biota to recycle organic nitrogen that is present into plant available forms.

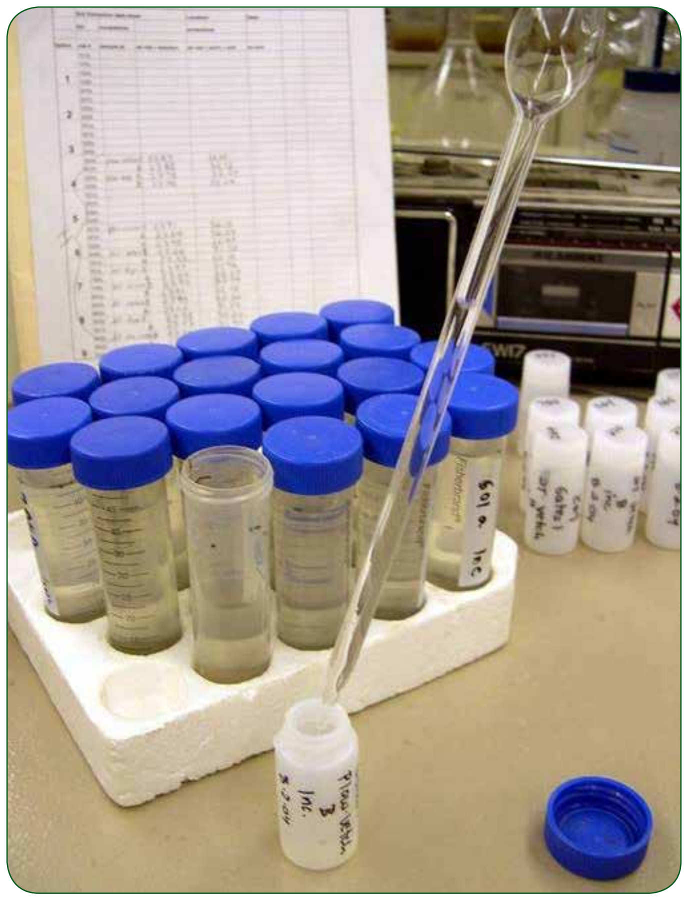


FIGURE 2.40. Potentially Mineralizable Nitrogen (PMN) processed in the lab.The difference between pre-incubation and post-incubation measurements is used as an indicator of N mineralization.

Managing constraints and maintaining optimal nitrogen mineralization

Soils with high levels of nitrogen-rich organic matter (e.g., soils where legumes are in rotation or that frequently receive animal manure) tend to have the highest populations of microbes involved in nitrogen mineralization and the highest PMN rates. Follow management suggestions provided for improving soil protein and respiration constraints to manage for optimal nitrogen mineralization.

FIGURE 2.41. Nitrogen is the most limiting nutrient in crop production. The center two rows of sweet corn are severely nitrogen deficient.

Scoring function

Below is the scoring function graph for potentially mineralizable nitrogen in coarse, medium, and fine textured soils (Figure 2.42). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71). It should be noted that while none of the scoring functions currently are calibrated to decline with very high nitrogen mineralization potential, extremely high N mineralization could increase losses of N to the environment, and thus impact air and water quality.

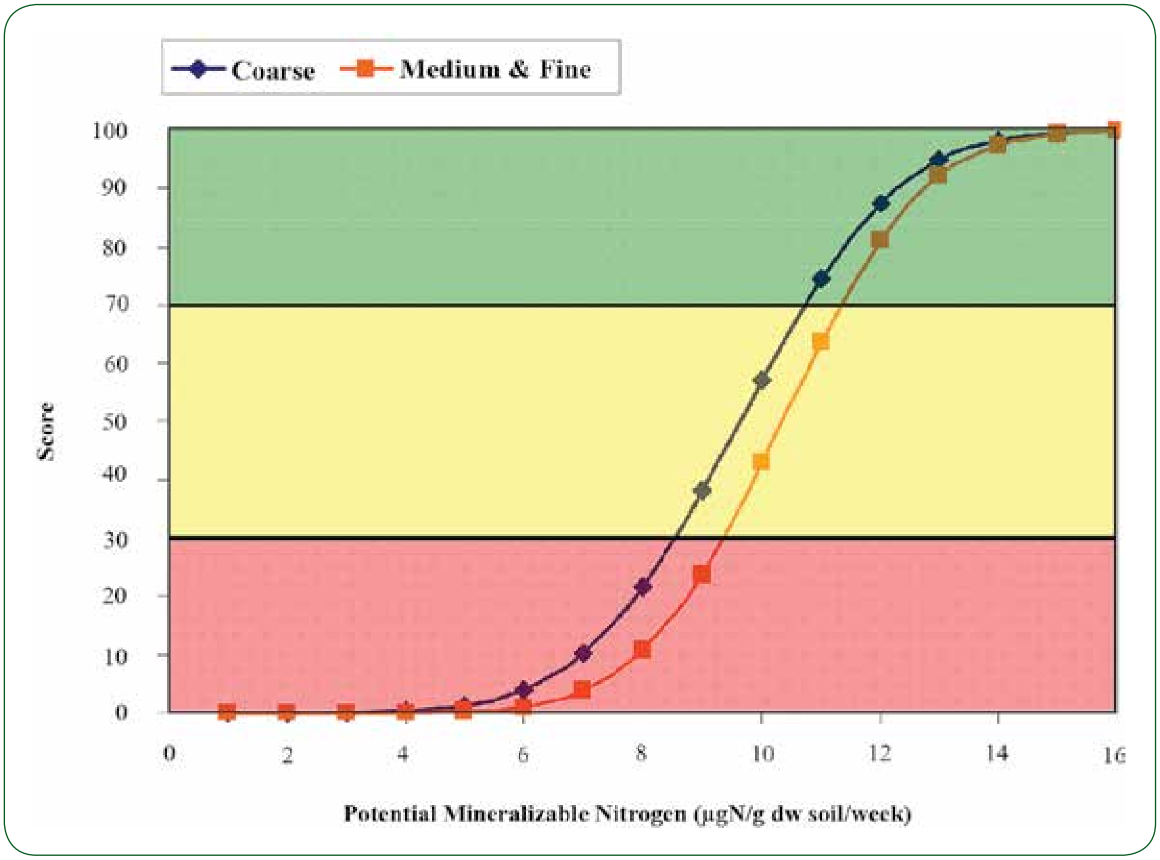


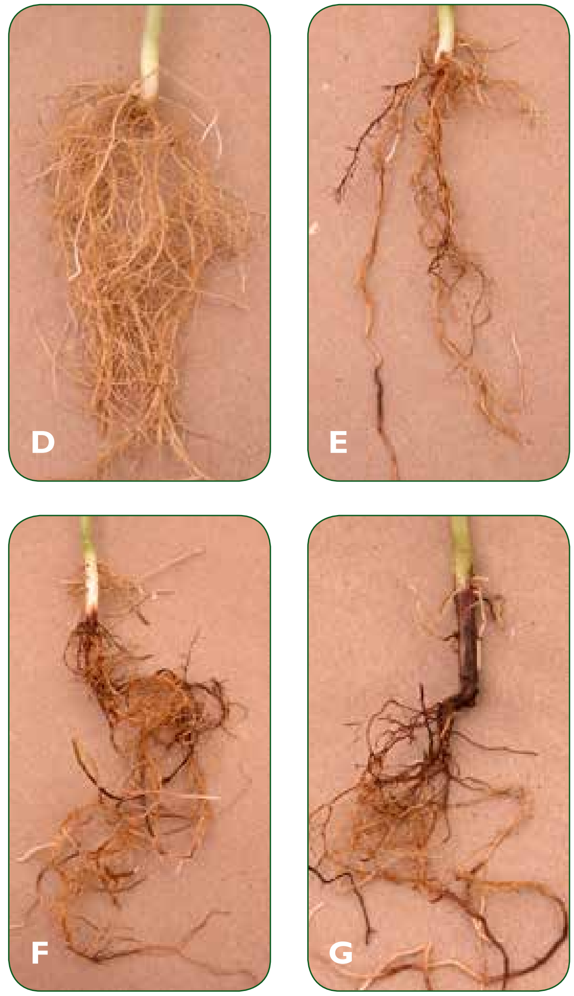
FIGURE 2.42. Scoring function graph for Potentially Mineralizable Nitrogen (PMN) for three textural categories. In this case the higher score signifies potentially higher levels of N rich organic matter, indicating higher levels of microbial populatioin involved in N mineralization.

Add-on Test: Root Pathogen Pressure

Root pathogen pressure is a measure of the degree to which sensitive test-plant roots show symptoms of disease when grown for a set time in controlled conditions in assayed soil. It is assessed qualitatively, after roots are washed, by visual inspection for root size, color, texture and the absence or presence of symptoms of damage by root pathogens. These include the fungi *Fusarium*, *Rhizoctonia*, and *Thielaviopsis*, the oomycete *Pythium*. The apparent pathogen pressure is given a rating from 2 to 9, with higher numbers indicating greater pathogen-induced damage.

Basic Protocol:

- Approximately 200 ml of fresh soil is placed in each of 4 cone-tubes which have cotton balls placed in the bottom to prevent soil loss through the drainage holes (Figure 2.43 A).
- Each tube is planted with one green bean seed. Commercially available, treated seeds are used to more closely represent on-farm conditions (B).
- The hilum (curved) side of the seed is placed flat, horizontally, to encourage successful seed germination and emergence (straight vertical shoots).
- The plants are maintained in a greenhouse under supplemental light and watered regularly for 4 weeks (C).
- The plants are removed from their containers and the roots washed and rated as described in the examples shown to the right:



Rating System:

2 = White and coarse textured hypocotyl and roots; healthy (D);

3 = Light discoloration, with lesions covering up to a maximum of 10% of hypocotyl and root tissues (E);

5 = Moderate damage, with lesions covering approximately 25% of hypocotyl and root tissue, with tissues remaining firm (F);

7 to 9 = Advanced damage and decay, with 50 to 75% (or more for higher ratings) of hypocotyl and roots showing lesions and severe symptoms of pathogen damage (G).

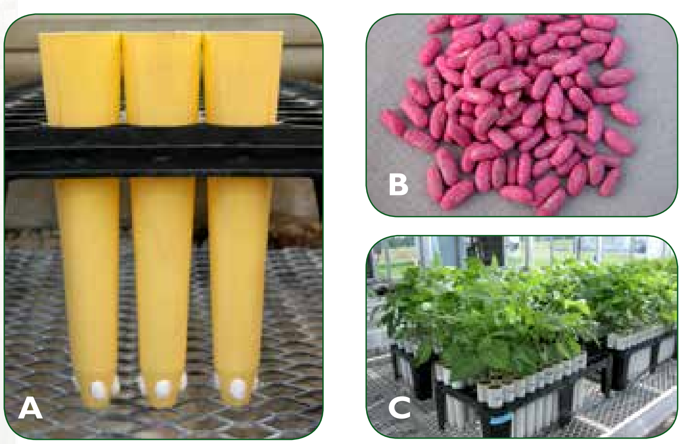


FIGURE 2.43 A-G. Test and rating system for Root Pathogen Pressure.

How root pathogen pressure relates to soil function:

Pathogen pressure refers to the degree to which plants encounter potentially growth-limiting attack by disease causing organisms. This is a function of:

- the presence of pathogens
- the compatibility between pathogens and the plants that are growing
- environmental conditions including which other microbial communities are present at the time, weather, and soil physical and chemical characteristics, particularly those that can stress plants or make them more susceptible to pathogen attack, such as poor drainage, high compaction, or nutrient deficiencies (Figure 2.44).

Healthy roots are essential for vigorous plant growth and high yield as they can efficiently obtain nutrients and water from soil. Root pathogenesis negatively impacts plant growth and root effectiveness, as well as more beneficial root associated microbiota in their contribution toward proper functioning of other important soil processes (Part I, page 16).

While one-size-fits-all pathogen pressure assays for lab testing of soils are difficult to devise, several relevant options for certain crops and pathogens are available. For vegetable production systems, a soil bioassay with beans was shown to be highly effective in assessing root pathogen pressure as a component of overall soil health. Beans are susceptible to the major pathogens that impact vegetable, legume, and forage crops grown in the Northeast region, which makes them suitable as an indicator plant. The selection of other indicator plants might be needed for the proper assessment of root pathogen pressure of soils in different production systems.

High pathogen pressure identified by the assay indicates that disease-causing organisms are present, and that the other members of the microbial community are not suppressive of them. Lower pressure indicates either that few pathogens are present, or that the rest of the microbial community is able to prevent them from successfully colonizing the roots.

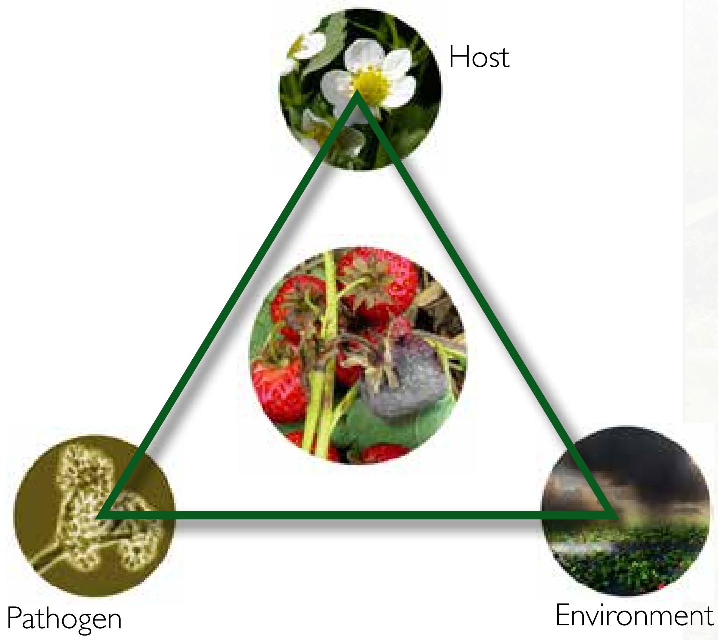


FIGURE 2.44. Disease Triangle, illustrating the interaction between susceptible host, compatible pathogen, and conducive environmental conditions necessary for the development of plant disease. For example: strawberry plants in the presence of the strawberry pathogen *Botrytis cineria*, in wet environmental conditions, will likely become infected with Botrytis grey mold.

Managing constraints and maintaining low pathogen pressure

To manage root pathogen pressure constraints in the field, make sure to evaluate rotations and cover crops for their ability to suppress pathogens, and especially avoid consecutively planting hosts of the same pathogen. Some cover crops (e.g. sorghum-sudangrass, mustards) can be used to effectively biofumigate against certain pests and pathogens. Plants differ in their efficacy as hosts for various pests. Some produce compounds that inhibit or suppress pathogens, or may stimulate microbial communities that are antagonistic or parasitic to crop pathogens.

Organic matter inputs from rotational and cover crops, green manures, and composts have a major impact (both positive, and negative if poorly chosen) on populations of soilborne microbial pathogens, plant parasitic nematodes, and other pests. Plant residues remaining from previous crops that have been diseased can harbor pathogens and serve as a source of inoculum in following seasons, allowing disease to spread. This makes rotation all the more important. It is also important to alleviate physical and chemical plant stressors that make crops more susceptible to pathogen attack, such as poor drainage, high compaction, poor irrigation practices, or nutrient deficiencies (Part III).

Soil health management keys to preventing pathogen pressure:

- keep note of seed, seedling, and mature plant health and disease throughout growing season
- improve sanitation of tools and equipment
- carefully manage diseased plant residues
- rotate with non-compatible or resistant crops and cover crops
- limit environmental conditions that are conducive to disease spread
- foster beneficial and disease suppressive microbial communities

Scoring function:

Below is the scoring function graph for root health assessment which is the same for sand, silt and clay textured soils (Figure 2.45). The red, yellow and green shading reflects the color coding used for the ratings on the soil health report (see page 71).

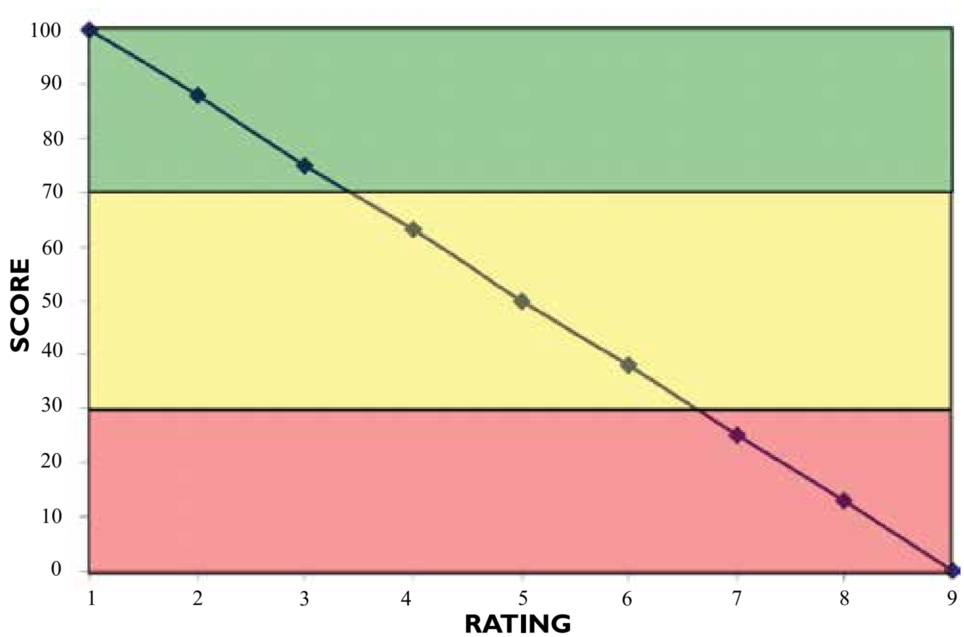


FIGURE 2.45. Scoring function graph for the Root Heallth Assessment. The score is the same regardless of soil texture. A low rating indicates there is little pathogen pressure in the field.

Add-on Test: Heavy Metal Contamination[3]

Heavy metal testing (also sometimes called total elemental analysis) is available for situations where contamination is suspected, or as a precaution. Heavy metal content to measure levels of metals of possible concern to human or plant health (e.g. arsenic, barium, cadmium, chromium, copper, lead, nickel, zinc) as well as other elements are measured. Testing soils for heavy metals can help identify whether contamination from past human activities (such as high traffic, industrial or commercial activity, spills, or pesticide application) is affecting the site.

It is important to understand that levels of metals can vary greatly across a site, and sometimes at a very small scale, so additional samples may be needed. More information is available from the Cornell Waste Management Institute's "Guide to Soil Testing and Interpreting Results" (available at http://cwmi.css.cornell.edu/guidetosoil.pdf).

Basic Protocol *(Total Soil Digestion)*

- A dried soil sample is digested in concentrated acid at high temperature.
- After cooling, samples are generally diluted with deionized water.
- Particulates in the digestate are removed by filtration, centrifugation, or by allowing the sample to settle.
- The sample is analyzed by inductively coupled plasma (ICP) or flame atomic absorption (AA) instruments.

Method details differ among different labs: Different acids, temperatures, and heating mechanisms are used, and improvements to methods are still being made. Nitric acid, perchloric acid, or a combination of the two are common. Heating methods include microwave digestion, hot plate digestion, and automated instruments. Depending on the method, additional acid or other reagents may be added. Some basic procedures are generally followed by the Cornell Nutrient Analysis Laboratory (http://cnal.cals.cornell.edu) and others according to standard EPA protocols.

In some situations less expensive screening tests (e.g., for lead) may be appropriate. Some laboratories (including the Cornell Nutrient Analysis Laboratory) offer total elemental analysis with lead screening. Screening procedures may involve methods similar to the protocol described above, or may use technology such as x-ray fluorescence instruments. For current and complete Standard Operating Procedures, please contact the Soil Health Lab (soilhealth@cornell.edu). The information below about interpreting results generally applies to both screening tests and total elemental analysis.

How Heavy Metals Relate to Soil Function

Soil characteristics can affect the transport and fate of heavy metals, and whether they can be readily taken up by plants or animals. Most heavy metals (e.g., barium, chromium[+3], copper, lead) are adsorbed strongly to clays and organic matter, which limits the potential for plants to take these up when soil pH is not in the acid range. A few - notably cadmium, nickel and zinc - may remain soluble enough at near-neutral pH to be excessively taken up by plants from contaminated soils. For most heavy metals, uptake (via plant roots) into food crops may be higher if soil is acidic (pH < 5-6), high in salts, or low in organic matter (Figure 2.46, following page). Arsenic adsorbs poorly on organic matter, but well on clays and iron oxides, and is more available to plants in non-acid (pH > 6) than acid soils.

Additionally, heavy metals (e.g., copper, nickel, zinc) at elevated concentrations in soil may suppress natural microbial processes. For example, soil copper at high levels inhibits organic matter decomposition (Figure 2.47).

Interpreting Heavy Metals Results[4]

Laboratories report the concentrations of individual heavy metals or other elements measured in a soil sample (usually in mg/kg or ppm, which are equivalent). Test results can inform decisions about how to manage a site, farm, or garden, and other activities, to promote healthy soils, high quality crops, and efforts to protect human health by reducing exposure to contaminants for healthier communities.

Yet, understanding heavy metals results is not always an easy task. There is no single standard for acceptable concentrations in the soils of farms, gardens, or residential yards. Some guidance can be found by comparing soil test results to soil background levels or state guidance values, where these are available.

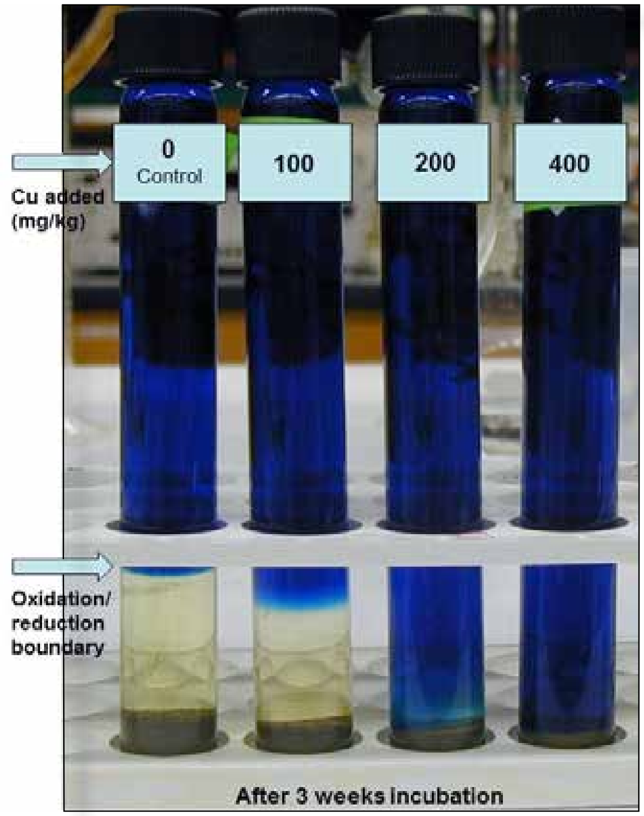


FIGURE 2.47. Simple colorimetric test for microbial inhibition in copper (Cu)-contaminated soils. Indigo carmine was used as redox indicator to measure O_2 consumption (indicating healthy microbial activity) in Arkport soils spiked with $CuSO_4$ 10 years earlier. *Source: M. McBride*

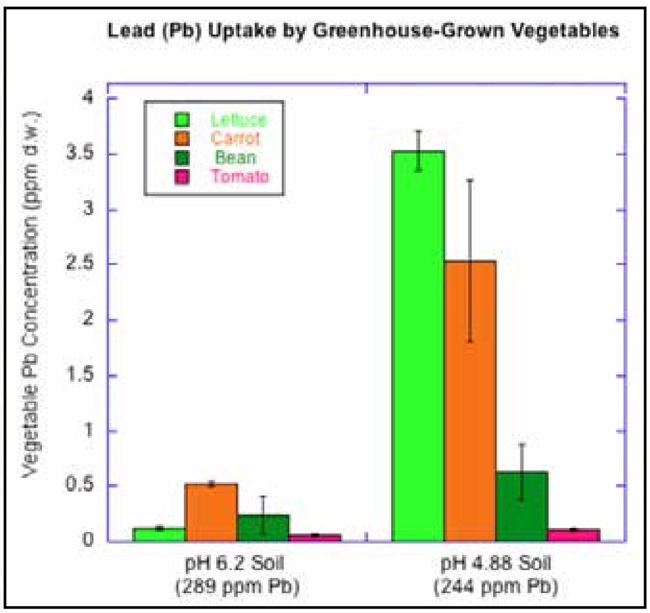


FIGURE 2.46. Lead uptake by vegetables is greater in low pH soil, and differs by crop type. *Source: Healthy Soils, Healthy Communities Project*

In New York State (NYS), soil test results can be compared to the Department of Environmental Conservation (DEC) Soil Cleanup Objectives (NYSDEC SCOs, 2006, Table 2.04). These values are developed by the NYSDEC and the NYS Department of Health for the NYS environmental remediation programs, but can be used outside of these programs as guidance levels to help interpret levels of chemicals in soil when considering human health and the environment. The guidance values for residential scenarios are typically the most appropriate reference point for farmers, gardeners, homeowners, and other citizens.

[3] Content adapted from resources developed by the Cornell Waste Management Institute (http://cwmi.css.cornell.edu/soilquality.htm) and the Healthy Soils, Healthy Communities Project (http://cwmi.css.cornell.edu/healthysoils.htm).

[4] Section on interpreting heavy metals results adapted from Healthy Soils, Healthy Communities Project resource: "Metals in Urban Garden Soils" (available at http://cwmi.css.cornell.edu/Metals_Urban_Garden_Soils.pdf).

[5] Section on addressing heavy metals concerns adapted from Healthy Soils, Healthy Communities Project resources: "Metals in Urban Garden Soils" (available at http://cwmi.css.cornell.edu/Metals_Urban_Garden_Soils.pdf) and "What Gardeners Can Do: 10 Best Practices for Healthy Gardening" (available at http://cwmi.css.cornell.edu/WhatGardenersCanDoEnglish.pdf).

Interpreting Heavy Metals (continued)

It is not uncommon to find heavy metals in soil at levels near or above guidance values. Health risks associated with metals in soils at levels slightly or moderately above guidance values cannot be ruled out, but are likely to be low. High levels of exposure can be associated with health effects, and the higher the levels are, the greater the concern.

Some heavy metals can be toxic to plants (phytotoxic) at levels below human health-based guidance values (Harrison et al. 1999). For example, copper can cause toxicity and stunted growth in some crops at concentrations above 75-100 ppm in soil. This is more likely to be a concern if pH is low. Nickel can cause toxicity and stunted growth in some crops at concentrations above 40-60 ppm (Figure 2.48). Zinc levels above 150 ppm may cause toxicity and stunted growth in some crops. However, at near-neutral pH (6.5 - 7.5), zinc is insoluble enough that toxicity to plants would require zinc levels above 200 ppm.

Other heavy metals may be taken up by plants and not harm the health or growth of the plant, even though they may be a concern for human health.

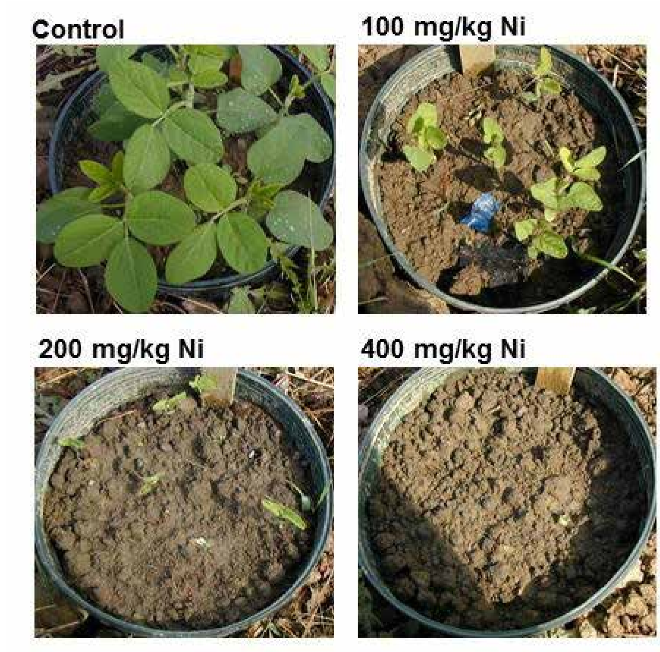


FIGURE 2.48. Increasing levels of nickel (Ni) contamination impede plant growth. *Source: M. McBride*

TABLE 2.04. Guidance values and background levels of metals commonly found in garden soils*. See Healthy Soils, Healthy Communities resource *Metals in Urban Garden Soils* for more information.

Metal	Level in soil (parts per million [ppm])		
	Guidance Value Protective of Public Health	NYS Rural Background Level	NYC Urban Background Level
Arsenic	16	< 0.2 - 12	4.1 - 26
Barium	350	4 - 170	46 - 200
Cadmium	2.5	< 0.05 - 2.4	0.27 - 1.0
Chromium	36	1 - 20	15 - 53
Copper**	270	2 - 32	23 - 110
Lead	400	3 - 72	48 - 690
Mercury	0.81	0.01 – 0.20	0.14 – 1.9
Nickel**	140	0 - 25	10 - 43
Zinc**	2200	10 - 140	64 - 380
* See NYSDEC 2006, NYSDEC and NYSDOH 2005, Retec Group, Inc. 2007			
** Can be toxic to plants below health-based guidance values			

Managing Heavy Metals in Soil[5]

When developing a site management plan for a contaminated site, it is important to balance the many known benefits of farming, gardening, outdoor recreation, and consuming fresh fruits and vegetables with possible risks from exposure to soil contaminants.

The type of crops being consumed also have varying levels of contaminants, depending on what part of the plant is being consumed (Table 2.05).

Soil amendments are an important technique for mitigating heavy metals in soils. For example, organic matter (composts, peat) forms strong complexes with heavy metals such as lead and cadmium, and limits availability to plant roots. Lime additions raise soil pH, reducing solubility and plant availability of most metals. Phosphate has been shown to reduce lead solubility under some circumstances, though it is generally not effective or practical for non-acid soils where lead solubility is already low.

In addition, the following strategies will help reduce risks:

- If needed, add clean soil or organic matter; adjust soil pH; promote good drainage (Figure 2.50 A).
- Wash hands / wear gloves when working with soil.
- Keep soil from coming indoors on shoes, pets, or clothing.
- Keep an eye on children.
- Avoid or contain contaminated areas: use raised beds where appropriate for growing edible crops (B); mulch, plant ground cover, or otherwise cover areas of bare soil to reduce dust.
- Wash produce well to remove soil particles from plant surfaces, and peel root crops (C).
- If contamination is a concern, consider planting food crops that are least likely to have contaminants on or in them (like fruits) or grow ornamental plants.
- Avoid or limit activities that can increase soil contamination, such as the use of certain fertilizers and treated wood.

TABLE 2.05. Crop type and contaminant considerations for managing heavy metals in soils.

Crop Type	Considerations
Root 	More likely to have higher levels of contaminants because edible portion grows directly in soil
Leafy Greens and Herbs 	More likely to have higher levels of contaminants because of dust/soil splash
Fruit 	Plant barriers help prevent contamination; surface contamination can be washed off of most fruits more easily

Using plants to remove heavy metals from soil (a type of phytoremediation) is generally not effective for reducing metals levels in farm or garden soils. Many metals are not readily taken up into plant tissue when soil pH is near neutral (6.5 – 7.5). For those metals that are more easily taken up by plants (such as cadmium, copper, nickel, and zinc), the plants that take them up most readily are also relatively small in stature and slow growing, and they will take many years to “clean up” soils with metals levels even moderately above guidance values. Also, unlike some other contaminants, metals are chemical elements and therefore are not broken down into less toxic compounds by phytoremediation. Metals that are removed from the soil are relocated into the roots or other parts of the plants, which means the plants must be disposed of properly, and not eaten or composted.

Amending soil with compost.

Gardening in a raised bed with clean soil and landscape fabric barrier.

Washing garden-grown vegetables.

FIGURE 2.50 A-C. Strageties to help reduce risk of heavy metal contamination in urban soils.

Add-on Test: Salinity and Sodicity

Soils become saline when the concentration of soluble salts (mostly made up of compounds of Mg^{+2}, Ca^{+2}, Na^{+}, K^{+}, Cl^{-}, SO_4^{-2}, HCO_3^{-} and CO_3^{-2}) in the soil profile becomes excessive. **Salinity** can be measured by electrical conductivity, and this is offered as the 'soluble salts add-on' with a Cornell Soil Health Assessment. **Sodic** soils are those with excessive sodium ion concentrations, relative to magnesium and calcium, measured by the sodium adsorption ratio. Salinity and sodicity are quite different from each other. These conditions may occur together or separately.

Basic Protocol

Electrical Conductivity (EC) - to measure salinity

Soluble salts are extracted from the soil with water, in a 1:1 soil:water suspension by volume, and the electrical conductivity of the supernatant is determined as follows:

- 20ml of distilled deionized water are added to 20 ml of dried ground soil and stirred;
- Suspension is settled for one hour;
- Electrical conductivity of the supernatant is measured with a calibrated conductivity meter (Figure 2.51).

FIGURE 2.51. Electrical conductivity (EC) meter used to measure salinity.

Sodium Adsorption Ratio (SAR) - to measure sodicity

- Sodium, calcium, and magnesium concentrations of the supernatant above can additionally be determined using inductively coupled plasma (ICP) spectrometry
- Sodium Adsorption Ratio (SAR) is calculated using the equation where concentrations of sodium (Na^{+}), calcium (Ca^{2+}) and magnesium (Mg^{2+}) are in meq/L:

$$\text{S.A.R.} = \frac{Na^{+}}{\sqrt{\frac{1}{2}(Ca^{2+} + Mg^{2+})}}$$

How salinity and sodicity relates to soil function

Problems with salts (salinity) and sodium (sodicity) may occur naturally, but are especially prevalent under irrigated agriculture in semi-arid and arid areas, where water from rainfall would not otherwise be adequate for crop production. This situation is prevalent in western regions of the United States. It is also prevalent in high tunnels and greenhouses used for season extension in the Northeast – these are effectively irrigated deserts when they are covered year-round. Localized saline-sodic soils may also occur in coastal regions when soils are affected by sea water, or in urban areas in cold climates where salt de-icing materials are used. Salinity and Sodicity have severe impact on growing crops through very different mechanisms.

High salinity decreases the osmotic potential of the soil water relative to plant water. This means that the crops must exert more energy to get water from a saline soil, which holds the water more tightly. Therefore soils with high salinity could have sufficient water but growing crops will lack acess to it and may wilt and die (Figure 2.52 A and B). In addition, high concentrations of some elements that make up the salts in the soil such as sodium and chloride can become toxic for some plants, affecting their metabolism and consequently reducing their growth.

High sodium concentrations break down soil structure, as sodium replaces calcium and magnesium on mineral surfaces. This prevents fine particles from sticking to each other, so that aggregates are dispersed into single grains. A sodium-affected soil becomes crusted and severely compacted, so that water cannot properly infiltrate or drain, and water storage is diminished as well (C) (page 43). This has a major impact on soil physical functioning, so that crops will not be able to grow properly. Sodic soils also have high pH, negatively affecting the availability of certain nutrients like phosphorus.

Salt affected corn.
Photo credit: University of Delaware

Cotton grown in saline-sodic soil (Turkey).

Crusting in a saline-sodic urban soil.

FIGURE 2.52 A-C. Management challenges in saline and sodic soils.

Scoring functions:

Tables 2.06 A and B below shows threshold criteria for interpreting salinity measured by the 1:1 volumetric extraction of soluble salts (A). These thresholds are general interpretations that are not crop specific (B). The effect of soil salinity is often judged by the extent to which crops respond to different levels of salinity. Some crops are very sensitive while some others are more tolerant. Vegetables sensitive to salinity include radish, celery, and green beans, while those with high salt tolerance include kale, asparagus and spinach. Crop response is also influenced by texture.

TABLE 2.06A. Interpretation of 1:1 soluble salts test (Dahnke and Whitney, 1988)

		EC (mmhos cm^{-1}) by Soil Texture			
Degree of Salinity	Crop response	Coarse sand to loamy sand	Loamy fine sand to loam	Silt loam to clay loam	Silty clay loam to clay
Non-saline	Almost negligible effects	0 - 1.1	0 - 1.2	0 - 1.3	0 - 1.4
Slightly Saline	Yield of the most sensitive crops reduced	1.2 - 2.4	1.3 - 2.4	1.4 - 2.5	1.5 - 2.8
Moderately Saline	Yield of most crops reduced	2.5 - 4.4	2.5 - 4.7	2.6 - 5.0	2.9 - 5.7
Strongly Saline	Only tolerant crops yield well	4.5 - 8.9	4.8 - 9.4	5.1 - 10.1	5.8 - 11.4
Very Strongly Saline	Only very tolerant crops yield well	> 9.0	> 9.5	> 10.1	> 11.5

TABLE 2.06B below shows general threshold criteria defined to classify a soil as saline, sodic, or saline-sodic. It is important to note that the pH of the soil is also important in defining these conditions.

ECe = Electrical Conductivity of a saturated soil extract
SAR = Sodium Asorbtion Ratio

	ECe	pH	SAR
Saline	> 4 mmho/cm	< 8.5	< 13
Sodic	< 4 mmho/cm	> 8.5	> 13
Saline-Sodic	> 4 mmho/cm	> 8.5	> 13

Managing salinity and sodicity concerns

Salinity and sodicity problems have multiple causes and may be difficult to address. In general, salts can be leached out of the soil with the application of excess water through natural rainfall or irrigation. But this is often problematic in regions where shallow groundwater is a primary source of the salts, which in turn is often the results of excessive irrigation. Such areas may therefore require installation of subsurface drainage to remove the excess groundwater before salts can be leached.

Sodicity is often addressed through the application of gypsum, where calcium substitutes for the sodium on the soil exchange complex, thereby improving soil aggregation and reducing pH. It is then important to leach the sodium out of the surface soil to prevent the reoccurrence of sodicity.

Soil Health Assessment Report

The raw data from the individual indicators and background information about sample location and management history from the sample submission form (page 34) are synthesized in an auto-generated and grower-friendly report (Appendix A). The soil health assessment report presents measured values, interpretive ratings, and constraints identified by soil health indicators in a summary page, followed by a short narrative description of each indicator's importance and status, and selection tables with suggestions for targeted management.

The soil health assessment report summary is laid out in a visually enhanced format to present information to growers and agricultural service providers (Figure 2.53, following page). The sections of the summary page include:

1) **Background information:** includes the farm and agricultural service provider's name and contact information, provided sample name or field identification, sample lab ID, date of sampling, current and prior crop and tillage, provided soil type and both provided and measured soil texture information.
2) **Measured indicators:** provides a list of physical, biological, and chemical indicators that were measured for soil health assessment. Note that values measured for add-on indicators are provided separately.
3) **Indicator values:** presents the values of the indicators that were measured in the laboratory or field, in the units of measure as provided in the indicator descriptions that follow the report's cover page (see Appendix A for a complete sample report).
4) **Ratings:** interprets that measured value using the provided texture-adjusted scoring functions (pages 27-29) on a scale of 0 to 100, where higher scores are better. Ratings are color coded. Those in red (30 or less) are particularly important to take note of as they may indicate a constraint to proper soil functioning. Any in yellow (between 30 and 70), particularly those that are close to a rating of 30, are also important in addressing current or potentially developing soil health problems. Green (70 or higher) indicates high scores, which suggest optimal or near optimal functioning.
5) **Constraints:** If the rating of a particular indicator is poor (red color code), associated soil health constraints will be highlighted in this section. This is useful for identifying priorities for targeting management efforts. Suggested management practices to address the identified constraints can be found in Part III of this manual, and are briefly summarized in tabular form at the end of the assessment report.
6) **Overall quality score:** computed by averaging the individual indicator ratings to provide an indication of the soil's overall health status. However, it is of greater importance to identify which particular soil processes are constrained in functioning or suboptimal, so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information. The overall quality score is further rated as follows: less than 40 is regarded as very low, 40-55 is low, 55-70 is medium, 70-85 is high and greater than 85 is regarded as very high. The highest possible quality score is 100 and the lowest possible is 0, thus it is a relative overall soil health status indicator.

Poor aggregation can result in poor water infiltration and storage.

Cornell Soil Health Assessment

(1)

Corey Corn
123 Horizon Rd
New Iowa, NY, 13026

Agricultural Service Provider:
Doe, John
Assessments Inc.
john@doe.com

Sample ID:	S_1
Field/Treatment:	West Upper
Tillage:	7-9 inches
Crops Crown:	COG, COG, COG
Date Sampled:	5/1/2015
Given Soil Type:	Lima
Given Soil Texture:	Silt Loam
Coordinates:	42.44790 °N; 76.47570 °W

Measured Soil Textural Class: Silt Loam **Sand: 37%** **Silt: 53%** **Clay: 10%**

Test Results

	(2) Indicator	(3) Value	Rating (4)	Constraint (5)
Physical	Available Water Capacity	0.15	42	
Physical	Surface Hardness	87	84	
Physical	Subsurface Hardness	290	50	
Physical	Aggregate Stability	22.0	22	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
Biological	Organic Matter	2.9	32	
Biological	ACE Soil Protein Index	4.5	26	Organic Matter Quality, Organic N Storage, N Mineralization
Biological	Respiration	0.39	23	Soil Microbial Abundance and Activity
Biological	Active Carbon	450	27	Energy Source for Soil Biota
Chemical	pH	6.9	100	
Chemical	Phosphorus	4.5	100	
Chemical	Potassium	67.8	93	
Chemical	Minor Elements Mg: 419 Fe: 1.1 Mn: 12.9 Zn: 1.9		100	
(6)	**Overall Quality Score**		58	Medium

FIGURE 2.53. Sample Soil Health Assessment Report with (1) Background info, (2) Measured indicator, (3) Indicator value, (4) Rating, (5) Constraints, and (6) Overall quality score.

Using the Assessment of Soil Health Information

The Cornell Assessment of Soil Health focuses on identifying priorities and opportunities for improved soil management. The color coded results and constraints listed on the summary page help the user get an overview of the field's soil health status.

Identified constraints in soil process functioning are highlighted in red, and the associated soil processes represented by these constrained indicators are listed. While an overall soil quality score is provided at the bottom of the report summary page to integrate the suite of indicators, it is important to note that the most important information is which indicators are suboptimal, because it is this information that informs management decisions. As an entry point in our understanding of soil health, any measured soil constraint can be taken as a management target.

Spade and buckets used to collect soil health samples.

The soil health report is part of an overall Soil Health Management Planning Projcess and can be used to:

- Understand soil processes and past management impacts
- Identify constraints, assess soil health status
- Select and implement managment strategies that address needs and are feasible for the operation
- Monitor change
- Measure progress and adjust management

It is important to recognize that the information presented in the report is not intended as a measure of a grower’s management skills, but as a tool to understand soil processes and past management impacts to inform management decisions towards addressing specific soil constraints that have not been previously measured as part of standard soil testing.

When multiple constraints are considered together, management strategies can be developed that select particular practices to address needs that are feasible for the operation and can restore functionality to the soil. These strategies become part of the Soil Health Management Plan discussed in Part III.

Using Soil Health Assessments in Soil Health Management Planning

Considerations in interpreting soil health assessments

First some general guidance to consider when embarking on evaluating the information gained from soil health assessments, and using it to decide on management solutions:

The report is a management guide, not a prescription: Nutrient management has largely been prescription-based (for example, a soil test report is returned with a recommendations to 'add 80 pounds of potassium per acre to increase plant available potassium'). The soil health report shows the aspects of the soil needing attention in order to alleviate constraints and thus enhance productivity, resilience, and sustainability. However, there is not a single and specific prescribed treatment for a given identified constraint, because options for addressing soil health constraints are more complex and varied (and also still less well understood) than options for alleviating nutrient deficiencies. Rather multiple diverse management options are provided for any given constraint, to guide the producer in understanding the types of practices that would alleviate the constraint identified. The choice and details of management efforts to be used in overcoming identified soil health constraints are dependent on various factors related to the operation, as will be discussed in the Soil Health Management Planning Process section in Part III.

Different management approaches can be used to mitigate the same problem: A number of different management practices that achieve similar outcomes can be used to address a constraint, as shown in the management suggestions tables provided as part of the soil health assessment report (see Part III). For example, growers seeking to increase aggregate stability in their fields need to find ways to protect and build soil aggregates through improving biological activity that accomplishes this, as discussed previously (page 42). They might approach this by using manure, growing shallow, dense-rooted cover crops, mulching, reducing tillage, or a combination of these methods, depending on their operational opportunities and challenges.

Management practices can affect multiple indicators: A single management practice can affect multiple indicators and the functioning of soil processes associated with them. For example, adding manure to the soil will improve soil aggregation, increase organic matter, increase active carbon and soil protein contents, increase microbial activity, and improve soil nutrient status. The magnitude of such synergistic effects are dependent on the specific management practices, soil types, and management history.

Certain indicators are related, but over-interpretation of these relationships may be misleading: While several soil health indicators used in this assessment provide information about interrelated processes, the degree of interrelationship varies with soil type and previous management history. For example, a general relationship exists between total soil organic matter and active carbon contents. However, active carbon is an indicator of actively decomposing organic fractions that are readily available to the soil microbial community. A soil may be high in stabilized soil organic matter from past high carbon inputs and microbial activity, but it may be lacking the fresh decomposable component currently, and thus may show relatively low active carbon content. An example of such a situation is provided in the case study in Part III, pages 97-103.

Direct comparison of two fields that have been managed differently may lead to confounded interpretations: Comparing two soil health assessment reports of fields with different management practices, histories, and soil types should be done with care. The absence of baseline data and similar inherent soil types for such comparisons makes it difficult to conclude on beneficial effects of a management practice. However, if a field was managed the same way and then divided up into comparable sections with different management practices (preferably replicated), a soil health assessment can be used to compare management alternatives.

Soil health changes slowly over time: Soil health problems have generally developed as a result of long-term management choices, so it can be expected that a "heavy footprint" on soil health parameters cannot be instantaneously alleviated as is the case for most nutrient deficiency problems. Generally, management practices to address soil health constraints take variable amounts of time for desired effects to be observed and measured. Some changes in the indicators can be seen in the short term, while others may take a much longer period to be realized. For example, fertilizer application for nutrient deficiencies, and even targeted deep subsoiling to alleviate a subsoil plow pan, or surface disturbance to alleviate compacted surface soils, may produce immediate effects within a season. But with conversion to no-tillage it may take 3-5 years before beneficial changes in soil health and productivity become noticeable. The speed of change also depends on climate and soil type. For example in very cold or very warm climates, measurable changes may take longer. Some producers are experiencing more rapid changes when they strategically combine multiple locally-adapted practices into soil health management systems, such as combining reduced tillage with cover cropping, grazing of those covers, and improved rotations.

REMEMBER: SOIL HEALTH MANAGEMENT IS A LONG-TERM INVESTMENT!

The Comprehensive Assessment of Soil Health Report fits into the Soil Health Management and Planning Framework to be discussed in further detail in Part III.

Growing Aroostook cereal rye cover crop. Photo credit: Troy Bishopp

Part III
Soil Health Management

The Soil Health Management Planning Framework[1]

Cornell's Comprehensive Assessment of Soil Health makes it possible to identify biological and physical constraints in addition to those identified by standard nutrient testing. Soil health constraints beyond nutrient deficiencies and excesses limit agroecosystem sustainability, resilience to drought and extreme rainfall, as well as progress in soil and water conservation. Each grower is generally faced with a unique situation in the choice of management options to address soil health constraints and each system affords its own set of opportunities or limitations to soil management. A more comprehensive understanding of soil health status can better guide farmers' soil management decisions. However, until recently, there has not been a formalized decision making process for implementing a soil health management system. Our approach aims to alleviate field-specific constraints, identified through standard measurements, and then maintain and monitor the measurement unit for improved soil health status. To that end, we created a frameowrk for developing Soil Health Management Plans (SHMP) for a farm operation (Figure 3.01).

FIGURE 3.01. The comprehensive assessment of soil health, used to determine soil health status, is an integral part of the Cornell Soil Health Management Planning and Implementation Framework.

Each grower is faced with unique situations and management options to choose from to address each soil health constraint. Gowers, usually in conjunction with an Ag Service Provider, will align their needs and abilities to allow for the development of management solutions.

The framework includes:

- Six general steps for the planning and implementation proccess (Figure 3.02, pages 77-82).
- A Comprehensive Assessment of Soil Health report format that more explicitly provides initial interpretation, prioritization, and management suggestions, from which a SHMP can then be developed (Part II and Appendix A).
- Resource concerns indentified through soil health assessment are detailed in a listing specific to each indicator showing constrained soil functioning for which relevant NRCS cost-shared practices may be applied (pages 80-81).
- A pilot SHMP template for such plans that includes purpose, site information, assessment results and interpretation, and planned practices via a multi-year managment calendar outlining a specific plan for each field (page 81 and Appendix B).

[1] The newly revised Soil Health Management Planning Process was adapted from work presented in Moebius-Clune, Bianca, Dorn Cox, Brandon Smith, Dan Moebius-Clune, Robert Schindelbeck, and Harold van Es. 2014. Implementation of a Soil Health Management Plan Resolves Pond Eutrophication at Tuckaway Farm, NH. What's Cropping Up? Vol. 24, No.5, Sep – Oct, a newsletter for NY field crops and soils, Department of Crop and Soil Science, Cornell University, Ithaca, NY.

The soil health assessment, described in Part II, is an integral part of the Cornell Soil Health Management Planning and Implementation Framework that enables farmers, usually with assistance from Agricultural Service Providers, to develop a more direct interpretation of the assessment to guide farm-specific planning and implementation decisions for soil health management systems (Figure 3.03). The process is designed to alleviate field-specific constraints identified through the soil health assessment, and then maintain improved soil health.

The remainder of this section will focus on describing the framework for management planning and implementation, based on information gained from assessments of soil health. A discussion will follow with a summary of the general considerations for management options and opportunities. We have included a case study of how such a Soil Health Management Plan was implemented at the Tuckaway Farm in New Hampshire at the end of this section (pages 97-103) to provide an example of the process and share the outcomes achieved in one of the farm's fields.

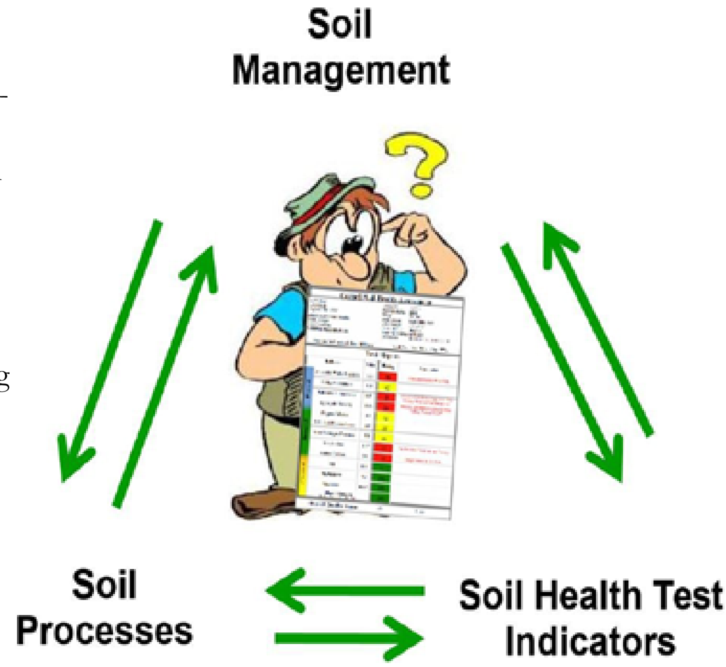


FIGURE 3.03. The soil health report, which identifies constraints and guides prioritization, is just one step in the soil health management planning process.

Soil Health Management Planning Process

1. Determine farm background and management history

Compile background info: history by management unit, farm operation type, equipment, access to resources, situational opportunities or limitations.

2. Set goals and sample for soil health

Determine goals and number and distribution of soil health samples to, according to operation's background and objectives.

3. For each management unit: identify and explain constraints, prioritize

The Soil Health Assessment Report identifies constraints and guides prioritization. Explain results based on background where feasible, and adjust priorities.

4. Identify feasible management options

Using the management suggestions table available as part of the Soil Health Report, or online with NRCS practice linkages, identify which of these suggestions may be feasible for the operation.

5. Create short and long term Soil Health Management Plan

Integrate agronomic science of Steps 2 – 4 above with grower realities of Step 1 to create a specific short-term schedule of management practices for each management unit and an overall long-term strategy (see worksheet Appendix B).

6. Implement, monitor, and adapt

Implement and document management practices. Monitor progress, repeat testing, and evaluate outcomes. Adapt the plan based on experience and data over time. Remember that soil health changes slowly.

FIGURE 3.02. The six steps of the Soil Health Management Planning Process.

Six Steps of the Soil Health Management Planning Process

The Cornell Soil Health Management Planning Process involves six steps which are described with a brief conceptual example for a corn grain operation here. A worksheet to guide this process is also included at the end of the manual in Appendix B.

1. Farm Background and Management History

Each farm is unique as is each management unit within a farm. In this first step the grower and the ag service provider work together to compile background information. It is critical to first understand the operation's land base, soil types, cropping system, current and past soil management, and the producer's inclinations. Opportunities (such as neighbor's ability to provide manure, easy access to rental equipment, or a son or daughter coming back to the operation with new skills) and limitations (such as having very tight economic margins, having no resources for or access to new equipment, having highly erodible soils, or having a short growing season) need to be identified to guide the planning process.

Step 1. Farm Background and Management History

- Farm is far from dairies so lacks access to manure
- Northern climate with short growing season
- Soil 'addicted to tillage' from decades of use of the moldboard plow, disking and harrowing before annual corn grain
- Access to diverse inventory of equipment
- Grower is very open-minded and willing to try 'anything'

2. Set Goals and Sample for Soil Health

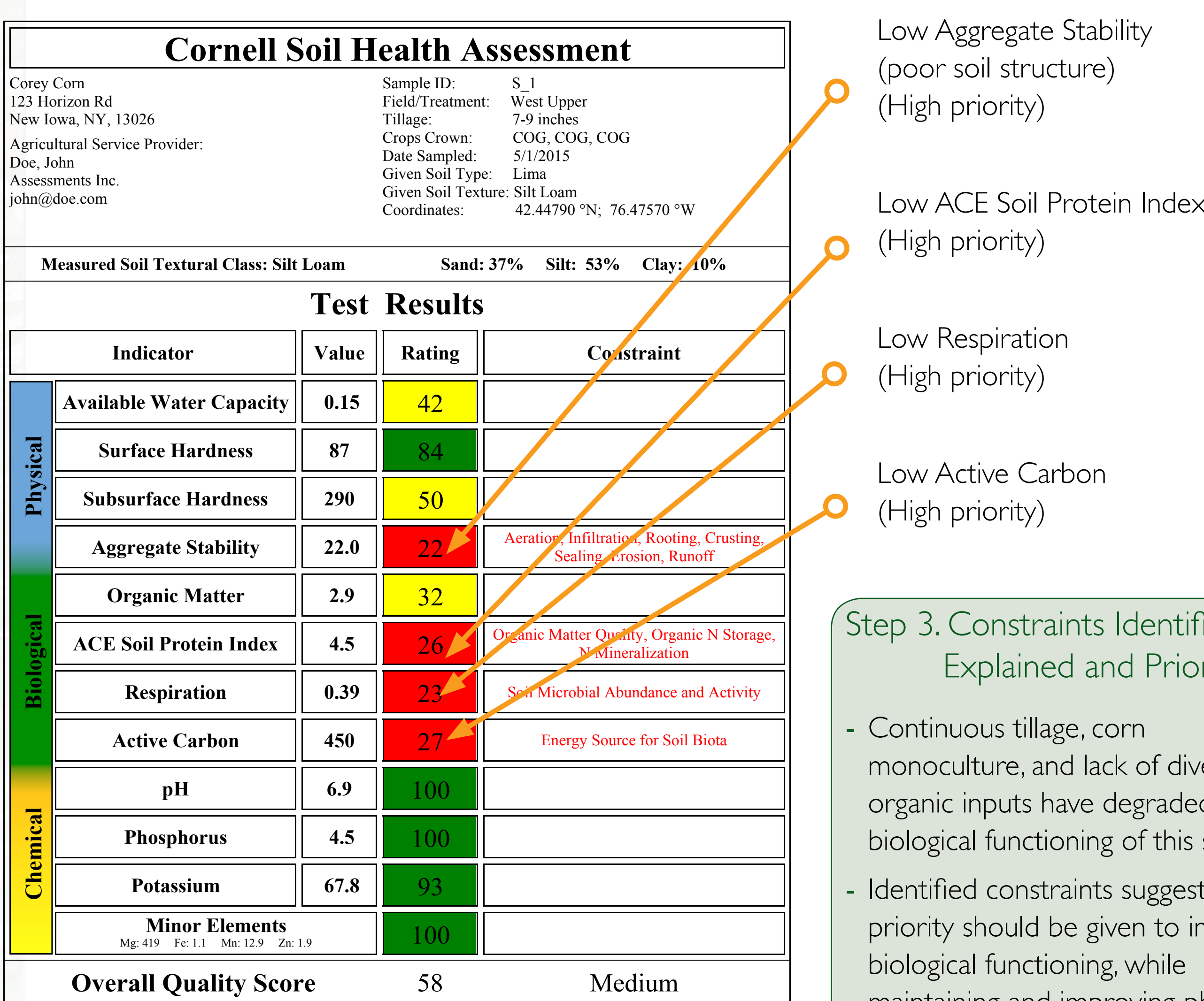
Setting goals facilitates making decisions about how and where to sample. Once baseline conditions of the farm are understood, the information can be used to further define problems and opportunities. Targeted management units for soil health can be set and soil health sampling can begin. Identifying and sampling from field management units (Area A versus Area B), where single management factors have been altered, provides particularly useful information when their soil health assessment results are compared. This same strategy can be used to evaluate the application of the identical management practice on different soil types. It is important that as much information as possible can be collected at this stage so that the plan will fit both the needs of the landowner and the available resources.

Step 2. Goals and Sampling

- Determine what is causing crop growth issues, especially in extremely wet years in a particular field
- Use field diagrams to document representative areas where data on soil performance would provide information useful to troubleshoot growth issues
- Record purposes for sampling each zone

3. Constraints Identified, Explained and Prioritized

The Comprehensive Assessment of Soil Health Report, as described in detail in Part II, measures indicators of agronomically and environmentally important soil processes and then applies scoring functions to interpret measured results in the context of soil conditions and management options (Figure 3.04). The soil health assessment report's color coded results help the user get an overview glance of the field's soil health status. The main benefit of this approach is that the identification of physical, biological and chemical constraints prompts farmers to seek improved – more sustainable - soil and crop management practices. The process links specific constraints in functioning of important soil processes (highlighted in red when the score is below 30), to management solutions through a farmer-centered decision process. Identified constraints should be given the highest priority in targeting management decisions. It is also encouraged to consider improving management for soil processes associated with indicators rated to be functioning suboptimally (shown in yellow), particularly when the score is close to 30. Indicators rated with high scores (green) should be maintained. Remember, the field's management history can often provide insights that help explain the field's current soil health condition. Step 3 is critical to creating workable management plans. Land managers can monitor changes over time through further assessment, and adapt management plans to achieve chosen goals.



Cornell Soil Health Assessment

Corey Corn
123 Horizon Rd
New Iowa, NY, 13026

Agricultural Service Provider:
Doe, John
Assessments Inc.
john@doe.com

Sample ID: S_1
Field/Treatment: West Upper
Tillage: 7-9 inches
Crops Crown: COG, COG, COG
Date Sampled: 5/1/2015
Given Soil Type: Lima
Given Soil Texture: Silt Loam
Coordinates: 42.44790 °N; 76.47570 °W

Measured Soil Textural Class: Silt Loam **Sand: 37%** **Silt: 53%** **Clay: 10%**

Test Results

	Indicator	Value	Rating	Constraint
Physical	Available Water Capacity	0.15	42	
	Surface Hardness	87	84	
	Subsurface Hardness	290	50	
	Aggregate Stability	22.0	22	Aeration, Infiltration, Rooting, Crusting, Sealing, Erosion, Runoff
Biological	Organic Matter	2.9	32	
	ACE Soil Protein Index	4.5	26	Organic Matter Quality, Organic N Storage, N Mineralization
	Respiration	0.39	23	Soil Microbial Abundance and Activity
	Active Carbon	450	27	Energy Source for Soil Biota
Chemical	pH	6.9	100	
	Phosphorus	4.5	100	
	Potassium	67.8	93	
	Minor Elements (Mg: 419 Fe: 1.1 Mn: 12.9 Zn: 1.9)		100	
	Overall Quality Score		58	Medium

FIGURE 3.04. Example report of measured indicator ratings that identify soil health constraints. For a full sized report see page 71.

Step 3. Constraints Identified, Explained and Prioritized

- Continuous tillage, corn monoculture, and lack of diverse organic inputs have degraded the biological functioning of this soil
- Identified constraints suggest that priority should be given to improving biological functioning, while maintaining and improving physical funtioning is also desired

4. Identify Feasible Management Options

Table 3.01, below, and 3.02 on the following page are examples of information included in the soil health assessment report that show recommended management approaches targeted at addressing specific measured soil constraints for both the short- and long-term. Combining these with growers' needs and abilities will allow for an active evaluation scenario and the development of management solutions. In addition, 'success stories' of specific management practices that effectively address targeted soil constraints can enhance the knowledge base of soil management consequences. There are no specific 'prescriptions' for what management regimen should be pursued to address the highlighted soil health constraints, yet we can recommend a number of effective practices to consider when addressing specific constraints. The Soil Health Management Toolbox (page 83) lists the main categories of action for soil management.

Step 4. Identifying Feasible Management Options

- Growing fresh and readily available organic material. Manure is not available to be added, but would have otherwise been an appropriate option
- Reduce tillage intensity
- Rotate with different short season crop to allow for cover cropping
- Identify window for shallow-rooted cover crop mix that includes a legume

TABLE 3.01. Example of management suggestions for Physical and Biological constraints from Figure 3.04 (p79). Constrained and suboptimal indicators are flagged in red and yellow in the report management table. Black text indicates no constraint.

Management Suggestions for Physical and Biological Constraints		
Constraint	**Short Term Management Suggestions**	**Long Term Management Suggestions**
Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Surface Hardness High	• Perform some mechanical soil loosening (strip till, aerators, broadfork, spader) • Use shallow-rooted cover crops • Use a living mulch or interseed cover crop	• Shallow-rooted cover/rotation crops • Avoid traffic on wet soils, monitor • Avoid excessive traffic/tillage/loads • Use controlled traffic patterns/lanes
Subsurface Hardness High	• Use targeted deep tillage (subsoiler, yeomans plow, chisel plow, spader.) • Plant deep rooted cover crops/radish	• Avoid plows/disks that create pans • Avoid heavy loads • Reduce traffic when subsoil is wet
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Root Pathogen Pressure High	• Use disease-suppressive cover crops • Plant on ridges/raised beds • Monitor irrigation • Biofumigate	• Use disease-suppressive cover crops • Increase diversity of crop rotation • Sterilize seed and equipment • Improve drainage/monitor irrigation
Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

TABLE 3.02. Example of management suggestions for Chemical constraints from Figure 3.04 (p79). Constrained and suboptimal indicators, if any, would be flagged in red and yellow in the report management table. Black text throughout this example indicates that there are no constraints for Chemical indicators.

Management Suggestions for Chemical Constraints		
Constraint	**Short Term Management Suggestions**	**Long Term Management Suggestions**
pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Micronutrients Deficient	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Micronutrients Excessive	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels
High Salinity	• Leach soils • Use fertilizers with a low salt index (avoid chlorine and ammonium/urea fertilizers) • Do not use Chilean nitrate	• Test compost for soluble salts • Use electroconductivity meter to monitor salts in the soil and irrigation water • Improve drainage

5. Create Short and Long Term Soil Health Management Plans

This step develops the detailed plan that a producer can follow. The plan must address prioritized constraints in a way that is feasible economically and logistically for the producer. Management approaches taken from the soil health management toolbox (page 83) can be used singularly or in combination as the same constraint might be overcome through a variety of management approaches. A specific short-term schedule of management activities is developed for each field or management unit, and an overall long-term strategy and direction is defined. Alternatives for weather contingencies may be listed as well. The options that a grower chooses may depend on farm-specific conditions such as soil type, cropping, equipment, labor availability, etc. It is important to align the agronomic science of Steps 3 and 4 with the grower realities and goals of Steps 1 and 2 to create a specific schedule of management practices for each management unit and an overall long-term strategy in this step. Table 3.03 on the following page provides a template for the Soil Health Management Planning process.

Step 5. Create a Plan

Short Term:

- *Spring:* drill barley, timothy and clover mix (adds fresh, diverse, non-corn derived organic materials and active roots earlier in season than corn)
- *Summer:* harvest barley (produces income)
- *Summer and fall:* mow timothy-clover mix as green manure (adds further and protein-rich organic material)

Long Term:

- *Winter:* learn about strip tillage and prepare to transition soil to reduced tillage system with improved rotation

TABLE 3.03. Soil Health Management Planning Process Worksheet.

Date	Operation implemented	Constraint addressed	Notes
EXAMPLE: Aug 2015	Subsoil with yeoman's plow	Subsoil compaction	Choose appropriate soil moisture conditions
Long Term Directions to Pursue:			

6. Implement, Monitor and Adapt

This step is continuous and feeds back into the planning process over time. In this step the grower is implementing the plan from step 5, documenting actions, successes and failures of management practices, and monitoring progress in problems that were initially identified. This process is critical for continued learning and improved success. The soil health assessment can be used over time to monitor change, measure progress and evaluate outcomes. The soil health management plan becomes a living document that is adapted based on experience and outcomes over time. It is important to remember that soil health has usually degraded over many years or decades, and so building it back up should be expected to take quite some time. Continue to adjust management for continuous improvement.

Step 6. Implement, Monitor, Adapt

- This farmer may find, for example, that the timothy and clover mix is ready to mow earlier or later than initially planned, or may decide that it is worth leaving the mix growing in that field for an additional season for hay, if a nearby market develops

Soil Health Management Options and Opportunities

Once a grower has entered and gone through the initial steps of the planning process, including getting the soil health status and identifying constraints of a particular management unit, the next action is to identify feasible management options.

As has been understood for a long time, soil chemical constraints can be managed through application of amendments such as lime or wood ash for low pH, or fertilizers, manures, and composts to add required nutrients. For soil health management the scope of alleviating constraints and maintaining balance is broadened to also include managing for biological and physical soil process functioning, as was previously discussed for each indicator.

In general the goals are to decrease soil disturbance, and increase soil cover, species diversity, and the portion of time when living roots are growing (NRCS soil health management principles). However, specific practices need to be chosen based on what is known about current soil health status and farm characteristics. Practices may even temporarily need to counter the above principles to most effectively alleviate current constraints, and redirect the system toward building soil health. Practices, especially new ones, need to be implemented thoughtfully and appropriately to avoid failures that can occur, especially in degraded systems. Not all soil management practices are practical or adaptable to all farm situations. Trying out practices on a smaller scale first, and modifying them to suit the particular farm operation is recommended. A lot can be learned from local and regional innovative farmers and researchers, especially when no such information is readily available.

Growers like Donn Branton of Le Roy, New York work with their Ag Service Provider to test their soil health status and guide management decisions.

FIGURE 3.05. Four management strategies in the Soil Health Management Toolbox.

The Soil Health Management Toolbox

There are four main management strategies for improving soil biological and physical health in annual or mixed production systems: reducing or modifying tillage, rotating crops, growing cover crops or interseeding, and adding amendments or inoculants (Figure 3.05).

The options within each strategy are numerous and the combinations are endless. In livestock systems, there are additional modifications to grazing strategies that can be employed. These are beyond the scope of this manual at this time, although the same soil health concepts and principles can be applied to these systems.

Adopting broader soil health management systems is particularly critical to our agriculture as extreme weather conditions are increasing due to our changing climate. Soil health management facilitates both adaptation to extreme and changing conditions, and coincidentally also mitigation of these changes.

Information on additional resources can be found in Part IV, beginning on page 105.

General Management Considerations from the Toolbox

Tillage Considerations

As new technologies have been developed, the reliance on full width tillage to kill weeds, incorporate crop debris and amendments, and prepare seedbeds has been diminished. At the same time, we now have a better understanding of how critical decreasing soil disturbance is for diverse and active biological activity that is critical for well-functioning, healthy soil. Extensive tillage temporarily stimulates certain species making up the microbial community to 'burn off', or decompose, organic matter quickly. This reduces soil aggregation, resulting in crusting and soil compaction, in addition to decreased beneficial microbial activity. It is now well understood that reducing tillage intensity, and mechanical soil disturbance in general, can improve soil health and, over time, maintain or even increase yields, while reducing production costs due to saved labor, equipment wear, and fuel.

There are many different strategies for reducing tillage intensity

- **No Tillage**: A no-till planter or transplanter does minimal soil disturbance to plant the crop (Figure 3.06 A). This is true, "single-pass" planting.
- **Ridge Tillage:** Crops are planted into minimally disturbed ridges that generally remain in the same place. Only surface soils are disturbed when ridges are rebuilt annually around the planted crop.
- **Strip Tillage:** A shank set just below the depth of the compacted layer (if present, B) rips a compacted layer while a series of coulters forms a narrow, shallow ridge in preparation for planting (C). Plants are later sown into tilled strips with a pass of the planter.
- **Zone Tillage:** Similar to strip tillage, but without the rip shank, which is not necessary when you lack subsoil compaction. Instead of preparing the entire field as a seedbed, only a narrow band is loosened by zone and strip tillage, enabling crop or cover crop residue to remain on the soil surface as a mulch. In single pass planting, the strips are simultaneously prepared and the seeds are sown.
- **Permanent drive rows:** Drive rows are particularly possible with new GPS enabled technologies, often better facilitates reduced tillage systems.
- **Roller crimpers, rotovators:** These are being developed to be set to disturb only the surface inch of the soil, and other minimal disturbance methods for managing spring cover crops.
- **Cover crop interseeders and no-till drills:** These may be used to avoid additional tillage passes for establishing cover crops.
- **Frost Tillage:** Frost Tillage can be a means of alleviating soil compaction or injecting manure in the winter. It is done when the soil is frozen between 1 and 3 inches deep. Such conditions generally only occur on a few days per winter, depending on location and year in the Northeast (D).

(A) No-till planted sweet corn into a killed sweet clover fall cover crop.

(B) Two-row strip tillage unit with an opening coulter, followed by a vertical shank, two closing coulters to form a small ridge then a rolling basket to prepare the ridge for planting.

(C) Strip tillage with a vertical shank follwed by two wavy coulters.

(D) Soil following frost tillage. The large clods will mellow and break down as a result of subsequent freeze-thaw action.

FIGURE 3.06 A-D. Examples of different reduced tillage systems.

The soil below the frost layer is non-plastic or dry, ideal conditions for tillage without compaction. Frost-tilled soil leaves a rough surface, but subsequent freeze-thaw action loosens the soil and allows the clods to fall apart in the spring, so that it is ready for an early spring crop.

Details about benefits and disadvantages of different strategies can be found in *Building Soils for Better Crops* and other resources. A summary table is below (Table 3.04).

Reduced tillage can be used for all crops, or it can be part of a rotation, modified based on the cropping sequence. Different tillage practices can be rotated depending on crop and soil management goals and concerns.

For some crops such as potato, more intensive tillage and soil disturbance is generally used to establish and harvest the crop, although some growers even plant potatoes using zone tillage. The subsequent sweet corn (or other) crop(s) may be more easily strip- or no-tilled into a killed winter cover crop.

The type and timing of tillage are site-specific and dependent on the cropping system and equipment availability. Reducing both tillage frequency and intensity will reduce the loss of organic matter and lead to improved soil aggregation and microbial activity. This will result in soils that are less susceptible to compaction and other soil health problems, and more resilient to extreme weather.

TABLE 3.04. Tillage System Benefits and Limitations. Modified from: *Building Soils for Better Crops, 3rd Edition*

Tillage System	Benefits	Limitations
Full-Field Tillage		
Moldboard plow	Easy incorporation of fertilizers and amendments. Buries surface weed seeds and also diseased debris/pathogen surviving structures. Dries soil out fast. Temporarily reduces compaction.	Leaves soil bare. Surface crusting, lack of infiltration and water storage, and accelerated erosion is common. Destroys natural aggregation and enhances organic matter loss. High energy requirements. Causes plow pans.
Chisel Plow	Same as above, but with more surface residues.	Same as above, but less aggressive destruction of soil structure, less erosion, less crusting, no plow pans, and less energy use.
Disc harrow	Same as above.	Same as above, but additional development of disk pans.
Restricted Tillage		
No-till	Little soil disturbance and low organic matter losses. Few trips over field. Low energy use. Most surface residue cover and erosion protection.	Harder to incorporate fertilizers and amendments, but new injection equipment is being developed. Wet soils slow to dry and warm up in spring. More challenging to alleviate compaction without tillage options. Higher disease and weed pressure if not combined with appropriate rotation and cover cropping.
Zone-till/ Strip-till	Same as above.	Same as above, but fewer problems with compaction and cold spring soils.
Ridge-till	Easy incorporation of fertilizer and amendments. Some weed control as ridges are built. Zone on ridge dries and warms more quickly for better germination.	Hard to use together with sod-type or narrow crop rotation. Equipment needs to be adjusted to travel without disturbing ridges.

Crop Rotation Considerations

Initially, crop rotation was practiced as a way to avoid depleting the soil of various nutrients and manage pathogens and pests. Today, crop rotation is also an important component of soil health management in many agricultural production systems. Crop rotations can be as simple as rotating between two crops and planting sequences in alternate years or they can be more complex and involve numerous crops over several years or even at the same time for improved soil health (Figure 3.07). Proper crop rotations generally increase species diversity, and reduce insect pressure, disease-causing pathogens, and weed pressure by breaking lifecycles through removal of a suitable host or habitat. Additionally, crop rotation can improve nutrient management and improve soil resiliency (to drought, extreme rainfall and disease) especially after root crops such a carrot or potato that usually involve intensive tillage. Generally yield increases when crops in different families are grown in rotation versus in monoculture (referred to as the "rotation effect").

One basic rule of crop rotation is that a crop should not follow itself. Continuous mono-cropping generally results in the build-up of disease causing pathogens, nematodes, insects and weeds that can lead to yield reductions and the need for increased inputs such as herbicides, insecticides and other pesticides. A cropping sequence for soil health management should include the use of cover crops and/or season-long soil building crops. Rotating with a diversity of root structures and make-ups, from taproots to fibrou-rooted crops from a variety of plant families, will also improve the soil's physical, chemical and biological health and functioning. Note that successful crop rotation sequences are farm specific and depend on unique combinations of location and climatic factors, as well as economic and resource limitations.

The following page contains a list of general principles for crop rotation.

FIGURE 3.07. Wheat is a good rotation crop in an intensive vegetable production rotation especially if Northern root-knot nematode is a problem. All grain crops are non-hosts for *Meloidogyne hapla.*

General Principles for Crop Rotation

- **Grow the same annual crop for only one year**, if possible, to decrease the likelihood of insects, diseases, and nematodes becoming a problem.
- **Don't follow one crop with another closely related species**, since insect, disease, and nematode problems are frequently shared by members of closely related crops.
- **Use crop sequences that promote healthier crops**. Some crops seem to do well following a particular crop (for example, cabbage family crops following onions, or potatoes following corn). Other crop sequences may have adverse effects, as when potatoes have more scab following peas or oats.
- **Follow a legume forage crop, such as clover or alfalfa, with a high nitrogen-demanding crop**, such as corn, to take advantage of the nitrogen supply. Grow less nitrogen-demanding crops, such as oats, barley, or wheat, in the second or third year after a legume sod.
- **Use crop sequences that aid in controlling weeds**. Small grains compete strongly against weeds and may inhibit germination of weed seeds, row crops permit mid-season cultivation, and sod crops that are mowed regularly or are intensively grazed help control annual weeds.
- **Use longer periods of perennial crops, such as forages, on sloping land, highly erodible soils, or soils where intensive tillage is difficult to avoid when annual crops are in place**. Using sound conservation practices, such as no-till planting, extensive cover cropping, or strip-cropping (a practice that combines the benefits of rotations and erosion control), may lessen the need to grow perennials.
- **Grow a deep-rooted crop or cover crop**, such as alfalfa, safflower, sunflower, sorghum sudan grass, or radish, as part of the rotation. These crops scavenge the subsoil for nutrients and water. Channels left from decayed roots can promote water infiltration and access to subsoil water and nutrients by following crops.
- **Grow some crops that will leave a significant amount of residue**, like sorghum or corn harvested for grain, to help maintain organic matter levels.
- When growing a wide mix of crops - as is done on many direct marketing vegetable farms - **try grouping crop mixes into blocks according to plant family, timing of crops (all early season crops together, for example), type of crop (root vs. fruit vs. leaf), or crops with similar cultural practices** (irrigated, using plastic mulch) to facilitate integrating cover crops.
- The SARE publication *Crop Rotations on Organic Farms* has more information that is useful for conventional as well as organic systems.

Modified from: *Building Soils for Better Crops, 3rd Edition*

Cover Cropping Considerations

Cover crops are usually grown for less than one year. They provide a canopy, organic matter inputs, increased species diversity, and living root activity for soil protection and improvement between the production of main cash crops. They can also be interseeded between some main crops. They can be grown as monocultures, or as mixes of two or many more species. When specifically used for improved soil fertility (often by incorporating), cover crops are also referred to as green manures. However it should be noted that often the greatest benefits are derived from cover crops that are terminated in place as this prevents damaging soil disturbance, and allows roots to decompose in the field and create continuous pores. Roots are also generally more effective at contributing soil organic matter than above ground biomass.

Cover crops with shallow fibrous root systems, such as many grasses, build soil aggregation and alleviate compaction in the surface layer. Cover crops with deep tap roots can help break-up compacted layers, bring up nutrients from the subsoil to make them available for the following crop, and provide access to the subsoil for the following crop via root channels left behind. Cover crops can thus recycle nutrients that would otherwise be lost through leaching during off-season periods. Leguminous cover crops can also fix atmospheric nitrogen that then becomes available to the following crop. Other benefits from cover crops include protection of the soil from water and wind erosion, improved soil aggregation and water storage, suppressing soil-borne pathogens, supporting beneficial microbial activity, increasing active and total organic matter, and sequestering carbon.

Winter wheat after unseasonable rainfall.

When selecting cover crops it is important to consider:

- What are your goals for using the cover crop(s)? Which constraints are you addressing, or which aspects of soil health are you aiming to maintain?
- Where can cover crops fit into the rotation? Summer, winter, season-long, interseeded?
- When and how should the cover crop be killed or incorporated? Winter-kill vs. chemical applications vs. rolled or chopped?
- What cover crops are suitable for the climate?
- What cover crops fit with the current production practices including any equipment constraints?
- What is the susceptibility or host status of the cover crop to major pathogen(s) of concern on your operation?

Dead cover crop material left on the soil surface can become an effective mulch that reduces evaporation of soil moisture, increases infiltration of rainfall, minimizes temperature extremes, increases soil organic matter, and aids in the control of annual weeds. Leguminous cover crops suitable for the Northeastern US include various clovers, hairy vetch, field peas, alfalfa, and soybean, while popular non-leguminous cover crops include rye, oats, wheat, oilseed radish, sorghum Sudan grass, and buckwheat. Additional resources for cover crop species that can be used for building soil health are included in Part IV of this manual.

Winter cover crops

FIGURE 3.08. A radish cover crop will winter kill. Desicated roots will create channels in the soil surface, improving infiltration, surface drainage and soil warming. Photo credit: Troy Bishopp.

Winter cover crops are generally planted in late summer to fall, typically following harvest of a cash crop. Certain grasses, leguminous, and other cover crops can be planted. Some crops like buckwheat, radishes, and oats will be winter-killed, so they are a good option before a cash crop planted in early spring, or when termination options are limited (Figure 3.08).

Other winter cover crops will require termination in the spring via tillage, rolling, herbicides or other early spring management prior to the planting of the next cash crop. These can also produce biomass and help protect and dry out the soil in favorable conditions. Winter cover crops are a good option before main crops planted in late spring or early summer, or when there are good termination options, including spring grazing or forage harvest. Although in northern climates the choices are limited by the short growing season, planting a winter cover crop can provide protection from soil erosion, suppression of weeds and root pathogens, contribution of nitrogen to the next crop, and increased soil organic matter and aggregation. For late harvested crops, winter cover crops might be better interseeded into the cash crop, allowing for a larger range of options (especially for including legumes), since interseeding can occur much earlier. Some winter cover crops commonly planted in the Northeast include winter rye, hairy vetch, oats, wheat, red clover, radish, and various mixtures of the above (Figure 3.09).

Season-long cover crops

Full season cover crops serve as rotational crops and are an excellent way of accumulating a lot of plant biomass to build organic matter, alleviate compaction problems, feed the soil microbial community and suppress disease. However, this often means taking the field out of cash crop production for a season. This will especially benefit fields with low fertility, farms with limited access to manures and other sources of organic amendments, or farms that can use this cover crop as a forage for livestock.

Relay cover cropping is also another option. This is when a cover crop such as red clover is spring seeded into wheat, and then continues to grow after the wheat crop is harvested. It is important to keep in mind that some cover crops such as buckwheat, ryegrass, crown vetch and hairy vetch have the potential to become a weed problem if they set seed.

Summer fallow cover crops

Summer fallow cover crops are more common in vegetable than field crop rotations. A fast growing cover crop can be planted between vegetable crops. For example, buckwheat can be grown after early spring lettuce and prior to planting a crop of fall broccoli. This option is severely limited in the north by the short growing season. In shorter season climates, a more successful option may be to interseed a cover crop into the main crop once the latter becomes established, but it is important to avoid competition by the cover crop for water and nutrients.

FIGURE 3.09. Mix of winter rye, wheat, barley, and hairy vetch. Cover crop mixes are an excellent way of accumulating plant biomass to build organic matter, alleviate compaction problems, feed soil microbes and suppress disease. Photo credit: Dorn Cox

Cover crop mixes

Cover crop mixes are getting increasing attention these days, as it is being recognized that greater plant diversity also increases microbial community diversity and functioning. Grass and legume combinations have long been used (as for example oat-pea mix in the fall, or rye-vetch mix over winter), but "cover crop cocktails" that often include eight or more species of various grasses and legumes are being increasingly evaluated by farmers and researchers alike. There are several reasons for this approach:

1) Different cover crops provide different benefits, so mixes can be chosen to improve a larger number of soil functions. For example a legume (for nitrogen contributions), a shallow rooted grass (for improved aggregation and to alleviate surface hardness), and a deep rooted crop such as radish (to alleviate subsoil compaction) can be combined to achieve all of these benefits.
2) Depending on weather factors, some species may do better in a given year than others. Seeding a mix of many species ensures that at least some of these species can take advantage of the prevailing weather conditions.
3) Because different species have different root architectures and growth habits, various niches can be occupied, so that often more biomass is produced by a mix of species than by a single species.

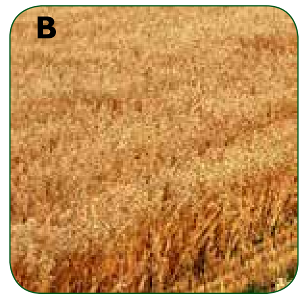
Growing Cover Crops Profitably and *Building Soils for Better Crops* have additional, useful information (see Part IV).

Four common cover crops in the Northeast:

Winter rye (*Secale cereale*) is very winter hardy and can be seeded late into the fall after late harvest crops (Figure 1.10 A). It can serve as a nutrient catch crop, reduce erosion, increase organic matter, suppress weeds, reduce soil-borne pathogen populations. It can be sown with legumes if desired, but it has also been found to somewhat inhibit the growth of certain crops following it. Rye will grow aggressively in spring and sometimes may need to be quickly killed before it matures to reduce potential weed problems, deplete soil moisture and immobilize nitrogen. Rye can be incorporated as a green manure, mowed, rolled, or killed with an herbicide in reduced tillage systems, preferably several weeks prior to planting the main crop. Some farmers have had great success no-till planting soybeans into rolled rye (page 96).

Winter rye (*Secale cereale*)

Oat (*Avena sativa*) is not winter hardy in the Northeast. However in early spring the killed oat biomass can serve as mulch for weed suppression (B). It can be mixed with a legume and also be used to prevent erosion, scavenge excess nutrients, add biomass, and act as a nurse crop. A nurse crop is an annual crop used to assist in the establishment of a perennial crop.



Oat (*Avena sativa*)

Sudan grass and sorghum sudan grass hybrids (*Sorghum bicolor x S. bicolor var. sudanese*) are fast growing during warm weather, although they are not winter hardy in the Northeast (C). However, in early spring the killed biomass can serve as mulch for weed suppression. It can be used as a soil builder, subsoil loosener and weed suppressor when sown at high rates. When used for their biofumigant properties, incorporating young tissue (1 to 3 months old) when the soil is warm (microbially active) is recommended, especially for control of plant-parasitic nematodes. To promote increased root growth, it should be mowed or grazed multiple times during the growing season.

Sudangrass and sorghum-sudangrass hybrids (*Sorghum bicolor x S. bicolor var. sudanese*)

Hairy vetch (*Vicia villosa*) is an excellent spring biomass producer and leguminous nitrogen contributor therefore making it good for weed suppression and as a nitrogen source (D). It improves topsoil tilth by reducing surface crusting, ponding, runoff, and erosion. In the Northeast, it needs to be planted by late summer for good establishment and overwintering.

Hairy vetch (*Vicia villosa*)

FIGURE 3.10 A-D. Common cover crops in the Northeast.

Organic Amendment Considerations

Organic matter is critical for maintaining balanced soil biological communities, as these are largely responsible for maintaining soil structure, increasing water infiltration and building the soil's ability to store and release water and nutrients for crop use. Organic matter can be maintained better by reducing tillage and other soil disturbances, and increased by improving rotations and growing cover crops as previously discussed. Organic materials can also be added by amending the soil with composts, animal manures, and crop or cover crop residues imported to the field from elsewhere. The addition of organic amendments is particularly important in vegetable production where minimal crop residue is returned to the soil, more intensive tillage is generally used, and land is more often a limiting factor making the use of cover crops more challenging. Various organic amendments can affect soil physical, chemical and biological properties quite differently, so decisions should be based on identified constraints and soil health management goals. Organic amendments derived from organic wastes should not only be tested for nutrients, but also for contaminants such as heavy metals.

Animal manure

FIGURE 3.11. Applying manure can have many soil and crop benefits.

Applying manure can have many soil and crop health benefits, such as increased nutrient levels (nitrogen, phosphorus, and potassium in particular, but also micronutrients) as well as easily available carbon that will benefit the soil microbial community (Figure 3.11). Not all manures are equal however. Manure nutrient and carbon contents vary depending on the animal, feed, bedding, and manure-storage practices. Manure containing a lot of bedding is typically applied as a solid, while manure with minimal bedding is applied as a liquid. Manure solids and liquids may be separated, and solids can also be composted prior to application to help stabilize nutrients, especially nitrogen. Due to the variability in nutrient content, manure analysis is beneficial and takes the guesswork out of estimating manure nutrient content and characteristics. Manuring soil can increase total soil organic matter, cation exchange capacity and water holding capacity over time, and fresh uncomposted manure, especially when solid, is very effective at increasing soil aggregation. Careful attention should be paid to the timing and method of application to meet the needs of the crop or cropping sequence. Excessive or untimely application can cause plant or soil damage, food pathogen concerns, or degraded water resources.

Compost

FIGURE 3.12. The stable products of composting are an important source of OM.

Unlike manure, compost is very stable and generally not a readily available source of nitrogen, but it is important to recognize that phosphorus remains highly available. The composting process uses heat and microbial activity to quickly decompose simple compounds like sugars and proteins, leaving behind more stable complex compounds such as lignin and humic materials. The stable products of composting are an important source of organic matter (Figure 3.12). The addition of compost increases available water holding capacity by improving organic matter content and pore space that holds water. It also improves cation and anion exchange capacities, and thus the ability for nutrients to be stored and released for plant use. Compost is less effective at building soil aggregation than fresh manure, because the readily-degradable organic compounds have already been decomposed, and it is the microbial process of decomposition that helps build aggregates. Composts differ in their efficiency to suppress various crop pests, although they can sometimes be quite effective. Compost should not be used alone to meet crop nitrogen demand, as this will result in over-application of phosphorus, and thus can increase environmental risk. Properly produced composts are safe to use on human food crops with respect to pathogens.

Crop and cover crop residues

Crop or cover crop residue (whether grown in place or imported from a different field) is usually referred to as “green manure” and is another important source of organic matter (Figure 3.13). Green manure cover crops can be grown specifically to improve soil fertility, organic matter content, and microbial diversity and activity. Crop residues and green manures can either be incorporated or left on the surface to protect the soil against erosion and disturbance, and to improve surface aggregation (Figure 3.14). This results in reducing crusting and surface compaction. A soil with better aggregation (aggregate stability) is more resilient in heavy rain storms and is capable of greater water infiltration and storage. However, diseased crop debris can harbor inoculum that can become a problem during the next season if a susceptible crop is planted. Crop rotation with non-host crops belonging to different plant families, and/or the appropriate use of cover crops will reduce pathogen inoculum. Removal and composting of diseased crop debris may be an option in some situations. Incorporation or plowing down of crop debris to encourage the decomposition process may be an option depending on the tillage system and crop rotation sequence.

Other Sources of Organic Amendments

- Municipal wastes (yard debris, biosolids, municipal composts)
- Organic wastes from food processing industries
- Organic wastes from paper mills, timber industry and brewing facilities
- Post-consumer food wastes (home, restaurant, and institutional)

FIGURE 3.14. Residue mulch on surface. Crop residues can either be incorporated or left on the surface to protect the soil against erosion and disturbance.

FIGURE 3.13. Crop residues (green manure) can improve soil fertility, OM content, and mircrobial diversity and activity. Photo credit: Jeff Vanuga, USDA-NRCS

Considerations for adapting to and mitigating climate change

Soil health management provides an opportunity to increase profits and decrease risks through adaptations to a changing climate, and to contribute to solving this critical environmental issue.

Throughout the long history of life on Earth, soil organisms, plants, and other living things have played a major role in the cycling of three important greenhouse gases: carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). In our atmosphere, these gases trap heat that otherwise would escape. For many millions of years the concentrations of these gases were relatively constant and created a planet with a comfortable average temperature of about 59^0 F, which has promoted the abundant life we are familiar with. Since the Industrial Revolution, however, all three of these gases have been steadily on the rise, leading to a rapid pace of climate change that is affecting natural ecosystems and agriculture worldwide (Figure 3.15).

Soil organisms, plants, and animals are important as both sources (producers) and sinks (absorbers) of greenhouse gases. How we manage our soils, crops, and livestock will thus play a major role in determining the future pace of climate change, with implications for farming and food security. We can mitigate (decrease the magnitude of) these impacts – particularly the impacts of CO_2 and N_2O – through better soil health management, and at the same time build resistance and resilience, so that our systems are better adapted to these changes.

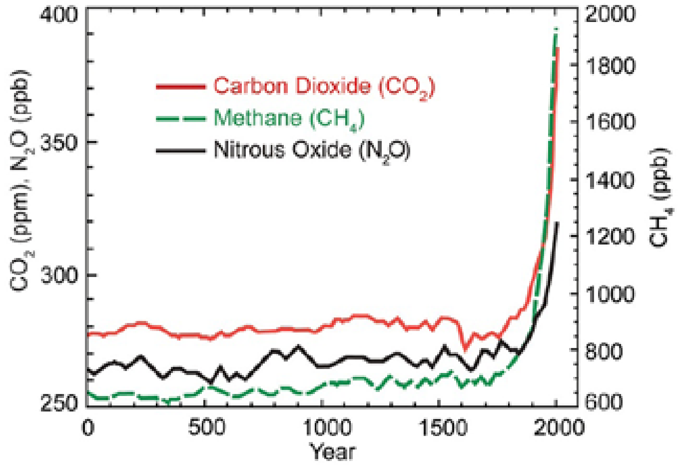


FIGURE 3.15. Greenhouse gas concentrations have been rising significantly since the Industrial Revolution.
Source: IPCC Fourth Assessment Report (2007)

Soil health management for carbon sequestration: capturing and storing carbon in soils

Many of the practices emphasized in this manual for increasing soil organic matter and improving soil health also increase soil carbon (since organic matter is mostly carbon). This carbon stored ("sequestered") in soil is carbon that otherwise would be in the air as the greenhouse gas, carbon dioxide (CO_2).

- **Winter cover cropping and growing perennial forages or other vegetation** increases the annual carbon capture from the atmosphere (via photosynthesis), and some of this carbon remains in the soil as organic matter.
- **Including nitrogen-fixing legumes** as winter cover crops or rotation crops adds benefit by reducing the need for synthetic nitrogen fertilizers, which are energy-intensive to manufacture and transport. This further reduces CO_2 emissions associated with farming (and saves money on nitrogen fertilizer).
- **Reducing tillage** slows decomposition of soil organic matter and release of CO_2 into the atmosphere. Also, fewer tillage operations reduces the CO_2 emissions from tractor driving (and saves on labor and fuel costs for the farmer).
- **Using manure, composts, and other organic amendments** directly adds carbon-rich organic matter to the soil, and also can reduce the need for synthetic nitrogen fertilizers and associated CO_2 emissions.

Rebuilding soil organic matter thus plays a role in climate change mitigation (reducing the "carbon footprint" of agriculture). At the same time, it increases adaptation to these changes by building resilience to extreme weather. Improved infiltration and drainage minimize crop stress, valuable top soil loss, and flooding during extreme rainfall events. Increased water holding capacity, in combination with better infiltration, allows for more water storage to buffer against short term drought.

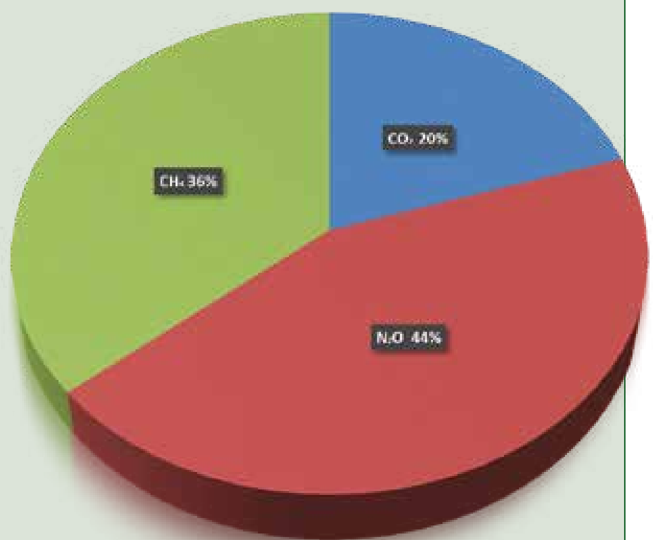
Soil health management to prevent nitrous oxide emissions

Nitrous oxide (N_2O) is about 300 times more potent in its global warming potential than CO_2 on a molecule-to-molecule basis. Over 70% of total U.S. N_2O emissions come from agriculture, largely from excessive and poorly timed use of nitrogen fertilizers. While small amounts of this come from soil microbial nitrogen mineralization processes that cycle nitrogen from organic nitrogen to ammonium and nitrate, most comes from "denitrification" in water logged (low oxygen, anaerobic) soils that convert most of the nitrate (NO_3^-)to the inert form of nitrogen gas (N_2), while releasing significant amounts of N_2O (Part I, Figure 1.10).

- **Improved soil drainage** will reduce denitrification and nitrogen losses (as well as CH_4 losses) from water-logged soils, and greater water storage will reduce risk of applied nitrogen to be lost to the environment after a crop lost to drought. This also cuts costs for the farmer!
- **Optimizing timing and amount applied, and splitting fertilizer applications** can significantly reduce emissions and improve profit margins. Timing and amount should be based on crop demand, soil health measures, and new web-based decision tools and apps that take into account real-time weather effects (e.g., soil temperature, moisture, rainfall) on available nitrogen.
- **Organic sources of nitrogen,** such as legume rotation crops, manures, and composts will release nitrogen more slowly and 'spoon feed' the crop.

U.S. Agriculture's Greenhouse Gas Emissions

While nationally and globally, CO_2 emissions (mostly fossil fuels like coal, oil, and gas) are the biggest contributor to climate change, N_2O and CH_4 are of bigger concern for agriculture. They are such potent greenhouse gases that on a "CO_2- equivalent basis their emissions from the U.S. agriculture sector contribute more to global warming than CO_2 emissions from tractor driving or other fossil fuel energy use on the farm.



Greenhouse gas emissions from U.S. Agriculture (CO_2 equivalent basis, 2007, USEPA).

These sources have the added benefit of allowing you to reduce the fossil fuel emissions associated with manufacturing and transporting synthetic fertilizers.

- **Perennial plants and winter cover crops** such as winter rye "scavenge" excess nitrogen from the soil and help store this in plant tissue over the winter and spring when it could otherwise be lost due to wet conditions. Decomposition then releases nitrogen to the subsequent cash crop.

In summary, healthy soils store more carbon and require fewer inputs. Thus, they have reduced carbon emissions associated with manufacture, transport, and application of inputs. They are also better able to prevent saturation and soil loss, and store water from large rainfall events to carry a crop through a short-term drought. Healthy soils therefore minimize greenhouse gas emissions, plant stress, and risk to the farmer of challenging weather events. Sustaining healthy productive soils also reduces the need for land clearing, deforestation, and related CO_2 emissions internationally.

Cover crop being planted without tillage on previously manured field. Photo credit: Troy Bishopp

The larger picture above shows a rolled rye crop with emerging soybeans planted two weeks previous on 30 inch centers. The inset photo shows the roller/crimper on the front of the tractor with the soybean planter on the back. This method has found success in organic systems where the rye controls weeds by mulching the soil below the beans.

Case Study: Implementation of a Soil Health Management Plan resolves pond eutrophication at Tuckaway Farm, NH[2]

Tuckaway Farm, a 250 acre multi-generational diversified organic operation in Lee, NH is managed by Dorn Cox and his family. Dorn, who holds a PhD from the University of New Hampshire, is also the executive director of GreenStart, an educational non-profit organization set up to foster a resilient food and energy system in New Hampshire (NH) by providing technical education and practical agricultural examples. In 2009 Dorn discovered that the Cornell Comprehnsive Assessment of Soil Health was available while discussing soil testing with Brandon Smith, then State Agronomist of the NH NRCS. "It was a good fit for GreenStart's mission and I was excited, because the test not only incorporated biological, physical, and chemical indicators, but it also presented an approach for land management planning and adaptive management." In the spring of 2010 he submitted his first samples.

A collaborative project was initiated among partners at NH NRCS, Cornell, Greenstart, NH Conservation Districts, and NH farms in four counties that led to the expanded Soil Health Management Planning framework presented in this section (pages 76-82). The goal was to develop a framework, analogous with the NRCS's Nutrient Management Planning process, but with biological and physical test results to be explicitly integrated into conservation planning, along with standard soil test results. Tuckaway Farm became the first of over a dozen test cases for the new planning and implementation framework. Through the particular soil health constraints identified, this case became strong evidence for the need to take a broader soil health assessment-based planning approach. Implementation of a targeted set of soil health management practices has now resolved eutrophication problems that had made the farm irrigation pond unusable for recreation. The following case study uses the Tuckaway Farm's experience with the Soil Health Management Planning to demonstrate how the process plays out on an actual farm.

Planning, implementation and evaluation for a field at Tuckaway Farm in 6 steps

1. Farm Background and Management History

Dorn and his father Chuck tell the story of a 30 year evolving family endeavor. Much of the land has been in long-term continuous organic hay for off-farm sales, with limited use of inputs such as wood ash and horse manure. The farm has added vegetable rotations and fruit over the years, and more recently dairy, eggs, meat, grains, and oils, among other products, all with organic certification. A Comprehensive Nutrient Management Plan determined that net nutrient exports off the farm were causing nutrient deficiencies in many long-term hay fields. The land base can potentially sustain a much larger number of animals. Management change has sped up in more recent years around the region, with additional products being developed, experimentation with reduced tillage, cover crops, and rotational grazing, and a decrease in hay export as the younger generation farmers are building animal-based enterprises. Diverse equipment, owned by the farm, Greenstart, and the county conservation district, is available.

[2] Case study adapted from Moebius-Clune, Bianca, Dorn Cox, Brandon Smith, Dan Moebius-Clune, Robert Schindelbeck, and Harold van Es. 2014. Implementation of a Soil Health Management Plan Resolves Pond Eutrophication at Tuckaway Farm, NH. What's Cropping Up? Vol. 24, No.5, Sep – Oct, A newsletter for NY field crops and soils, Department of Crop and Soil Science, Cornell University, Ithaca, NY.

The Pond Field, the subject of this case study, is a long-term hay field, occasionally grazed outside of the CNMP-required buffer strip around the pond's perimeter. The field's soil is an inherently well-drained but easily eroded Hollis-Gloucester fine sandy loam of mostly 8-15% slope that levels near the pond at the bottom of the slope. Forage growth was mediocre, and legume content was very low, when the field was assessed for the project (Figure 3.16 A). Dorn Cox noted that the pond had previously served as their swimming pond. Over time, it had become overgrown with algae, indicating excess phosphorus availability in the water (B), despite the fact that manure-spreading buffers were attended to in accordance with their CNMP.

FIGURE 3.16 A-B. Pond field. At initial assessment, grass forage growth was of low vigor, and forage legume content was very low (A). In addition, the former recreational pond was eutrophic with heavy algal growth visible at the edges (B).

2. Goals and Sampling

Goals for the farm included improving soil health, productivity, on-farm nutrient and carbon cycling, and long-term sustainability, and regaining use of the pond for recreational purposes. A number of representative fields on the farm were sampled to assess baseline status and to guide changes in management as the enterprise evolves.

3. Constraints: Identified, Explained, and Prioritized

Overall, soil health at Tuckaway Farm was found to be medium to high, with generally high total organic matter and aggregate stability due to low tillage and long-term perennial forage growth. Compaction was a prominent soil constraint, however (Figure 3.17). Severe surface compaction and suboptimal subsurface hardness were identified as factors driving decreased soil functioning and low plant vigor in Pond Field, likely due to traffic on wet soils during haying and grazing. Active carbon was suboptimal or constraining in every field, likely resulting from low plant vigor and thus low fresh root and shoot contributions to soil organic matter. P, pH and particularly K were suboptimal in many fields. Suboptimal K in Pond Field further contributed to low plant vigor and low legume content, while pH and P were on the low end of the optimal range. Eutrophication problems from excessive P inputs into the pond were consequently not due to high soil P. Rather, eutrophication was explained by poor physical and biological soil health. Severe compaction on a grazed slope with suboptimal vegetation growth was causing excessive runoff during rain events, and accordingly, water quality problems.

Note that the example soil health report on the following page has been updated to fit the 2015 format and suite of standard tests.

Measured Soil Textural Class: Silt Loam   Sand: 46%   Silt: 53%   Clay: 1%

Test Results

	Indicator	Value	Rating	Constraint
Physical	Available Water Capacity	0.17	58	
Physical	Surface Hardness	233	24	Rooting, Water Transmission
Physical	Subsurface Hardness	325	36	
Physical	Aggregate Stability	83.6	96	
Biological	Organic Matter	5.3	91	
Biological	ACE Soil Protein Index	TEST UNAVAILABLE IN 2010		
Biological	Respiration	TEST UNAVAILABLE IN 2010		
Biological	Active Carbon	566	51	
Chemical	pH	6.1	78	
Chemical	Phosphorus	3.1	89	
Chemical	Potassium	37.8	48	
Chemical	Minor Elements Mg: 81 Fe: 2.6 Mn: 14.6 Zn: 1.6		100	
	Overall Quality Score		67	Medium

FIGURE 3.17. Updated version of the Pond Field Conrell Assessment of Soil Health report from 2010, with the 2015 tests and format. This report is showing that compaction drives the lack of soil functioning observed for this field. In addition, there is suboptimal nutrient and pH conditions contributing to poor plant growth, which in turn explains suboptimal Active Carbon availability. The Potentially Mineralizable Nitorgen (PMN) and Root Health Rating (RHR) tests that were assessed in 2010 were replaced by ACE Soil Protein Index and Respiraton in 2014. PMN and RHR tests are still available as Add-on analyses (pages 57-69) to the Comprehensive Assessment of Soil Health package.

4. Feasible Management Options

Surface and deep targeted soil disturbance were identified as feasible and most promising options for alleviating compaction (see table 3.01, page 80 for management suggestions). Improved selection of cover and pasture crop species was considered, but this necessarily had to be the second step, based on low vigor and the need to jump-start the system through initial loosening of the soil. However, they were deemed essential for improving and maintaining biological activity in the longer term. Woodash and manure were identified as the most feasible immediate ways to address nutrient and biological activity constraints. It was noted that bedrock for the soil type is generally at 10-20", so that improving water dynamics and preventing erosion was particularly important, but it was also acknowledged that bedrock proximity might cause challenges for mechanical compaction management in some areas.

5. Short and Long-Term Soil Health Management Plan

The short-term management calendar included the following immediate remediation in the first year of the case study:

- Deep ripping with the available yeoman's plow along slope contours (30" spacing, to maximum depth possible considering bedrock), to alleviate subsoil compaction, low infiltration, and erosion issues.
- Interseeding tillage radish or similar deep rooted fall brassica in order to keep soil pores open, implemented in the same pass as the above if feasible.
- Woodash application followed by aerway incorporation to address suboptimal K along with surface compaction, and to maintain P and pH in their optimal ranges.

A combination of rotational grazing or haying during appropriate soil moisture conditions was recommended. Grazing was to be followed with aerway incorporation of manure to maintain soil P while also minimizing chances of erosion. Interseeding of additional species, such as warm season annual forages (sorghum sudangrass or forage soybean) during the following season was planned to increase biomass production and thus biological activity. Monitoring compaction levels and possible follow-up with further mechanical alleviation was planned for subsequent years.

6. Implement, Monitor and Adapt

Implemented Practices: The plan was implemented with some adaptations due to farm scheduling, weather constraints and equipment availability (Figure 3.18 A-D, page 101). A yeoman's plow and aerway with one hole offset were used according to plan, but no woodash was applied, nor were additional crops interseeded in the first fall. The three shank yeoman's plow was set to 20" depth and 30" spacing between shanks (A), followed by the aerway with one-hole offset on the same day (B). All grazing was stopped on the slopes above the pond starting in that first fall. The wet spring in the second season delayed woodash spreading further, until after two cuts of dry hay had been removed, and the spreader was available for covering multiple fields. Woodash was surface spread in October of the second season using the Conservation District's Stolzfus wet lime and woodash spreader loan program (C). The slope above the pond was then seeded to a hairy vetch, winter rye, wheat, barley mix in a single pass cultivation using a Unimog U1200 tractor with a front mounted Howard rotovator set to 3", and rear mounted Great Plains no-till drill (D). The mix was planted to address surface compaction for improved infiltration, as well as to produce one of multiple potential crops depending on needs at harvest: feed grain, cover crop seed (usable as on-farm custom winter mix, or separable with the farm's spiral separator), or a single cut of legume mix dry hay harvestable in the subsequent summer.

Observed Results: See Figure 3.19 A-D, page 102. Prior to implementation, significant runoff was evident during rain events. Algal growth prevented use of the pond for recreational purposes (A). Water flow from the slope during rainfall was noticeably reduced after deep rip and aerway treatments, despite the wet spring in the second season, and the pond started to clear and became usable for recreation that summer. Runoff reduction appeared even greater post grain-vetch-mix planting that fall, and the pond's water quality continued to improve into the following summer (third) season (B and C). The effect of wood ash was evident in the spring of the third season as vigorous clover growth returned to the field, and the grain-vetch mix grew with satisfactory vigor (D). 5 years after implementation, the field continued to be productive and the pond remained clear. Dorn and Chuck plan to continue to monitor soil health status moving forward.

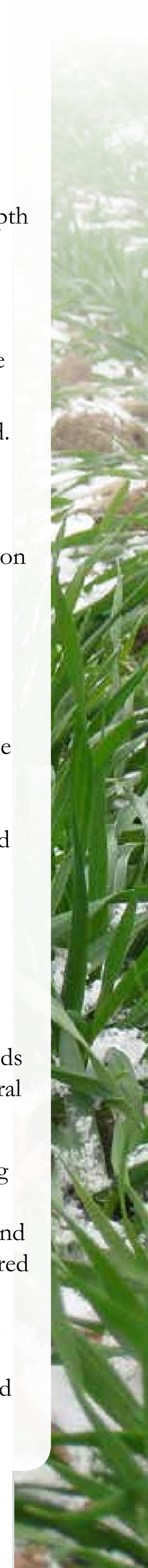


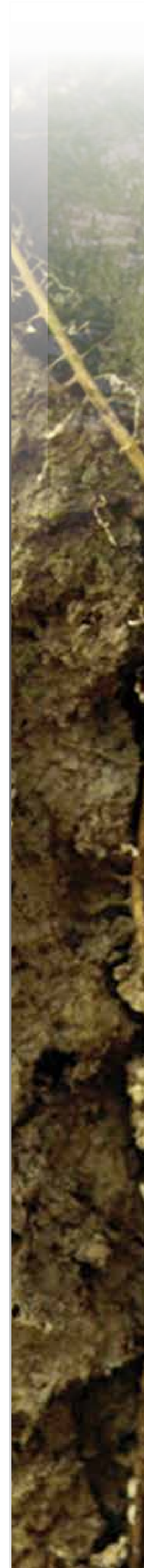
FIGURE 3.18 A-D. Soil Health Management Plan Implementation: Deep ripping with a yeoman's plow along the slope's contours (A) to alleviate subsoil hardness, followed by aerway treatment (B) to alleviate surface hardness in the fall of the first season. Wood ash application to alleviate low pH, and K and P deficiencies (C), followed by single pass shallow rotovator cultivation and seeding of grain-vetch mix (D) to further alleviate surface compaction and produce crop.

FIGURE 3.19 A-D. Heavy algal growth as was seen along the pond's perimeter prior to implementing the Soil Health Management Plan (A). Clear water (B), regained recreational use (C), and improved legume content and satisfactory crop vigor (D) after implementation of the first approximately 20 months of a situationally adapted Soil Health Management Plan.

Case Study Conclusions

In this case study, a targeted set of soil health management practices were implemented to alleviate previously unidentified compaction, in addition to interacting minor biological and chemical constraints. These treatments have resolved eutrophication problems in a pond that can now be used once again for recreation and remains clear years after implementation of the plan. This case demonstrated strong evidence for the need to move beyond simple Nutrient Management Planning, to more comprehensive Soil Health Management Planning. Interactions between nutrient-related constraints and biological and physical limitations in soil conditions were highlighted: in this case, the lack of infiltration from compaction and poor rooting allow for simultaneous occurrence of nutrient deficiencies in soil and nutrient excesses in water. We further illustrated the limitations of applying prescribed best management practices (e.g. buffers), in the absence of using environmental monitoring and systems indicators to provide feedback for adaptive nutrient and soil health management. Biological and physical constraints must be explicitly identified through soil health assessment, and managed comprehensively alongside nutrient-related constraints. Management must be adapted in response to seasonal conditions and observations, in order to achieve satisfactory progress in soil and water conservation.

Northeast producer crimping winter rye and planting soybeans in one pass. Photo credit: Jenn Thomas-Murphy



Part IV
Additional Resources

Additional Resources

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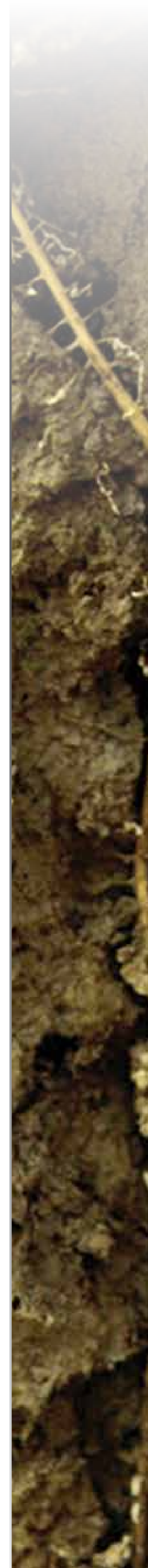

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Good pasture management leads to good soil health.

Selected Web Resources:

Cornell Soil Health

(http://soilhealth.cals.cornell.edu): is a resource on soil health in New York and the Northeast. It contains a more extensive list of available web-based resources.

National Sustainable Agriculture Information Service

(http://attra.ncat.org/): contains information pertaining to sustainable agriculture and organic farming including in-depth publications on production practices, alternative crop and livestock enterprises, innovative marketing, organic certification, and highlights of local, regional, USDA and other federal sustainable ag activities.

Northeast Sustainable Agriculture Research and Education

(http://www.nesare.org): search the project report database for the latest in sustainable research and education projects that are ongoing in the northeast including information on soil management.

Soil Science Society of America

(http://www.soils.org): is the website for the soil science professionals.

USDA-Natural Resources Conservation Service (NRCS) Soil Survey and Soil Health Information

(http://soils.usda.gov)
(http://www.nrcs.usda.gov/wps/portal/nrcs/main/national/soils/health/): Helping People Help the Land. Websites provide a wealth of information of soil taxonomy, soil survey maps, soil biology, soil function, soil health educational materials, etc. for educators, researchers and land managers.

Agency for Toxic Substances and Disease Registry ToxFAQsTM

(http://www.atsdr.cdc.gov/toxfaqs/index.asp): contains information about contaminants found at hazardous waste sites.

Cornell Waste Management Institute

(http://cwmi.css.cornell.edu/soilquality.htm): fact sheets and other resources provide a variety of information related to soil contaminants, soil testing, and best practices, including "Sources and Impacts of Contaminants in Soils", "Guide to Soil Testing and Interpreting Results", and "Soil Contaminants and Best Practices for Healthy Gardens."

Selected Web Resources: *Continued*

Healthy Soils, Healthy Communities Project

(http://cwmi.css.cornell.edu/healthysoils.htm): a community-research-Extension partnership led by Cornell University, the New York State Department of Health, and NYC Parks GreenThumb, funded by National Institute of Health and National Institute of Environmental Health Sciences. Research and Extension activities address contamination in urban gardens and provide resources for gardeners and others, including:

"What Gardeners Can Do: 10 Best Practices for Healthy Gardening" (http://cwmi.css.cornell.edu/WhatGardenersCanDoEnglish.pdf) and

"Metals in Urban Garden Soils" (http://cwmi.css.cornell.edu/Metals_Urban_Garden_Soils.pdf)

New York State Department of Health, "Healthy Gardening: Tips for New and Experienced Gardeners"

(http://www.health.ny.gov/publications/1301/index.htm): provides information to help gardeners learn more about where to plant, how to prepare new gardens, and how to grow and harvest healthier fruits and vegetables.

New York State Department of Health, Lead Poisoning Prevention

(http://www.health.ny.gov/environmental/lead): provides information to help people prevent lead poisoning.

US Environmental Protection Agency, Urban Agriculture and Improving Local, Sustainable Food Systems

(http://www.epa.gov/brownfields/urbanag/): resources from the Office of Brownfields and Land Revitalization provide information intended for people working on agriculture projects as a part of brownfield redevelopment and reuse. The website includes educational resources, success stories, FAQs, and more.

Soil Renaissance

(http://soilrenaissance.org/): a multi-organizational effort lead by Farm Foundation, NFP and the Samuel Roberts Noble Foundation to advance soil health and make soil health the cornerstone of land use management decisions by bringing together relevant stakeholders around critical needs.

USDA Agricultural Research Service Northern Great Plains Research Laboratory Cover Crop Chart

(http://www.ars.usda.gov/Main/docs.htm?docid=20323): designed to assist producers with decisions on the use of cover crops in crop and forage production systems.

TM

Appendix A

Sample 2015 Standard Package

Cornell Soil Health Assessment Report

Cornell Soil Health Assessment

Rachel T's Organic Grains
Hill Rd.
Newfield, NY, 14111

Agricultural Service Provider:
Mr. Bob Consulting
Farmland TSP
rrs3@cornell.edu

Sample ID: Jj_1204
Field/Treatment: Low Field
Tillage: 7-9 inches
Crops Crown: COG, COG
Date Sampled: 4/13/2015
Given Soil Type: Bath silt loam
Given Soil Texture: Silt Loam
Coordinates: Coordinates Not Provided

Measured Soil Textural Class: Silt Loam **Sand: 33%** **Silt: 57%** **Clay: 10%**

Test Results

	Indicator	Value	Rating	Constraint
Physical	Available Water Capacity	0.22	88	
Physical	Surface Hardness	230	25	Rooting, Water Transmission
Physical	Subsurface Hardness	390	15	Subsurface Pan/Deep Compaction, Deep Rooting, Water and Nutrient Access
Physical	Aggregate Stability	77.1	93	
Biological	Organic Matter	3.0	35	
Biological	ACE Soil Protein Index	6.1	43	
Biological	Respiration	0.68	62	
Biological	Active Carbon	440	25	Energy Source for Soil Biota
Chemical	pH	5.5	11	Low pH: Toxicity, Nutrient Availability
Chemical	Phosphorus	6.4	100	
Chemical	Potassium	67.3	93	
Chemical	Minor Elements Mg: 166 Fe: 4.2 Mn: 6.6 Zn: 1.9		100	

Overall Quality Score 57 Medium

Measured Soil Health Indicators

The Cornell Soil Health Assessment measures several indicators of soil physical, biological and chemical health. These are listed on the left side of the report summary, on the first page. The "value" column shows each result as a value, measured in the laboratory or in the field, in units of measure as described in the indicator summaries below. The "rating" column interprets that measured value on a scale of 0 to 100, where higher scores are better. Ratings in red are particularly important to take note of, but any in yellow, particularly those that are close to a rating of 30 are also important in addressing soil health problems.

- **A rating of 30 or less indicates a *Constraint* and is color-coded red.** This indicates a problem that is likely limiting yields, crop quality, and long-term sustainability of the agroecosystem. In several cases this indicates risks of environmental loss as well. The "constraint" column provides a short list of soil processes that are not functioning optimally when an indicator rating is red. It is particularly important to take advantage of any opportunities to improve management that will address these constraints.
- **A rating between 30 and 70 indicates *Suboptimal* functioning and is color-coded yellow.** This indicates that soil health could be better, and yield and sustainability could decrease over time if this is not addressed. This is especially so if the condition is being caused, or not being alleviated, by current management. Pay attention particularly to those indicators rated in yellow and close to 30.
- **A rating of 70 or greater indicates *Optimal or near-optimal* functioning and is color-coded green.** Past management has been effective at maintaining soil health. It can be useful to note which particular aspects of management have likely maintained soil health, so that such management can be continued. Note that soil health is often high, when first converting from a permanent sod or forest. In these situations, intensive management quickly damages soil health when it includes intensive tillage, low organic matter inputs, bare soils for significant parts of the year, or excessive traffic, especially during wet times.
- **The Overall Quality Score** at the bottom of the report is an average of all ratings, and provides an indication of the soil's overall health status. However, the important part is to know which particular soil processes are constrained or suboptimal so that these issues can be addressed through appropriate management. Therefore the ratings for each indicator are more important information.

The Indicators measured in the Cornell Soil Health Assessment are important soil properties and characteristics in themselves, but also are representative of key soil processes, necessary for the proper functioning of the soil. The following is a summary of the indicators measured, what each of these indicates about your soil's health status, and what may influence the relevant properties and processes described.

A Management Suggestions Table follows, at the end of the report, with short and long term suggestions for addressing constraints or maintaining a well-functioning system. This table will indicate constraints identified in this assessment for your soil sample by the same yellow and red color coding described above. Please also find further useful information by following the links to relevant publications and web resources that follow this section.

Texture is an inherent property of soil, meaning that it is rarely changed by management. It is thus not a soil health indicator *per se*, but is helpful both in interpreting the measured values of indicators (see the Cornell Soil Health Assessment Training Manual), and for deciding on appropriate management strategies that will work for that soil.

Your soil's measured textural class and composition:
Silt Loam Sand: 33% Silt: 57% Clay: 10%

Available Water Capacity (AWC) is a measure of the porosity of the soil, within a pore size range important for water retention. Measured by the amount of water held by the soil sample between field capacity and wilting point by applying different levels of air pressure, the value is presented in grams of water per gram of soil. This value is scored against an observed distribution in regional soils with similar texture. A physical soil characteristic, AWC is an indicator of the amount of plant-available water the soil can store, and therefore how crops will fare in droughty conditions. Soils with lower storage capacity will cause greater risk of drought stress. AWC is generally lower when total organic matter and/or aggregation is low. It can be improved by reducing tillage, long-term cover cropping, and adding large amounts of well-decomposed organic matter such as compost. Coarse textured (sandy) soils inherently store less water than finer textured soils, so that managing for relatively high water storage capacity is particularly important in coarse textured soils. While the textural effect cannot be influenced by management, management decisions can be in part based on an understanding of inherent soil characteristics.

> **Your measured Available Water Capacity value** is **0.22 g/g**, corresponding with a score of **88**. This score is in the **High** range, relative to regional soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates proper soil functioning.** Please refer to the management suggestions table at the end of this document.

Surface Hardness is a measure of compaction that develops when large pores are lost in the surface soil (0-6 inches). Compaction is measured in the field using a penetrometer, and the resultant value is expressed in pounds per square inch (p.s.i.), representing the localized pressure necessary to break forward through soil. It is scored by comparison with a distribution observed in regional soils, with lower hardness values rating higher scores. A strongly physical characteristic of soils, surface hardness is an indicator of both physical and biological health of the soil, as growing roots and fungal hyphae must be able to grow through soil, and may be severely restricted by excessively hard soil. Compaction also influences water movement through soil. When surface soils are compacted, runoff, erosion, and slow infiltration can result. Soil compaction is influenced by management, particularly in timing and degree of traffic and plowing disturbance, being worst when the soil is worked wet.

> **Your measured Surface Hardness value** is **230 p.s.i.**, corresponding with a score of **25**. This score is in the **Low** range, relative to regional soils. **Surface Hardness should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Subsurface Hardness is a measure of compaction that develops when large pores are lost in the subsurface soil (6-18 inches). Subsurface hardness is measured and scored similarly to surface hardness, but deeper in the profile, and scored against an observed distribution in regional soils with similar texture. Large pores are necessary for water and air movement and to allow roots to explore the soil. Subsurface hardness prevents deep rooting and thus deep water and nutrient uptake by plants, and can increase disease pressure by stressing plants. It also causes poor drainage and poor deep water storage. After heavy rain events, water can build up over a hard pan causing poor aeration both at depth and at the surface, as well as ponding, poor infiltration, runoff and erosion. Impaired water movement and storage create greater risk during heavy rainfall events, as well as greater risk of drought stress. Compaction occurs very rapidly when the soil is worked or trafficked while it is too wet, and compaction can be transferred deep into the soil even from surface pressure. Subsoil compaction in the form of a plow pan is usually found beneath the plow layer, and is caused by smearing and pressure exerted on the undisturbed soil just beneath the deepest tillage operation, especially when wet.

> **Your measured Subsurface Hardness value** is **390 p.s.i.**, corresponding with a score of **15**. This score is in the **Low** range, relative to regional soils with similar texture. **Subsurface Hardness should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Aggregate Stability is a measure of how well soil aggregates or crumbs hold together under rainfall or other rapid wetting stresses. Measured by the fraction of dried aggregates that disintegrate under a controlled, simulated rainfall event similar in energy delivery to a hard spring rain, the value is presented as a percent, and scored against a distribution observed in regional soils with similar textural characteristics. A physical characteristic of soil, Aggregate Stability is a good indicator of soil biological and physical health. Good aggregate stability helps prevent crusting, runoff, and erosion, and facilitates aeration, infiltration, and water storage, along with improving seed germination and root and microbial health. Aggregate stability is influenced by microbial activity, as aggregates are largely held together by microbial colonies and exudates, and is impacted by management practices, particularly tillage, cover cropping, and fresh organic matter additions.

> **Your measured Aggregate Stability value** is **77.1%**, corresponding with a score of **93**. This score is in the **High** range, relative to regional soils with similar texture. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates proper soil functioning.** Please refer to the management suggestions table at the end of this document.

Organic Matter (OM) is a measure of the carbonaceous material in the soil that is biomass or biomass-derived. Measured by the mass lost on combustion of oven-dried soil, the value is presented as a percent of the total soil mass. This is scored against an observed distribution of OM in regional soils with similar texture. A soil characteristic that measures a physical substance of biological origin, OM is a key or central indicator of the physical, biological, and chemical health of the soil. OM content is an important influence on soil aggregate stabilization, water retention, nutrient cycling, and ion exchange capacity. OM acts as a long-term slow-release pool for nutrients. Soils with low organic matter tend to require higher inputs, and be less resilient to drought and extreme rainfall. OM is directly derived from biomass of microbial communities in the soil (bacterial, fungal, and protozoan), as well as from plant roots and detritus, and biomass-containing amendments like manure, green manures, mulches, composts, and crop residues. The retention and accumulation of OM is influenced by management practices such as tillage and cover cropping, as well as by microbial community growth. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease organic matter content and overall soil health with time.

> **Your measured Organic Matter value** is **3.0%**, corresponding with a score of **35**. This score is in the **Medium** range, relative to regional soils with similar texture. **This suggests that, while Organic Matter content does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Soil Proteins are the fraction of the soil organic matter that are present as proteins or protein-like substances. This represents the large pool of organically bound N in the SOM, which microbial activity can mineralize, and make available for plant uptake. Measured by extraction with a citrate buffer under high temperature and pressure (hence Autoclave Citrate Extractable, or ACE proteins), the value given is expressed in mg extracted per gram of soil. As the method used extracts only a readily extractable fraction of the total amount of soil proteins in the SOM, we present this value as an index rather than as an absolute quantity. A measure of a physical substance, protein content is an indicator of the biological and chemical health of the soil, and is very well associated with overall soil health status. Protein content, as organically bound N, influences the ability of the soil to make N available by mineralization, and has been associated with soil aggregation and water movement. Protein content can be influenced by biomass additions, the presence of roots and soil microbes, and tends to decrease with increasing soil disturbance such as tillage.

> **Your measured ACE Soil Protein Index value** is **6.1**, corresponding with a score of **43**. This score is in the **Medium** range, relative to regional soils. **This suggests that, while Soil Protein Content and Oranic Matter quality does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Soil Respiration is a measure of the metabolic activity of the soil microbial community. Measured by capturing and quantifying carbon dioxide (CO_2) produced by this activity, the value is expressed as total CO_2 released (in mg) per gram of soil over a 4 day incubation period. Respiration is scored against an observed distribution in regional soils, taking texture into account. A direct biological activity measurement, respiration is an indicator of the biological status of the soil community, integrating abundance and activity of microbial life. Soil biological activity accomplishes numerous important functions, such as cycling of nutrients into and out of soil OM pools, transformations of N between its several forms, and decomposition of incorporated residues. Soil biological activity influences key physical characteristics like OM accumulation, and aggregate formation and stabilization. Microbial activity is influenced by management practices such as tillage, cover cropping, manure or green manure incorporation, and biocide (pesticide, fungicide, herbicide) use.

> **Your measured Soil Respiration value** is **0.7 mg**, corresponding with a score of **62**. This score is in the **Medium** range, relative to regional soils with similar texture. **This suggests that, while Soil Microbial Community status does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.** Please refer to the management suggestions table at the end of this document.

Active Carbon is a measure of the small portion of the organic matter that can serve as an easily available food source for soil microbes, thus helping maintain a healthy soil food web. Measured by potassium permanganate oxidation, the value is presented in parts per million (ppm), and scored against an observed distribution in regional soils with similar texture. While a measure of a class of physical substances, active carbon is a good leading indicator of biological soil health and tends to respond to changes in management earlier than total organic matter content, because when a large population of soil microbes is fed plentifully with enough organic matter over an extended period of time, well-decomposed organic matter builds up. A healthy and diverse microbial community is essential to maintain disease resistance, nutrient cycling, aggregation, and many other important functions. Intensive tillage and lack of organic matter additions from various sources (amendments, residues, active crop or cover crop growth) will decrease active carbon, and thus will over the longer term decrease total organic matter.

> **Your measured Active Carbon value** is **440 ppm**, corresponding with a score of **25**. This score is in the **Low** range, relative to regional soils with similar texture. **Active Carbon should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Soil pH is a measure of how acidic the soil is, which controls how available nutrients are to crops. A physico-chemical characteristic of soils, pH is an indicator of the chemical or nutrient status of the soil. Measured with an electrode in a 1:1 soil:water suspension, the value is presented in standard pH units, and scored using an optimality curve. Optimum pH is around 6.2-6.8 for most crops (exceptions include potatoes and blueberries, which grow best in more acidic soil – this is not accounted for in the report interpretation). If pH is too high, nutrients such as phosphorus, iron, manganese, copper and boron become unavailable to the crop. If pH is too low, calcium, magnesium, phosphorus, potassium and molybdenum become unavailable. Lack of nutrient availability will limit crop yields and quality. Aluminum toxicity can also be a concern in low pH soils, which can severely decrease root growth and yield, and in some cases lead to accumulation of aluminum and other metals in crop tissue. In general, as soil OM increases, crops can tolerate lower soil pH. Soil pH also influences the ability of certain pathogens to thrive, and of beneficial organisms to effectively colonize roots. Raising the pH through lime or wood ash applications, and organic matter additions, will help immobilize aluminum and heavy metals, and maintain proper nutrient availability.

> **Your measured pH value** is **5.5**, corresponding with a score of **11**. This score is in the **Low** range, as the measured pH is very low. **Soil pH should be given a high priority in management decisions based on this assessment, as it is likely to be an important constraint to proper soil functioning and sustainability of management at this time.** Please refer to the management suggestions table at the end of this document.

Extractable Phosphorus is a measure of phosphorus (P) availability to a crop. Measured on a modified Morgan's extractant, using a rapid-flow analyzer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency or excess. P is an essential plant macronutrient, and its availability varies with soil pH and mineral composition. Low P values indicate poor P availability to plants, and excessively high P values indicates a risk of adverse environmental impact through runoff and contamination of surface waters. Most soils in the Northeast store unavailable P from the soil's mineral make up or from previously applied fertilizer or manure. This becomes more available to plants as soils warm up. Therefore, incorporating or banding 10-25 lbs/acre of soluble 'starter' P fertilizer at planting can be useful even when soil levels are optimum. Some cover crops, such as buckwheat, are good at mining otherwise unavailable P so that it becomes more available to the following crop. When plants associate with mycorrhizal fungi, these can also help make P (and other nutrients and water) more available to the crop. P is an environmental contaminant and runoff of P into fresh surface water will cause damage through eutrophication, so over-application is strongly discouraged, especially close to surface water, on slopes, and on large scales.

> **Your measured Extractable Phosphorus value** is **6.4 ppm**, corresponding with a score of **100**. This score is in the **High** range, as the extractable phosphorus level is within the optimal range for agronomic and environmental purposes. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates proper soil functioning.** Please refer to the management suggestions table at the end of this document.

Extractable Potassium is a measure of potassium (K) availability to the crop. Measured on a modified Morgan's extract using an ICP Spectrometer, the value is presented in parts per million (ppm), and scored against an optimality curve for sufficiency. K is an indicator of soil nutrient status, as it is an essential plant macronutrient. Plants with higher potassium tend to be more tolerant of frost and cold. Thus good potassium levels may help with season extension. While soil pH only marginally affects K availability, K is easily leached from sandy soils and is only weakly held by increased organic matter, so that applications of the amount removed by the specific crop being grown are generally necessary in such soils.

> **Your measured Extractable Potassium value** is **67.3 ppm**, corresponding with a score of **93**. This score is in the **High** range, relative to known plant response thresholds in similarly textured soils. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates proper soil functioning.** Please refer to the management suggestions table at the end of this document.

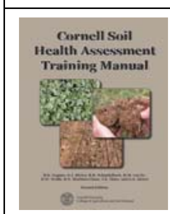
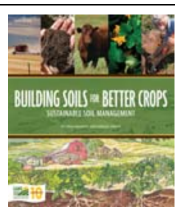
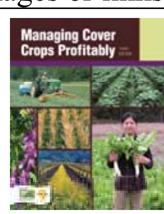
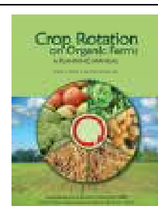
Minor Elements, also called secondary (calcium, magnesium and sulfur) and micro (iron, manganese, zinc, copper, boron, molybdenum, etc.) nutrients are essential plant nutrients taken up by plants in smaller quantities than the macro nutrients N, P and K. If any minor elements are deficient, this will decrease yield and crop quality, but toxicities can also occur when concentrations are too high. This assessment's minor elements rating indicates whether four measured micronutrients (magnesium, iron, manganese, and zinc) are deficient or excessive. Micronutrient availability is strongly influenced by pH and organic matter. Low pH increases the availability of most micronutrients, whereas high pH increases the availability of molybdenum, magnesium and calcium. High OM and microbial activity tend to increase micronutrient availability. Note that this test does not measure all important micronutrients. Consider submitting a sample for a complete micronutrient analysis to find out the levels of the other micronutrients.

> **Your Minor Elements Rating** is **100**. This score is in the **High** range. Magnesium (166 ppm) is sufficient, Zinc (1.9 ppm) is sufficient, Iron (4.2 ppm) is not excessive, and Manganese (6.6 ppm) is not excessive. **This suggests that management practices should be geared toward maintaining this condition, as it currently indicates proper soil functioning.** Please refer to the management suggestions table at the end of this document.

Overall Quality Score: an overall quality score is computed from the individual indicator scores. This score is further rated as follows: less than 40% is regarded as very low, 40-55% is low, 55-70% is medium, 70-85% is high and greater than 85% is regarded as very high. The highest possible quality score is 100 and the least score is 0, thus it is a relative overall soil health status indicator. However, of greater importance than a single overall metric is identification of constrained or suboptimally functioning soil processes, so that these issues can be addressed through appropriate management. The overall soil quality score should be taken as a general summary rather than the main focus.

> **Your Overall Quality Score** is **57**, which is in the **Medium** range.

Pathogen Pressure refers to the degree to which plants encounter potentially growth-limiting attack by disease causing organisms. This is a function not only of the presence of pathogens, but also of the compatibility between pathogens and the plants that are growing, and the environmental conditions and other microbial communities that are present at the time. It is an important aspect of soil health management to keep note of seed, seedling, and mature plant health and disease throughout the growing season. Practices to limit plant disease incidence and spread may include improved sanitation for tools and equipment, careful management of diseased plant residues, rotation with non-compatible or resistant crops and cover crops, limitation of environmental conditions that are conducive to disease spread, and fostering of beneficial and disease suppressive soil microbial communities. While one-size-fits-all pathogen pressure assays for lab testing of soils are difficult to devise, several relevant options for certain crops and pathogens are available. One such test particularly relevant to vegetable crops is offered as an add-on to the Cornell Soil Health Assessment, as a root pathogen pressure bioassay. See the website for details on this.
Root pathogenesis influences plant growth and also the effectiveness of roots, and more beneficial root associated microbiota, in their contribution toward other important soil health characteristics. Pathogen pressure is influenced by the rest of the microbial community and by soil physical and chemical characteristics, particularly those that can stress plants or make them more susceptible to pathogen attack, such as poor drainage, high compaction, or nutrient deficiencies.
Your measured Root Pathogen Pressure value is **4.9**, corresponding with a score of **51**. This score is in the **Medium** range, relative to regional soils. **This suggests that, while Root Pathogen Pressure does not currently register as a strong constraint, management practices should be geared toward improving this condition, as it currently indicates suboptimal functioning.**

Links to Relevant Publications and Web Resources				
Click on the images or links to access further relevant information				
 Manual	 BSBC	 CoverCrops	 Rotations	Cornell Soil Health Website NRCS Soil Health Website SARE Website SoilQuality.org Website NY Cover Crop Guide Midwest Cover Crop Guide
Questions? Please email soilhealth@cornell.edu				Subscribe to our email list

Management Suggestions for Physical and Biological Constraints		
Constraint	**Short Term Management Suggestions**	**Long Term Management Suggestions**
Available Water Capacity Low	• Add stable organic materials, mulch • Add compost or biochar • Incorporate high biomass cover crop	• Reduce tillage • Rotate with sod crops • Incorporate high biomass cover crop
Surface Hardness High	• Perform some mechanical soil loosening (strip till, aerators, broadfork, spader) • Use shallow-rooted cover crops • Use a living mulch or interseed cover crop	• Shallow-rooted cover/rotation crops • Avoid traffic on wet soils, monitor • Avoid excessive traffic/tillage/loads • Use controlled traffic patterns/lanes
Subsurface Hardness High	• Use targeted deep tillage (subsoiler, yeomans plow, chisel plow, spader.) • Plant deep rooted cover crops/radish	• Avoid plows/disks that create pans • Avoid heavy loads • Reduce traffic when subsoil is wet
Aggregate Stability Low	• Incorporate fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage • Use a surface mulch • Rotate with sod crops and mycorrhizal hosts
Organic Matter Low	• Add stable organic materials, mulch • Add compost and biochar • Incorporate high biomass cover crop	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Incorporate high biomass cover crop
Soil Protein Index Low	• Add N-rich organic matter (low C:N source like manure, high N well-finished compost) • Incorporate young, green, cover crop biomass • Plant legumes and grass-legume mixtures • Inoculate legume seed with Rhizobia & check for nodulation	• Reduce tillage • Rotate with forage legume sod crop • Cover crop and add fresh manure • Keep pH at 6.2-6.5 (helps N fixation) • Monitor C:N ratio of inputs
Root Pathogen Pressure High	• Use disease-suppressive cover crops • Plant on ridges/raised beds • Monitor irrigation • Biofumigate	• Use disease-suppressive cover crops • Increase diversity of crop rotation • Sterilize seed and equipment • Improve drainage/monitor irrigation
Respiration Low	• Maintain plant cover throughout season • Add fresh organic materials • Add manure, green manure • Consider reducing biocide usage	• Reduce tillage/mechanical cultivation • Increase rotational diversity • Maintain plant cover throughout season • Cover crop with symbiotic host plants
Active Carbon Low	• Add fresh organic materials • Use shallow-rooted cover/rotation crops • Add manure, green manure, mulch	• Reduce tillage/mechanical cultivation • Rotate with sod crop • Cover crop whenever possible

Management Suggestions for Chemical Constraints		
Constraint	**Short Term Management Suggestions**	**Long Term Management Suggestions**
pH Low	• Add lime or wood ash per soil test recommendations • Add calcium sulfate (gypsum) in addition to lime if aluminum is high • Use less ammonium or urea	• Test soil annually & add "maintenance" lime per soil test recommendations to keep pH in range • Raise organic matter to improve buffering capacity
pH High	• Stop adding lime or wood ash • Add elemental sulfur per soil test recommendations	• Test soil annually • Use higher % ammonium or urea
Phosphorus Low	• Add P amendments per soil test recommendations • Use cover crops to recycle fixed P • Adjust pH to 6.2-6.5 to free up fixed P	• Promote mycorrhizal populations • Maintain a pH of 6.2-6.5 • Use cover crops to recycle fixed P
Phosphorus High	• Stop adding manure and compost • Choose low or no-P fertilizer blend • Apply only 20 lbs/ac starter P if needed • Apply P at or below crop removal rates	• Use cover crops that accumulate P and export to low P fields or offsite • Consider low P rations for livestock • Consider phytase for non-ruminants
Potassium Low	• Add wood ash, fertilizer, manure, or compost per soil test recommendations • Use cover crops to recycle K • Choose a high K fertilizer blend	• Use cover crops to recycle K • Add "maintenance" K per soil recommendations each year to keep K consistently available
Micronutrients Deficient	• Add chelated micros per soil test recommendations • Use cover crops to recycle micronutrients • Do not exceed pH 6.5 for most crops	• Promote mycorrhizal populations • Improve organic matter • Decrease soil P (binds micros)
Micronutrients Excessive	• Raise pH to 6.2-6.5 (for all high micros except Molybdenum) • Do not use fertilizers with micronutrients	• Maintain a pH of 6.2-6.5 • Monitor irrigation/improve drainage • Improve soil calcium levels
High Salinity	• Leach soils • Use fertilizers with a low salt index (avoid chlorine and ammonium/urea fertilizers) • Do not use Chilean nitrate	• Test compost for soluble salts • Use electroconductivity meter to monitor salts in the soil and irrigation water • Improve drainage

Appendix B

Soil Health Management Process Worksheet

Soil Health Management Planning Process Worksheet

1. Determine farm background and management history

Compile background info: history by management unit, farm operation type, equipment, access to resources, situational opportunities or limitations.

2. Set goals and sample for soil health

Determine goals and number and distribution of soil health samples needed, according to operation's background and goals.

3. For each management unit: identify and explain constraints, prioritize

Soil Health Assessment Report identifies constraints and guides prioritization. Explain results based on background where feasible, and adjust priorities.

4. Identify feasible management options

Using the management suggestions table available as part of Soil Health Report, or online with NRCS practice linkages, identify which of these suggestions may be feasible for the operation.

5. Create short and long term Soil Health Management Plan

Integrate agronomic science of Steps 2. – 4. above with grower realities of Step 1. to create a specific short-term schedule of management practices for each management unit and an overall long-term strategy (see worksheet next page)

6. Implement, monitor, and adapt

Implement and document management practices. Monitor progress, repeat testing, and evaluate outcomes. Adapt plan based on experience and data over time. Remember that soil health changes slowly over time.

Step 5. Create short and long term Soil Health Management Plan

Date	Operation implemented	Constraint addressed	Notes
EXAMPLE: Aug 2015	Subsoil with yeoman's plow	Subsoil compaction	Choose appropriate soil moisture conditions

Long Term Directions to Pursue:

Cornell University
College of Agriculture and Life Sciences