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# FUNDAMENTALS OF SOIL HEALTH

*A simple method of estimating the success of any method of farming is to observe how it is affected by disease. If the soil is found to escape the two common ailments—erosion and the formation of alkali salts—which afflict cultivated land; if the crops raised are found to resist the various insect, fungous, and virus diseases; if the livestock breed normally and remain in good fettle; if the people who feed on such crops and livestock are vigorous, prolific, and more or less free from the many diseases from which mankind suffers; then the method of farming adopted is supported by the one unanswerable argument—success.—Sir Albert Howard, Soil and Health, 1947.*

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Healthy soil is the foundation of organic farming. While conventional agriculture focuses on feeding the plants by directly applying soluble mineral nutrients, organic farming focuses on feeding the soil microbial community so that the soil, in turn, can feed the plant. If the soil is healthy, the plants growing on it will be healthy. It's that simple.

The concept of soil health goes back to the 1940s, when the British plant scientist Sir Albert Howard was experimenting with composting in India. Howard noticed that farmers who kept their soil healthy by applying lots of manure and compost had very healthy plants that weren't troubled by pests or diseases, even though the farmers didn't spray pesticides. Conversely, plants that were severely damaged by pests or diseases were almost always grown on unhealthy, infertile soil.

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Howard believed that the agricultural science of his day had made a critical mistake in separating the study of insects and plant diseases from the study of soil. Rather than viewing pests as an enemy to be attacked with the latest chemical weapon, Howard called them "Nature's Censors"—symptoms of the underlying problem of unhealthy soil. If farmers focused on restoring soil health by adding organic matter and stimulating soil microbiology, crop "yield and quality will rapidly improve," Howard predicted. "Then there will be little disease in soil or crop or livestock, and the foundations of the preventative medicine of to-morrow will be laid."

It took over half a century for mainstream agricultural scientists to heed Howard's advice, but today soil health is an established principle in agronomy and soil science. USDA's Natural Resources Conservation Service (NRCS) defines soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." According to NRCS, healthy soil regulates water, sustains plant and animal life, filters and buffers potential pollutants, cycles nutrients, and provides physical stability and support.

How do you know if your soil is healthy? One way is by simply looking at the plants, like Howard did. If they are lush, green, productive, and not suffering much from pests or diseases, chances are the soil is healthy. Another good indicator is soil organic matter—usually soils rich in actively cycling organic matter are healthy. But if you want to dig deeper, Cornell University and NRCS have both developed frameworks to assess soil health by measuring an assortment of physical, chemical, and biological properties. The following summary of soil health properties is based on these frameworks, with some modifications to make it even more relevant to organic management.

## Physical Properties

The easiest soil properties to measure are physical ones: bulk density, penetration resistance, water infiltration, available water capacity, and aggregate stability. A healthy soil is composed of about 45 percent soil mineral particles (sand, silt, and clay), 5 percent organic matter, and 50 percent pore space. That's right—half of soil should be holes. Ideally, about half of those pores will be filled with water and half with air, both of which are vital to plant roots and soil microorganisms.

Bulk density is a way to measure if a given sample of soil has the right proportion of solids to pores. It's measured by oven drying a soil core sample, then dividing that weight by the volume of the core. Bulk density is affected both by soil texture (the proportion of sand, silt, and clay in the soil) and by management practices. Ideal bulk density varies based on the soil texture, but should be less than 1.4 $g/cm^3$ for a silt loam. Bulk density higher than 1.6 $g/cm^3$ in a silt loam indicates that plant roots will have difficulty penetrating deeply into the soil.

Penetration resistance is closely related to bulk density. It measures how much force it takes to push a penetrometer (a probe equipped with a pressure gauge) into the soil. The easier it is to push the penetrometer into the soil, the healthier the soil. If the penetrometer measures higher than 300 psi while being pushed into the ground, that means the soil is compacted. Plants grown in compacted soil will have stunted root growth and will suffer from water deficiency.

Water infiltration measures the rate at which water (from rain or irrigation) infiltrates into the soil. The faster the water infiltration, the healthier the soil. Infiltration is measured by pounding a metal ring or an infiltrometer into the ground, pouring in a measured volume of water, and timing how long it takes that water to infiltrate into a thoroughly saturated soil. Again, water infiltration rates will vary depending on soil texture, but an ideal steady-state infiltration rate in a saturated loam soil is 0.2-0.4 in/hr.

Available water capacity measures a soil's ability to store water. It's measured in the lab by using high-pressure chambers to extract soil water to two different thresholds—field capacity (the highest amount of water a soil can hold without it draining out by gravity) and permanent wilting point (where the remaining water is in micropores that are inaccessible to plant roots). The difference between the two is the amount of water that is available for plant uptake. Healthy soils should have an available water capacity of at least 0.2 grams of water per gram of soil.

Aggregate stability is a measure of how well soil aggregates hold up under rainfall. This is an important indicator of soil health because if the aggregates fall apart when they get wet, the soil will crust at the surface and water will run off rather than infiltrate. Aggregate stability is tested using a raindrop simulator, which drips water onto oven-dry soil at a rate equivalent to a severe thunderstorm. In a healthy soil, at least 60 percent of the aggregates will survive intact after five minutes of simulated rainfall.

## Chemical Properties

Chemical soil tests have traditionally been used to determine fertilizer recommendations, which often do not take into account soil health or biological nutrient cycling. However, =chemical tests can also be used as indicators of soil health. The difference is how they are interpreted—instead of indicating a need for soluble fertilizer, low levels of most nutrients indicate that something is out of whack in the soil—maybe there isn’t enough actively cycling organic matter, or maybe the pH is too low or too high. A healthy soil will usually have adequate levels of plant available nutrients.

Plant available nutrients include phosphorus, potassium, calcium, magnesium, iron, manganese, zinc, and copper. Most soils contain large quantities of all essential plant nutrients within the soil particles themselves, but in forms that are unavailable for plant uptake. Typical nutrient tests use an extractant (most commonly Mehlich 3 solution) that dissolves a similar amount of soil minerals as plants are able to extract from the soil. Healthy soil should have at least 50 ppm of available potassium, about 20 ppm available phosphorus, and adequate amounts of trace minerals.

Soil pH is one of the most important physical properties because it affects the availability of other nutrients. It is measured by mixing soil with water, letting the solution settle, and measuring the pH of the water with an electronic pH meter.

Healthy soils will have a pH between 6.5 and 7.5. If the pH is below 6.5, the soil is too acidic; if it is above 7.5, it is too basic. Both conditions can negatively impact plant growth.

Soil salinity can be a problem in semiarid or arid irrigated areas, especially when the irrigation water contains even low levels of salts. Soil is prepared for a salinity test in the same way as for a pH test, except that the water is measured with an electroconductivity meter. An electroconductivity higher than 1 dS/m can start to impact sensitive crops like alfalfa and potatoes, and even relatively salt-tolerant plants like wheat will suffer if the electroconductivity exceeds 3 dS/m.

## Biological Properties


Soil health, especially in an organic system, is driven mainly by biology. A healthy soil will be rich in organic matter, actively cycling carbon, and all sorts of organisms. Quantifying this soil life is more challenging than quantifying physical or chemical properties, and soil labs are constantly developing ever-more-elaborate tests for soil microbial diversity and function. But the following tests serve as good indicators of healthy soil, even though they don't differentiate between different kinds of soil organisms.

Organic matter is probably the most important single indicator of soil health. Soils high in organic matter usually score well on other indicators, including aggregate stability, water infiltration, bulk density, and available nutrients. Soil organic matter is measured using the loss on ignition (LOI) test, where oven-dried soil is weighed, put in an oven to burn off the organic matter, and weighed again. Healthy soils will have at least 5 percent organic matter, sometimes much more.

Active carbon measures the percent of soil organic matter that is immediately available for active nutrient cycling by soil microorganisms. It correlates with particulate organic matter, which includes all organic matter particles smaller than 2 mm and greater than 0.053 mm in diameter. The test for active carbon, which is quicker and easier than the test for particulate organic matter, involves mixing soil with a potassium permanganate solution and measuring the absorbance value of the solution. A healthy soil should have a minimum of 700-800 ppm active carbon.

Potentially mineralizable nitrogen is a measure of the nitrogen that can be readily mineralized by the soil microbial community into plant-available ammonium. It is calculated by measuring the ammonium concentration in a soil solution immediately after collection and then again after incubating the soil for seven days. A healthy soil should measure at least 11-12μg of nitrogen per gram of soil dry weight after a week.

Soil protein index is a measurement of how much nitrogen is contained in proteins, nucleic acids, and other easily degradable molecules in the soil. Proteins are extracted from the soil with a sodium citrate buffer, centrifuged, and mixed with a reagent that turns the solution varying shades of purple based on the protein concentration. A healthy soil should have a protein index of at least 8-10 mg protein per gram of soil.

Soil respiration measures the amount of carbon dioxide released by soil microbes. It is measured by re-wetting air-dried soil and keeping it in a closed jar for four days with a test tube containing a potassium hydroxide (KOH) solution. The KOH solution absorbs all the carbon dioxide respired by soil microorganisms, which is measured using an electroconductivity meter. A healthy soil should respire 1 mg $CO_2$ per gram of dry soil over the four-day period.

Root health assessment measures the presence of pathogens in the soil using bean plants, which are susceptible to many of the common plant diseases. Bean seeds are planted in a sample of the soil and grown for four weeks, after which the roots are examined for lesions and other pathogen damage. Bean plants grown in healthy soil will have thick, light-colored roots with few or no lesions.

## How to Improve Soil Health

If your soil scores high on most or all of the soil health assessment properties, congratulations! Your management practices must be conducive to soil health. If your score isn't so great, don't panic. There are many tried-and-true ways of restoring degraded soils back to health.

Increase soil organic matter. This is the most important step for rebuildingdegraded soils. Almost all of the physical, chemical, and biological properties measured in the soil health assessment are improved when soils are high in active, cycling organic matter. Organic matter includes both the living organisms in the soil (plant roots, fungi, earthworms, arthropods, bacteria, actinomycetes, protozoa) and humus (the decaying remains of once-living organisms). Maintaining high levels of both soil organisms and humus is essential for soil health, and the best way to do this is to make sure that fresh organic matter is constantly added to the soil. This can be done by spreading manure or compost, leaving residues from harvested crops on the field, and growing green manure and cover crops.

Keep living plants on the soil as much as possible to maintain a healthy soil microbial community. Plant roots exude sugars and other molecules that feed soil microbes, which in turn provide essential nutrients to the plants. One of the most-studied plant-microbe interactions is the mycorrhizal relationship, where fungi grow around and within plant roots and exchange phosphates for sugars. Because these microbes depend on living plant roots for their survival, it's important to keep living plants on the soil for as much of the growing season as possible. If a crop is harvested early in the season, plant a cover crop to tide the microbes over until it's time for the next production crop in the rotation.

Keep the soil covered. Ecologist Paul B. Sears said in his 1935 book Deserts on the March, "Mother Earth is a staid and dignified old lady, no nudist by choice." There is no bare soil in nature. The ground in natural ecosystems is always covered, whether by growing plants, fallen leaves, or even a microbial crust. Weeds are just Mother Earth's attempt to be modest—if you don't like her choice of attire, give her something else to wear. Keep the soil covered with growing plants, crop residues, or mulch. That will keep the soil cool, moist, and hospitable to those essential soil microbes.

Minimize tillage. This goes hand-in-hand with keeping the soil covered and keeping living roots in the soil. When soil is broken apart by tillage—especially with a soil-inverting moldboard plow—a degradation in almost all soil health properties usually results. But using broad-spectrum herbicides like glyphosate to control weeds, as is done in conventional no-till, also harms the soil microbial community and is not allowed in organic farming anyways. So it's a balancing act to use as little tillage as possible, while still managing weeds and creating suitable conditions for crop growth. If it's necessary to till, use a conservation tillage implement like a chisel plow that stirs rather than inverts the soil, and try to keep at least 30-40 percent of the soil surface covered with residues. Keep cultivation to a minimum using mulches, cover crops, and intercropping.

Grow a diversity of plants. There are no monocultures in nature. Natural ecosystems contain dozens or even hundreds of different plants. While agriculture is inevitably going to be a simpler ecosystem than a forest or meadow, it's still best to avoid huge fields of just one kind of plant, especially if that same plant is grown more than one year in a row. A good crop rotation should intersperse row crops (corn and soybeans) with small grains (wheat and oats) and forages (legumes and grass). Wildflower strips on the edges of fields can provide habitat for beneficial insects, as can riparian buffers and filter strips of native grassland vegetation. A farm with a diversity of crops in the fields is a more pleasant place for people to live, too.

## For More Information

For details on which crop rotations and tillage practices are best in your region, contact your local state experiment station and organic farming organization. Most of the information in this paper is adapted from the following sources, which are good overall resources for soil health information:


Howard, Sir Albert. Soil and Health: A Study of Organic Agriculture. Schocken, 1975.
Moebius-Clune, B.N., D.J. Moebius-Clune, B.K. Gugino, O.J. Idowu, and R.R. Schindelbeck et al. Comprehensive Assessment of Soil Health – The Cornell Framework, edition 3.2. Cornell University, 2016. https://soilhealth.cals.cornell.edu/manual/

USDA-NRCS. "What Is Soil Health?" https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/soils/soil-health


 