Oregon State University Extension Service

Understanding Soil Health and Biota for Farms and Gardens

Shikha Singh, Linda Brewer and Scott Lukas

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Soil biota refers to the microorganisms, soil-dwelling animals and plants that live all or part of their lives in the soil.

Credit: Mayatnikstudio, Adobe Stock Image

Soil – a foundational resource

Together with sunlight, water and air, soils are the foundation of life on Earth. Soils link plants, the atmosphere, agriculture, food security, our health, the economy and the environment.

Federal soil management strategies in response to the 1930s Dust Bowl (Figure 1) largely focused on physical and chemical properties that reduce wind and water erosion.

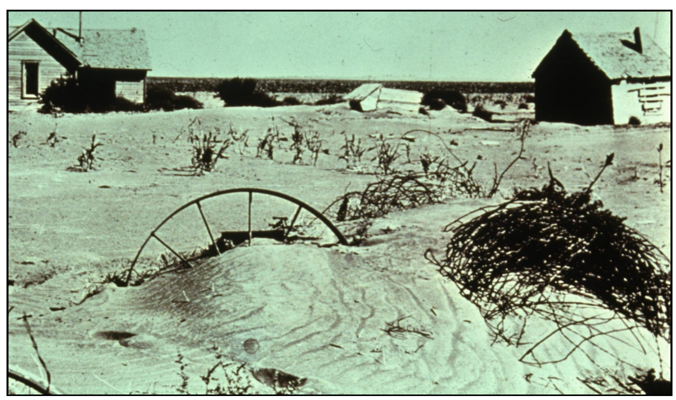

Figure 1. The Dust Bowl of the 1930s prompted federal action that gave rise to the Natural Resources Conservation Service.

Credit: Oregon State University

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Soil characteristics are the sum of physical, chemical and biological interactions in the soil as they are impacted by climate and management (Figure 2). The term soil biota refers to the microorganisms, soil-dwelling animals and plants that live all or part of their lives in the soil. Soil biota contributes to sustainable soils and ecosystem services. A diverse soil biota provides organic soil decomposition, nutrient cycling and carbon sequestration and determines the arrangement of sand, silt and clay in the soil.

This publication explores soil health by focusing on the activity, influence and management of soil biota.

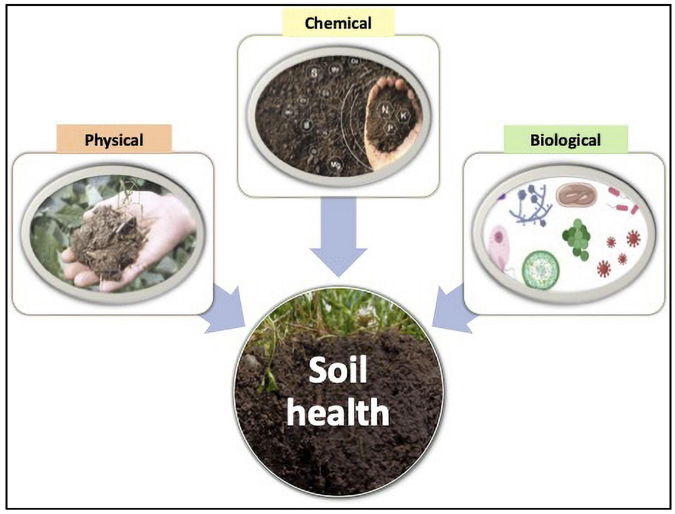

Figure 2. Components of the soil.

Credit: Shikha Singh

Soil health indicators

Soil health indicators are measurable physical, chemical and biological properties that correspond to soil processes and functions. Soil health indicators must be identified according to specific local soil characteristics and environmental conditions.

Soil components

Soil organic matter includes living and nonliving components, such as manure and plant and animal tissues. The carbon in microbial cells is one example of a living component. Humic material, which is the product of decomposed plant and animal residues, is part of the nonliving component. Soils store the most resistant forms of humic materials for decades or centuries.

Evaluating soil health

Soil health can be evaluated as three broad components: physical, chemical and biological properties. The structure and aggregation of soils that affect aeration and drainage are physical components. The chemical component includes a measure of the soil's ability to hold positively charged ions (known as its cation exchange capacity), plant nutrients and pH. The biological component is the organisms that live in the soil.

Physical indicators of soil health

Texture, bulk density, porosity, soil structure and aggregate stability

Soil physical properties play a vital role in water movement, runoff and retention. Typically, soil organic matter and soil microbes influence these physical indicators. Likewise, soil air and water content determine microbial community makeup and activity. Root secretions, called exudates, cement soil particles together. They are sticky mucilages produced by most plants. They can also be byproducts of cellular decomposition. The aggregates formed influence how soils store and drain water.

- Soil texture is the percentage of sand, silt and clay making up the soil. It does not change in response to agricultural management practices or soil organic matter content.
- Bulk density is the mass of a given volume of a heterogeneous and often porous system. A soil with more void spaces — and thus better aeration and drainage — weighs less because more of its volume is empty space. Compacted soil or soil with fewer void spaces will weigh more per unit volume and will have reduced aeration and drainage. Densely compacted soils can hinder plant root growth. Bulk density may respond to agricultural management practices.
- Total soil porosity is the percentage of a soil volume that is not taken up by minerals or organic matter. Soil texture, bulk density and organic matter content determine total soil porosity and the capacity of soils to store water. Porosity responds to agricultural management practices.
- Soil structure is described by the shapes and sizes of aggregates or crumb structure. Structure influences soil drainage, water retention and aeration.
- Soil aggregate stability measures the soil's resistance to mechanical stress. Soils with greater aggregate stability are more resistant to erosion by wind or water. Glues and mucilage — byproducts of microbial and plant metabolism — contribute to aggregate stability. Soil aggregation influences void spaces, aeration, drainage and nutrient retention and provides habitat for soil biota.

The birth of the NRCS

The Soil Conservation Service was established in 1935 in response to the Dust Bowl. This federal agency was renamed in 1994 to the Natural Resources Conservation Service (NRCS). The NRCS provides resources to farmers and landowners to aid their conservation efforts.

Chemical indicators of soil health

Soil pH, cation exchange capacity and available nutrients

Soil health is related to the soil's capacity to provide nutrients for plant uptake and growth. Soil pH (how basic or acidic it is), cation exchange capacity (a measure of the soil's ability to hold positively charged ions), and available nutrient levels are some chemical indicators of soil health.

- Soil pH impacts the availability of plant nutrients. Near a pH of 7 (neutral), nutrients become more available to roots. If the soil pH is too low (acidic) or too high (alkaline), plant nutrients become less available to plants. At extremes of pH, some plant nutrients become toxic to plants. Individual plant species vary in their tolerance to soil pH.
- Cation exchange capacity is the ability of soils to retain and release cationic (positively charged) plant nutrients, such as ammonium, calcium, magnesium and potassium. The negative charges of soils attract and hold the positively charged plant nutrients (cations) with enough force to prevent their leaching while allowing an easy exchange with plants. Sandy soils have a lower cation exchange capacity than clay soils. Adding organic matter increases the capacity of any soil to attract and retain positively charged plant nutrients. A soil with a higher cation exchange capacity can retain more nutrients for plant use.
- Soil organic matter influences nutrient retention in soils. Organic matter cycling by soil microorganisms transforms organically bound nutrients into forms available to plants.

Biological indicators of soil health

Soil microbial biomass, microbial diversity, microbial respiration and microbial enzymes

Soil biota is key to nutrient cycling and continued plant and microbial nutrition (Figure 2). In agricultural systems, management practices affect microbial activity.

- Soil microbial biomass (the total weight of fungi, bacteria, protozoa and other microbes) is an important biological indicator of soil health.
- Soils with diverse microbiology are more resilient to disturbance and stress, such as drought. These soils have the capacity to rebound toward their original state despite changes due to management practices and soil disturbance.
- Soil respiration is the rate at which soil microbes consume carbon structures and release carbon dioxide. It indicates biological and microbial activity, decomposition, microbial activity, decomposition and soil health.
- Microbial enzymes play a critical role in decomposing organic matter into plant-available nutrients. Lower enzyme activity indicates a reduced rate of decomposition and reduced plant-available nutrients.
- Soil organic matter is a key soil component and an indicator of soil health. Soil microbes feed on organic matter. Organic matter includes living and dead organisms in soils, dead and decaying plant material, root exudates, humus and simple and complex carbon-rich molecules. Soil organic matter influences all the physical, chemical and biological properties of soil.
- Other biological indicators of soil health include the ratio of soil fungi to soil bacteria, mycorrhizal abundance and composition, presence or absence of bacterial and fungal pathogens, and abundance of bacteria associated with the root zone.

Environmental changes and soil management practices like liming and tillage alter soil biota. These shifts can also result from climatic change, drought, extensive wildfires or changing rainfall patterns. Microbial activity and shifts in microbial communities are site- and context-specific soil health indicators. Thus, shifts in soil activity and community at a specific site are relevant. Comparisons between different sites are not.

The effect of tillage

Tillage produces a measurable increase in carbon dioxide above the soil surface. This is because tillage introduces oxygen into the soil. Highly efficient aerobic bacteria break carbon bonds in organic matter and release carbon dioxide as a byproduct. This is one example of microbial respiration.

Did you know?

Soils in perennial systems, such as forests or orchards, tend to be dominated by fungi. Soils in annual systems, such as grains or vegetables, tend to be dominated by bacteria.

Soil is a living system

“A healthy soil has the continued capacity to function as a vital living system, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health.”

— adapted from the National Resources Conservation Service

Members of soil biota

Soil biota includes all living things in the soil. Some are easily seen with the naked eye, but others are not. Here are some of the soil community's principal members and their roles.

Bacteria: Bacteria are the most abundant soil microbes (Figure 3). These single-celled, mobile organisms thrive in thin water films surrounding soil particles and plant roots. They reproduce asexually. They are classified by shape, oxygen tolerance, food source and response to specific stains.

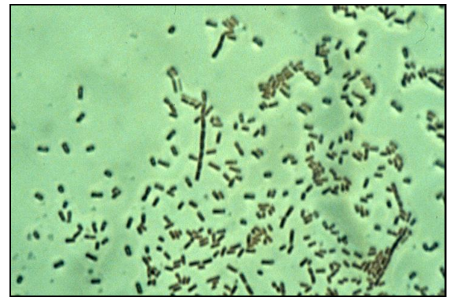

Figure 3. An acre of soil may house many billions of bacterial cells in the top 6-inch layer.

Credit: Natural Resources Conservation Service

Bacteria have at least one of four roles:

1. **Decomposers:** By releasing enzymes, these bacteria break organic matter into simpler compounds and make nutrients available to plants. These bacteria consume simple root exudates and more complex fresh plant residues. Decomposition promotes plant nutrient availability and environmental health.
2. **Mutualists:** These bacteria work in partnership with plants. Each member of the partnership benefits from the relationship. For example, the nitrogen-fixing mutualist bacteria in legume roots provide the plant with nitrogen in exchange for shelter and sugars from the plant.
3. **Pathogens:** Some bacteria cause plant disease. One example of pathogenic bacteria is *Pseudomonas solanacearum*, which causes bacterial wilt in potatoes.
4. **Lithotrophs (rock-eaters) or chemoautotrophs:** These bacteria gain their energy from compounds of nitrogen, sulfur, hydrogen or iron instead of carbon compounds. They are active where there is little sunlight, such as deeper in the soil or in aquatic systems. Sulfur-oxidizing bacteria and methane-producing bacteria are two examples. Where oxygen is limited, they play an important role in plant nutrient cycling, nutrient availability and decomposition.

Elements of soil health

Researchers have proposed many indicators to determine soil health. The Soil Health Institute identified a set of focal indicators to measure soil health, including:

- **Soil organic matter**, which impacts water and nutrient retention in soils, soil structure and soil microbial communities.
- **Carbon mineralization potential**, which shows the soil's microbial activity. Microbes convert organic matter into inorganic structures (mineralization) and influence the arrangement of sand, silt and clay in the soil (soil aggregation). These inorganic structures influence plant nutrients and ecosystem resilience.
- **Aggregate stability** measures soil aggregates' breakage resistance — how strongly soil particles adhere to one another. Higher aggregate stability promotes better resistance to erosion, improved root growth, nutrient retention and drainage. A smartphone app called Slakes measures aggregate stability using the phone's camera. It provides coefficients that indicate soil aggregate stability.

Actinobacteria: Like fungi, these bacteria grow hyphae (Figure 4). They are responsible for the earthy smell released by disturbed soils. Actinobacteria produce many antibiotics. They specialize in decomposing structural carbohydrates such as lignin, chitin, cellulose and other long-chain molecules that are difficult to decompose.

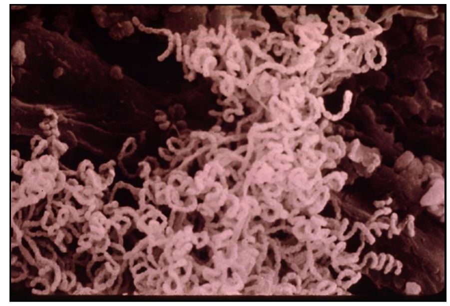

Figure 4. Actinobacteria grow hyphae-like fungi.

Credit: Natural Resources Conservation Service

Fungi: Fungi are both unicellular and multicellular organisms. They are immobile and may undergo sexual or asexual reproduction. Fungi reproduce by spores — the equivalent of seeds in plants.

They produce threads called hyphae. In soils, hyphae grow between soil particles and around or into roots (Figure 5). They can be assigned at least one of four roles:

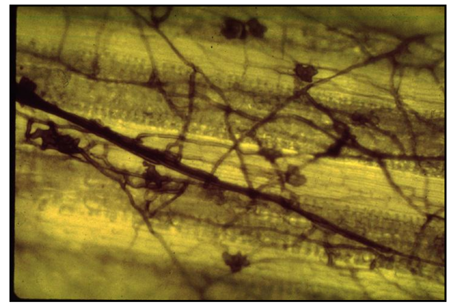

Figure 5. Fungi extend the functional reach of plant roots.

Credit: Natural Resources Conservation Service

1. Decomposers: Like actinomycetes, fungi break down complex structural carbohydrates such as lignin, chitin and cellulose.
2. Biological controllers and regulators: Some fungi regulate diseases and pests. Fungal hyphae form mesh-like structures that contribute to soil aggregation and structure formation.
3. Mutualists: Mycorrhizal fungi form symbiotic associations with plant roots and extend the functional reach of roots (Figure 6). These beneficial fungi concentrate scarce nutrients and water and transfer them to plants. In exchange, the mycorrhizal fungi receive plant root exudates as food. Mycorrhizal fungi may live on the outside of plant roots (Figure 7) or they may extend their hyphae into and between the cells of plant roots (Figure 8).
4. Pathogens: Fungi cause many plant diseases of economic importance. For example, *Fusarium solani* causes wilts and rots in potatoes.

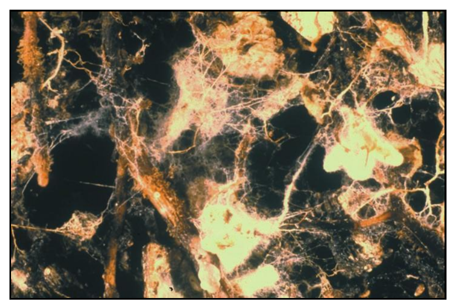

Figure 6. Plants benefit from a close relationship with mycorrhizal fungi.

Credit: Natural Resources Conservation Service

The common mushroom is the fruiting body of a much larger underground network of fungal biomass (Figure 9).

Protozoa: These single-celled organisms feed on dead and decaying microbes in the soil. They release plant-available nitrogen (Figure 10).

Nematodes: These cylindrical roundworms are abundant in soils. Many are predatory and feed on soil bacteria and fungi. Like protozoa, they also excrete plant-available nutrients (Figure 11). Some nematodes are plant pathogens or spread plant diseases.

Did you know?

Each ton of soil organic matter decomposed by microbes may yield as much as 220 pounds of nitrogen, 33 pounds of phosphorus and 33 pounds of sulfur in plant-available forms.

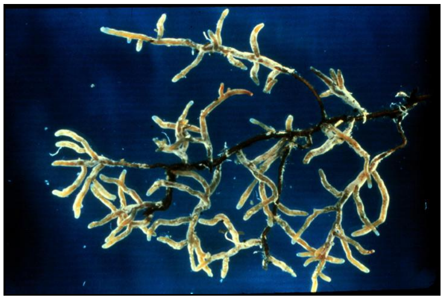

Figure 7. Ectomycorrhizal fungi form a netting around the exterior of a plant's root.

Credit: Natural Resources Conservation Service

Figure 8. The hyphae of this mycorrhizal fungus emerge from plant roots.

Credit: Natural Resources Conservation Service

Figure 9. The mushroom is a fungal fruiting body.

Credit: Natural Resources Conservation Service

Earthworms: These ecosystem engineers turn soils and increase soil fertility with their castings. Earthworms pull organic matter below the soil surface, where it becomes available to other decomposer organisms, and bring soil particles from deeper soil layers toward the surface. This activity may change the soil texture in the affected soil horizons. Their burrowing creates soil pores, which improve soil aeration and drainage and reduce soil compaction (Figure 12).

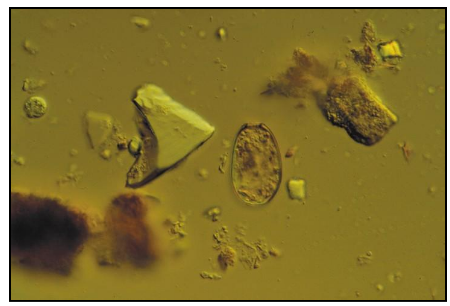

Figure 10. Protozoa (large oval organism at center) feeds on bacteria.

Credit: Natural Resources Conservation Service

Arthropods: Spiders are the most familiar arthropods; some are soil-dwelling. In soil systems, arthropods, such as millipedes, centipedes, symphylan, springtails and mites (Figures 13, 14, 15, 16, 17 and 18), may be pests that feed on plants. However, they perform beneficial functions as well. They shred organic matter and make bacterial enzymes more efficient. They can stimulate the activity of other soil microbes. Their activity may enhance soil aggregation and water-holding capacity. Their burrowing mixes soils to increase porosity and reduce compaction. Arthropods feed on soil pests and reduce their populations.

Figure 11. Not all nematodes cause plant disease or damage. They feed on bacteria, fungi, protozoa and other nematodes, recycling plant nutrients as they do so.

Credit: Natural Resources Conservation Service

The role of rhizospheric microbes in plant growth

The rhizosphere is a zone surrounding plant roots. Many microbes are present in the rhizosphere.

Figure 12. Earthworms promote soil health by pulling organic matter under the soil surface, burrowing and improving air and water flow in the soil. Their castings enrich the soil and contribute to soil aggregation.

Credit: Natural Resources Conservation Service

Figure 13. Millipedes shred dead plant matter as they feed on fungi and bacteria. These smaller particles are more readily broken down by other soil food web members.

Credit: Whitney Cranshaw, Bugwood

Figure 14. Centipedes are predators that feed on soft-bodied soil organisms.

Credit: Natural Resources Conservation Service

Figure 15. The symphylan is a close cousin of the centipede. They feed on plant roots but only become problematic when their numbers explode.

Credit: Natural Resources Conservation Service

Figure 16. The springtail is an arthropod that feeds on fungi and bacteria on plant roots. The nutrients they recycle become available to plants.

Credit: Natural Resources Conservation Service

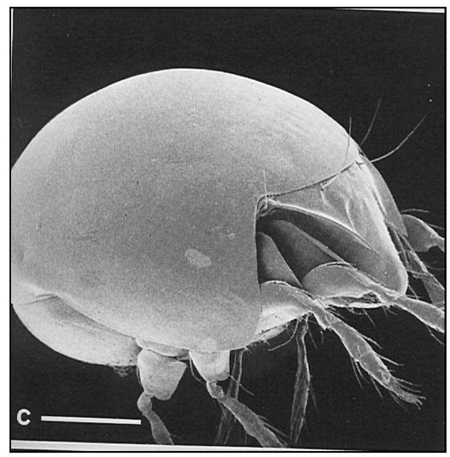

Figure 17. The oribatid turtle-mite is a micro-arthropod that feeds on fungi associated with plant roots.

Credit: Natural Resources Conservation Service

They are attracted to exudates secreted by plant roots that are a food source. They perform the following functions:

- Microbes living in the rhizosphere convert nutrients to plant-available forms.
- Some rhizospheric microbes chelate metals. Chelation is the bonding of ions and molecules with metal ions. Metal-containing chelates improve plant availability of metallic nutrients and can inhibit the action of plant pathogens.
- Microbes that live in the rhizosphere produce plant growth hormones that regulate cell division, cell growth and cell differentiation in plants.
- They convert mineral sources, including nitrogen, sulfur, carbon, phosphorus and metals, into water-soluble forms available to plants.
- They reduce environmental stress on plants, buffering against soil disturbance.

- Rhizosphere-dwelling microbes contribute to ecosystem stability and resilience to natural and human-caused disturbances. Maximizing the benefits of rhizospheric microbes may reduce the chemical inputs required for crop production.

Fostering microbes in the soil

Soil microbes play many roles in the ecosystem and impact crop productivity. Agricultural management impacts soil microbes. Sustainable farming practices improve the biological fertility of soils because they support diverse microbial populations. These diverse populations are more effective at converting essential nutrients into plant-available forms. Here are some other key points:

- A diverse microbial community can make the soil more resilient to environmental disturbance. However, higher diversity does not always mean better soil health. All plants support a unique set of soil microbes. Therefore, crop diversification is one way to support and diversify the soil microbial community. If circumstances disfavor one group of soil microbes, a diverse community is more likely to include other members that will step into the roles of the disfavored members.
- Crop rotation and intercropping with legumes or cover crop mixtures support greater soil microbial diversity. Annual intercrops rapidly produce root exudates that feed diverse soil communities.
- Reduced-tillage or no-till systems and increased organic matter inputs support microbial diversity. Organic matter additions become food for soil microbes. Reduced- and no-till systems protect soil fungi and larger biota, such as earthworms. They protect long-term carbon pools from consumption by other soil microbes.
- Chemical inputs may disrupt the soil microbial community. Greater soil organic matter and nutrient cycling and availability, better soil structure and aggregation and increased water retention contribute to plant resilience under drought stress. Such systems tend to remain more stable over time.
- Soil disturbance breaks down soil structure and microbial habitats. These habitats shelter microbes from predation and varying soil, water and air conditions. Soil disturbance introduces oxygen into the soil and increases microbial respiration of soil carbon. Soil disturbance discourages fungal growth.
- Mulching moderates soil temperature and moisture. It protects soil from solar energy and acts as a blanket to reduce water evaporation. As it decays, mulch becomes fodder for the soil microbial community, contributes plant nutrients and increases soil carbon storage.
- The rhizobacteria and mycorrhizal fungi that promote plant growth can be introduced by inoculation of soil or seed. Soil or foliar sprays can also introduce these fungi. Inoculum carriers like biochar can deliver beneficial microbes to the soil system.

The many features and functions of soil microbes influence soil health and promote plant growth. Shifting your practices to maintain and increase beneficial microorganism populations may promote more sustainable and productive cropping systems.

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About the authors

Shikha Singh

Assistant Professor Department of Crop and Soil Sciences Lind Dryland Experiment Station

Washington State University

Linda Brewer (https://horticulture.oregonstate.edu/users/linda-brewer)

Senior Faculty Research Assistant II, Department of Horticulture

Scott Lukas (https://extension.oregonstate.edu/people/scott-lukas)

Horticulture