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Soil Health: What Is It and Why Is It Important?

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Introduction

HEALTHY SOILS ARE THE FOUNDATION of productive, profitable, and sustainable farming systems. They are complex, living ecosystems that support plants, animals, and humans (United States Department of Agriculture-Natural Resources and Conservation Service n.d.). The ability to maintain soil health (and thus to sustain the health of those dependent on it) are key features. Indeed, soil with these characteristics make vigorous plant growth possible and allow it to provide habitat for soil organisms, nutrient cycling, and water storage and filtration. In turn, soil's physical, chemical, and biological properties can be altered by management practices, leading to either improved or degraded soil functioning. This bulletin discusses these basic concepts by describing the functions of healthy soil and illustrating their importance in maintaining sustainable and functioning agricultural systems.

Soil Health 101

To understand soil health, we must first describe what soil is. Soils are made up of roughly 45% mineral material, 25% air, and 25% water, with the remaining 1%–5% organic matter (OM). The OM portion is made up of living organisms as well as other organic materials, such as plant residues and soil organisms, which are in various stages of decomposition and breakdown. Although OM only makes up a small percentage of soil volume (2%–5% in average agricultural soils, and on the lower end of the spectrum in southern Idaho soils), its importance to soil health is disproportionately high. Soil OM provides a reservoir of plant nutrients, aids in soil aggregation, increases water holding capacity and infiltration, and reduces both compaction and crusting. Living organisms, which are included in the OM pool, are also key to the functioning of healthy soils and play a significant role in these functions. Ultimately, all functions of healthy soil are tied in some way to OM. Management practices that create or maintain OM generally increase soil health. Specific practices that improve soil health fall into five broad categories: minimizing disturbance, keeping soil covered, maintaining living roots, increasing biodiversity, and incorporating livestock when possible (USDA-NRCS). These five soil health principles affect many of the soil's physical, chemical, and biological properties.

Table 1. Soil properties and their categorization.

Physical	Biological	Chemical
Structure	Soil organisms	pH
Texture	Organic matter	Plant nutrients
Color	Mineralization and immobilization of nutrients	Base saturation
Porosity		Salinity
Temperature		Cation exchange capacity
Aggregate stability		

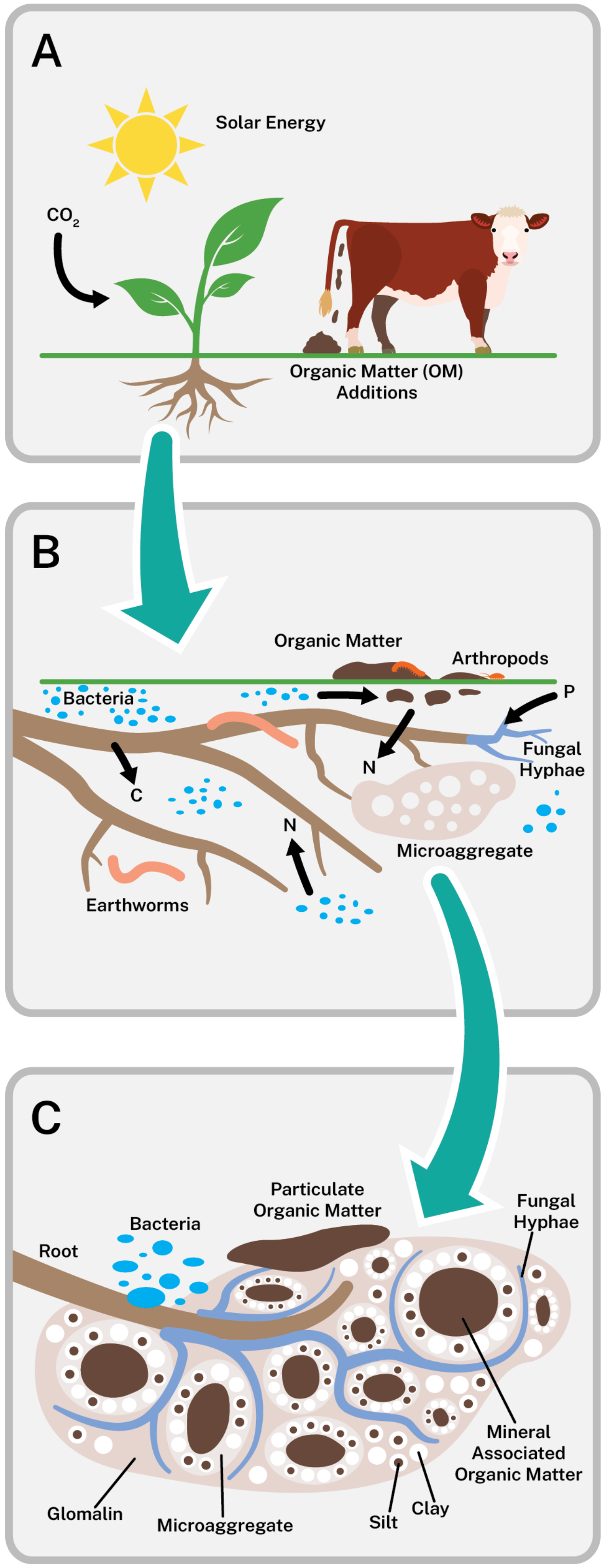

Figure 1. How soil aggregation is created. Plant roots and cattle manure add organic matter (**A**), soil organisms decompose organic additions and form macro- and microaggregates (**B**), and microaggregates are bound together by different types of organic matter, fungal hyphae, and roots (**C**).

Healthy soils provide invaluable services that are not only integral to maintaining ecosystem performance but also to the sustainable production of food, fuel, and fiber. Focusing on improving soil health provides an opportunity to balance ecosystem stewardship with utility to humans because healthy soils also serve to increase crop health, productivity, and resiliency. The primary functions of healthy soil covered in this bulletin include providing habitat for plant, animal, and microbial life; regulating water; and cycling nutrients and carbon. Additional functions not covered in detail include pest and disease suppression, filtering and buffering potential pollutants, carbon sequestration, and physical stability for human construction.

Organic Matter and Carbon Dynamics

The most important role that healthy soils play in agriculture concerns organic matter and the carbon cycling. Organic matter influences nearly every soil property and function, making it particularly important when managing for soil health. The creation of OM begins with plants. As plants photosynthesize, they draw in carbon from the atmosphere (Figure 1A). They use most of that carbon to build their leaves, stems, and fruits, but they also send about 25% of the photosynthetic energy out into the rhizosphere (plant root zone) where it becomes energy for microorganisms (Haller and Stolp 1985) (Figure 1B). The decomposition of plant and fauna residues both on and under the soil surface by microorganisms also adds carbon and other nutrients to the soil profile (Figures 1A and 1C). Organic matter exists as a continuum of decaying organic constituents (Lehmann and Kleber 2015) that are continually broken down by different fauna, getting smaller and smaller. All the while, the decomposed material **sorbs and desorbs, bonding and unbonding to the negatively charged surfaces of soil particles such as clays, sands, and silts** (Lehmann and Kleber 2015), a process that creates microaggregates (Figures 1B and 1C). Organic matter can be harder for microorganisms to access if it is sorbed to a soil particle or is inside an aggregate, making it more resistant to further breakdown.

Organic matter can be composed of living organisms, decomposing tissues, exudates of plants, and dead microorganisms (microbial necromass), material which is sometimes called "active organic matter" or particulate OM. Organic matter, which is sorbed (Figure 2) to soil particles or inside aggregates, is sometimes referred to as "stable organic matter" or mineral associated organic matter (MAOM). The active OM is more available to microorganisms but may be of a lower quality than MAOM. The MAOM, however, is protected from decomposition either by adsorption to clay and mineral particles or its location within soil microaggregates. Yet it can play important roles in soil structure and function and is also a quality food source for microorganisms and plants after it has been broken down (Lavallee et al. 2020).

Carbon (C) enters the soil via both living and dead organisms and makes up more than half of OM (58%) (Navarro et al. 1993) (Figure 1). Carbon-based compounds provide food for all soil organisms and fuel the soil food web. Living plant roots contribute carbon in the form of **root exudates** (excretions from plant roots), which directly feed and stimulate microbes. The more living roots present in the soil, the more root exudates are produced and the healthier and more diverse the microbial populations. In turn, certain types of microbes stimulate plant root growth, contributing to the production of even greater amounts of exudates. Dead organisms, in the form of plant material, animals, and microorganisms, contribute to soil carbon when they are broken down, decomposed, and mineralized by soil organisms. **Mineralization** refers to organic materials being converted to a plant-available form by microorganisms when the conditions are right, such as temperature and C:N (nitrogen) ratio.

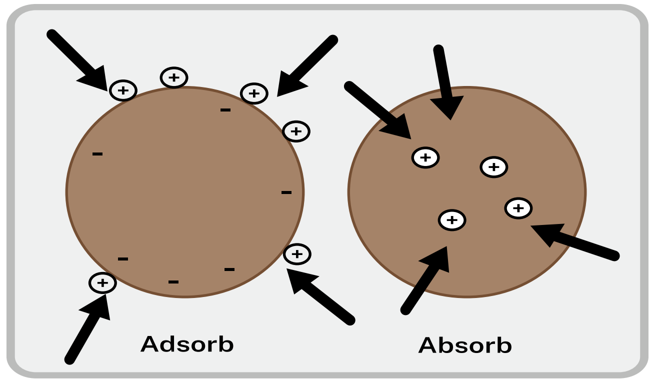

Figure 2. Adsorption and absorption. In adsorption, molecules attach to a surface; in absorption, molecules penetrate and spread inside.

Functions of Healthy Soil

Providing Habitat for Plant, Animal and Microbial Life

A **habitat** is the natural environment in which a species lives and grows. As such, a healthy soil habitat must provide **shelter** and **food** for the plants, animals, and microbes in it to live and grow. For plants, adequate "shelter" means good soil structure for roots to grow, with plenty of air and water. "Food" refers to the nutrients released through decomposition of organic matter, along with sunlight, water, and carbon dioxide, that allow plants to photosynthesize and grow. Indeed, plants are essential to supporting the soil food web because they help provide energy to microorganisms, who in turn convert inorganic compounds into the organic molecules that feed other soil organisms and plants (Figure 1). The initial source of food for larger soil organisms is organic material from plants, whether it be in the form of leaves, roots, or exudates, and starts the decomposition process.

To support the diversity of microbes and animals in soil, a diversity of shelters must be available, ranging from micropores to macropores, and living plant roots to organic materials in varying stages of decomposition. Similarly, a diversity of foods is necessary to support a healthy soil food web. These foods include plant root exudates, plant residues, bacteria, fungi, and insects living in the soil. Managing soils to improve and diversify habitat helps support and diversify the living organisms that thrive in the soil, which helps build better soil habitat to support more biomass and diverse organisms.

Nutrient Cycling and Fertility

Nutrients can be stored in many places in soils, including soil water solution (most readily available to plants in the short-term), in the actual mineral matter (largely inaccessible to plants in the short-term), and both on the surfaces of clays and organic matter as well as bound with carbon as part of organic matter itself (available gradually over time). Soil fertility evaluation focuses on the nutrients available in soil solution, which are more readily available to plants in the short-term, as well as those sorbed to clay and OM surfaces, which may be become available over a season. There are different chemical extractants used in this process to desorb or knock off nutrients from surfaces in order to measure them. Some researchers have speculated about whether or not this method of extraction is representative of how plants naturally obtain nutrients (Haney et al. 2018). The Haney Test is a newer soil health test that uses water as an extractant, in an attempt to more naturally mimic which nutrients plants can obtain in a short period.

Organic matter, composed primarily of organic carbon, also contains important plant nutrients, including N, phosphorus (P), and sulfur, and contributes directly to plant nutrition. When OM is decomposed by microbes in the soil, these plant nutrients release into the soil solution for plants to use. Organic matter also contributes indirectly to nutrient availability by increasing the **cation exchange capacity** (CEC) of soil. Cation exchange capacity is the ability of soil particles, like clay, and organic matter, which are negatively charged, to hold onto positively charged ions like calcium, magnesium, ammonium, and potassium. The CEC of soil increases when organic materials decompose and increase the soil OM pool. Increases in OM increase the ability of soil to retain plant nutrients. These nutrients are held loosely by OM and are released into soil solution for plant uptake throughout the growing season, rather than being lost to the environment.

Healthy soils play another critical role in nutrient cycling that involves specific types of microorganisms. These two groups of organisms are rhizobia and mycorrhizal fungi, both of which form mutualistic (mutually beneficial) relationships with plant roots. Rhizobia plays a significant role in N cycling while mycorrhizal fungi (Figures 1B and 1C) are important in the cycling and acquisition of less mobile plant nutrients (like P and zinc) and water.

Rhizobia are an important group of bacteria that can "fix" atmospheric N, which makes up nearly 80% of the atmosphere but is unusable by plants, into plant-available nitrogenous compounds. The process of N fixation by rhizobia is inherently "leaky," meaning that some of the N fixed by these organisms releases into the soil and is made readily accessible to plant roots. Much of the remaining N becomes available to nonhost plants when the N-rich host-plant, mostly legumes, roots, and nodules, and the free-living rhizobia die and decompose.

Mycorrhizal fungi are an agriculturally important group of fungi that associate with the roots of most plants. The hyphae, akin to fungal "roots," penetrate plant roots and extend the effective root surface area, giving plants access to water and nutrients from much farther than the roots themselves can reach (Figure 1B). Essentially, the extension enables plants to photosynthesize and grow more than they would on their own. In turn, a plant "feeds" the mycorrhizal fungi with sugars from photosynthesis. The relationship is especially important in P nutrition since mycorrhizal hyphae are more efficient than plant roots at taking up P, particularly when P is limited (Jansa et al. 2005). By increasing both nutrient and water uptake, and therefore contributing to increased overall plant health, mycorrhizal fungi help plants resist abiotic stress factors like drought and salinity and can help prevent colonization by disease-causing fungi.

In addition to microbes' ability to cycle and release plant nutrients, they also buffer excessive levels of nutrients through storage in their own biomass. This effectively prevents a rapid and sudden release of nutrients, since those nutrients are bound up in living tissue. As part of living organisms, nutrients are not available to plants (immobilized), but when the organisms are consumed or die, nutrients are mineralized and become available for plant uptake. The process protects valuable nutrients from being lost to the environment. The ultimate goal of managing for healthy agricultural soils is thus largely tied to soils' ability to provide nutrients for plant growth at the right time and in the right amount while reducing the potential loss of those nutrients to the environment.

Regulating Water and Air

Healthy soils play an important role in regulating water, largely through the effects of OM. Increasing OM by 1% in the top 6 inches of an acre can lead to an improvement in water-holding capacity by 2,800 gallons (Libohova et al. 2018); therefore, soils with high OM have a greater ability to hold water. However, unlike clays, which also have a greater water-holding capacity, OM holds the water less tightly for easier uptake by plants, acting much like a sponge.

In addition, organisms and OM help to build and maintain **soil aggregates**. Soil aggregates are formed through the binding of OM and mineral particles. Plant root exudates, microbial by-products, and fungal hyphae contribute to the "gluing" together of soil aggregates (Figures 1B and 1C). The crumbly, granular structure (Figure 3A) that results allows water to freely infiltrate and reduces both soil and water runoff. Furthermore, the structural development enables air flow through the soil, providing soil organisms and plant roots with much-needed oxygen. Soil aggregates are important to the physical structure of healthy soil and contribute to soil tilth and resistance to erosion. The difference in water flow that directly results from aggregate formation and aggregate breakdown can be seen in Figure 3, where well-aggregated soil allows water to infiltrate and crusted soil with no surface aggregates forces water to run off, carrying valuable topsoil and nutrients with it.

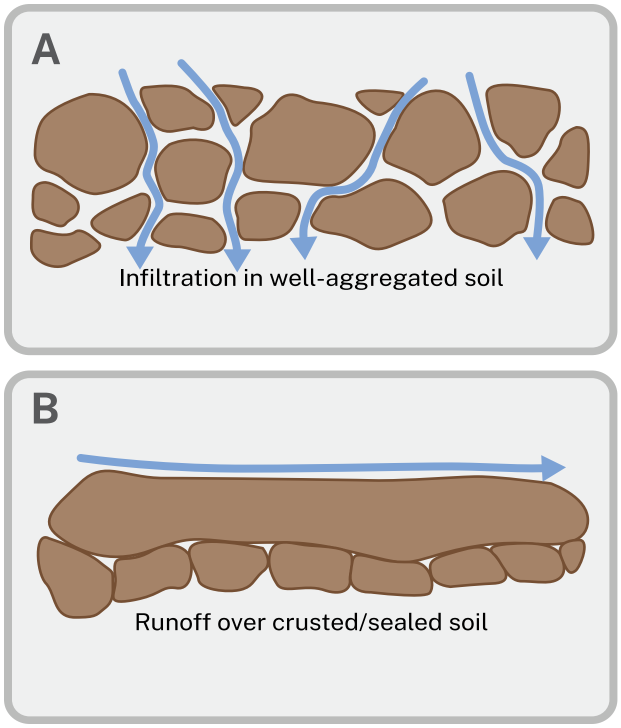

Figure 3. A comparison of water movement in soils: infiltration through well-aggregated soil (**A**) versus surface runoff over crusted or sealed soil (**B**).

Between the particles in aggregates are pores, spaces that fill with either water or air and help to buffer soil conditions in periods of both drought and flooding. The pore sizes within healthy aggregates vary, allowing for water storage during dry periods (held in smaller pores and more resistant to loss) and air space during rainy periods (resulting from large pores rapidly emptied by gravity). Ultimately, the diversity of pore sizes allows plants and other organisms in healthy soils to access water under drier conditions and access air and oxygen under wetter ones.

Conclusion

Healthy soils are integral to the sustainability of agricultural systems. The functions of healthy soils are directly or indirectly tied to OM and the living organisms in soil. These include carbon cycling, providing habitat for plants and soil organisms, nutrient cycling, storage, and regulating water and air in soils. As a result of the important roles that OM and living organisms play in healthy soils, management to enhance soil health inevitably involves managing OM and carbon in soils.

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