Soil Biology Affects Soil Health

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Soil Health

Soil health is an emerging concept that defines soil as a living ecosystem that continuously supports various life forms. **Healthy soils foster biodiversity, sustain improved crop production, and enhance soil nutrient cycling. Soil health focuses on four components: a) minimizing soil disturbance**, where, if the soil is minimally disturbed, then the soil is less susceptible to wind and water erosion and has more stable soil aggregates and soil organic matter; **b) making sure living roots are present throughout the year**, where a constant presence of living roots from crops and/or cover crops will increase soil organic matter and soil aggregate stability and enhance nutrient cycling; **c) maintaining soil cover**, where not removing crop resides from the soil, either by burning, harvest, and/or other means, and growing cover crops, will protect the soil from erosive forces; and **d) promoting aboveground plant biodiversity**, which will lead to diverse aboveground and belowground biological communities. Ensuring the presence of a combination of these four components in current agronomic practices should lead to healthier soil over an extended time.

Soil Biology

A holistic approach that addresses the complex nature of soil functions and relationships between biological, chemical, and physical properties is required to realize the full potential of soil health benefits. This approach helps to optimize ecosystem services in each agroecosystem. **Ecosystem services are the supporting, regulating, provisioning, aesthetic, and cultural benefits provided to people from healthy ecosystems**. Soil biology provides several agronomic and ecosystem services (Table 1).

Soil health can be measured through a combination of physical, chemical, and biological parameters; however, the greatest challenge is to capture the complex, dynamic, and interactive nature of these parameters and to identify which ones are most informative, and valuable. **Soil biota is comprised of living organisms in soil ranging from microscopic bacteria and fungi (soil flora/soil microbes) to larger soil fauna, including protozoa, nematodes, earthworms, and arthropods.** Soil biota is responsible for carrying out processes critical

Table 1. Summary of some of the agronomic and ecosystem services that are provided by soil biology (adopted and modified from Lehmann et al., 2020).

Soil Properties/Processes	Agronomic and Ecosystem Services
Soil nutrient cycling	Decomposition, soil carbon, nitrogen, and phosphorus cycling, nutrient retention, plant nutrition, mitigation of gas emissions
Symbiotic relationships	Nitrogen fixation, mycorrhizal associations, enhanced plant nutrition, acquisition of soil water, plant protection
Biodegradation of agrochemicals, pollutants, and waste	Microbial biodegradation, breakdown of pesticides in soil, improvement in water quality
Pathogen regulation	Regulate and suppress pathogenic agents, suppress plant disease
Soil structure	Soil aggregate stability, soil carbon sequestration, retention of soil structure and reduction of soil erosion hazards, greater aeration, improved water infiltration, greater water-holding capacity

for soil health's sustainability. How well the soil food web is maintained in the long term will decide the soil health of a given agroecosystem. When provided with a large amount of easily accessible food, the ensuing enhanced nutrient cycling by soil flora within the topsoil will foster plant growth. Translocation of carbon and other nutrients into deeper soil depths by soil fauna will potentially act as a stored nutrient source for the future.

Because of the small spatial scale of microscopic organisms and their ability to respond rapidly, biochemical properties and processes can be very sensitive indicators for detecting and signaling change on a smaller scale. Soil biological communities respond readily to biotic and abiotic stresses in the environment; for instance, soil microbial communities can be impacted by changes in soil pH, water content and availability, and soil organic carbon (labile carbon). Thus, soil biological properties are increasingly considered, investigated, and managed for their agronomic and ecological relevance, sensitivity, and functioning in a wide range of environmental settings. **By identifying soil biological attributes related to how much is present, community composition and functional diversity, and activities, we can get a sense of the ongoing soil processes that may be indicative of soil health.**

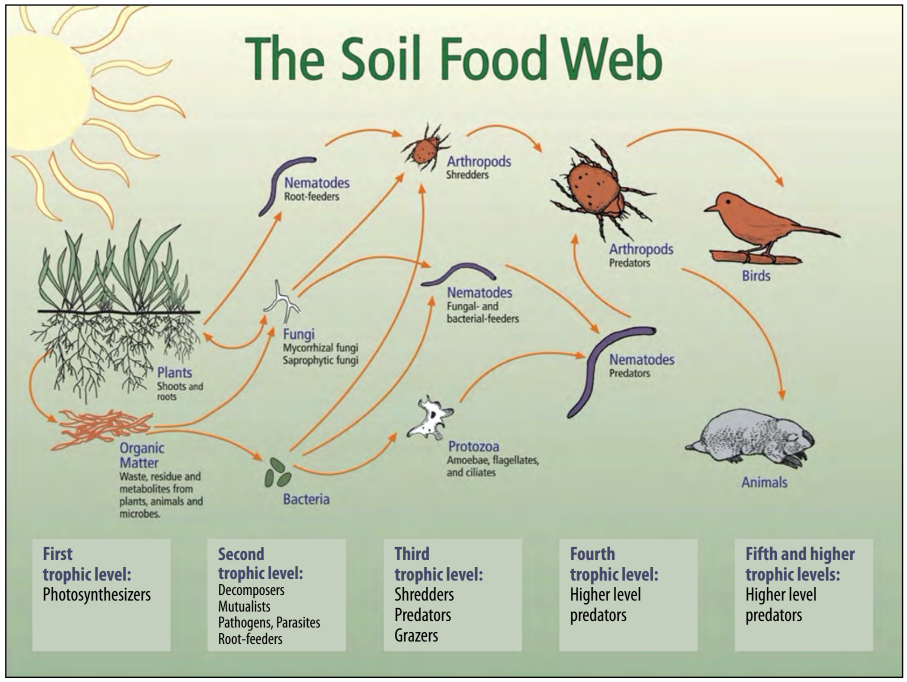

Figure 1. A diagrammatic representation of a soil food web (from Natural Resources Conservation Service - Soils. Soil and Water Conservation Society, U.S. Department of Agriculture. Soil Biology Primer Photo Gallery).

Soil Food Web and Soil Biology

Soil biota are an integral part of the soil food web. The soil food web is a complex network of living organisms interconnected with each other through the transmission and recycling of nutrients and energy, fed primarily by organic matter, particularly carbon as the energy source. Dead or decaying plants, animals, and macroorganisms and microorganisms all serve as food sources for microorganisms. The decomposition and digestion of organic matter start with soil bacteria and fungi, which, in turn, are eaten by nematodes, that are preyed upon by arthropods. **The association between plant roots and the microbes that dwell in the soil surrounding the plant roots (i.e.,**

the rhizosphere) is a critical component of the soil food web. Plant growth is supported by a symbiotic relationship where the plant roots secrete simple compounds, such as sugars, that support microbial populations, and the microbes help in nutrient availability and uptake. Earthworms consume organic matter, microorganisms, and microfauna. Earthworms, in turn, are consumed by larger organisms. Community composition varies depending on the agronomic practices and cropping systems used. The more groups of organisms there are in the food web, the more complex and diverse the food web.

The composition of organic matter ranges from easily degraded (i.e., labile) proteins and hemicellulose to recalcitrant (i.e., hard to break down) lignin, and, during the process of decomposition by soil microbes, nutrients such as nitrogen and phosphorus are released for plant uptake and microbial utilization.

When feeding on soil microbes and other organic soil materials, soil fauna often releases or excrete excess plant-available nutrients, such as nitrogen in the form of ammonium.

During the decomposition process, soil organisms also excrete substances that act as binding agents for soil aggregates, thus improving soil structure and subsequently enhancing penetration in soil and the growth of plant roots. In addition, soil biota is important for disease suppression, as some soil organisms can prey on various pest species, and for overall environmental protection, such as by enhancing soil-water filtration and breakdown of pollutants.

How Soil Biology is Impacted by Agronomic Practices

The rhizosphere is a small, but dynamic area of intense interactions between microbial communities and plant roots. Additional biologically active places are plant litter residue and earthworm and arthropod burrows. **Microbes are attracted to food sources and, in turn, release nutrients for plant growth.** As a result, maintaining living roots in the soil fuels the soil food web. Practices such as growing a cover crop following a cash crop, or not leaving the soil fallow, are important for maintaining healthy soil. Increasing the quantity and variety of food sources generally promotes biological diversity and functional complexity in soil. For instance, the inclusion of amendments, such as poultry litter, composted organic materials, or the retention of crop residue will provide organic matter for soil biota that can potentially attract beneficial microorganisms to increase resilience against pests and pathogens.

Practices such as crop rotation have an immense impact on the mycorrhizal fungal population in the soil. Mycorrhizal fungi produce glomalin and other related proteins that indirectly help with soil aggregate stability, increase organic matter, and increase nutrient availability for plant uptake. Additionally, **agroecosystems that are diverse in plant species, either by diversified crop rotation or by using cover crops, encourage soil biodiversity.** This accomplishes two main goals: first, it enables the soil to function better because there is a complex mix of soil biota, and secondly, it may reduce input costs, with a possible subsequent increase in profits.

Diversity among soil populations may result in functional redundancy because, in soil, different species can perform the same functions. Functional redundancy may increase soil resilience, especially during and/or after a sudden environmental stress. For instance, under extreme drought or high salinity conditions, with the loss of species, other species remain that perform the same role; thus, the function in the ecosystem is not lost and the soil exhibits stability. Practices such as tillage may lead to a flourishing of biological activity for a short period following tillage, but every time the soil is tilled the soil structure is changed, and the biological community is changed. Reduced tillage or no tillage can have a positive effect on soil fungi and soil fauna, as they reduce mechanical break up of roots, fungal hyphae, and habitat. It is understandable that

Table 2. Summary of several soil-biology-based metrics of soil health (adopted and modified from Fierer et al., 2021).

Microbial metric	Description	Interpretive use	Potential cautions
Soil microbial biomass	Amount of microbial biomass per mass of soil	Greater microbial biomass indicates a healthier soil	More microbial biomass does not always mean more biological diversity
Fungi: bacteria ratio	Abundance of fungi relative to bacteria in each soil	The abundance ratio indicates the complexity of the food web. A greater abundance of fungi compared to bacteria indicate ecological energy pathways toward the food web that is complex and food sources are degraded slowly	A better understanding of complex and multitrophic food webs is required, method of measurement may affect outcome
Microbial enzyme activities	Extracellular enzymes are associated with carbon, nitrogen and phosphorus cycling in soil	Greater enzyme activity indicates greater potential for nutrient cycling	Soil enzymes vary depending on the conditions of the agronomic system; thus, caution is required on which enzyme to choose and to use the activities in relative comparisons
Mycorrhizal fungi (MF) abundance	Abundance and composition of MF, glomalin-related soil proteins	Greater abundance will render better plant growth; greater glomalin concentration indicates better soil health	Plant root and MF relationship is dynamic and moves along a mutualism and parasitism continuum
Carbon (respiration, including in-situ soil respiration) and nitrogen mineralization rates	Measured by production of carbon dioxide (CO_2) during respiration, including quantification of the soil surface CO_2 efflux in the field, incubation to measure net inorganic nitrogen concentration	Increased carbon and nitrogen mineralization is an indication of an active microbial community and increased nutrient availability	Large releases of carbon and nitrogen during mineralization is often not desirable; in-situ respiration measurements cannot distinguish living root and microbial contributions to respiration because both emit CO_2
Permanganate oxidizable carbon (POXC, the labile carbon pool)	Measured by permanganate oxidizable carbon method in the laboratory	Dynamic driver of carbon mineralization	By oxidizing the mineral associated carbon, this process can overestimate carbon content utilization by soil biological communities
Microbial community composition and microbial functional gene composition	Deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) sequencing and known gene identification	Changes in microbial community or functional composition correlates with other soil health metrics, may indicate dominant processes in soil	Difficult to identify which microbes are most relevant
Direct measurement of earthworms	Extraction of earthworms from known volume of soil	Aid in organic matter decomposition, translocate nutrients into deeper soil depth, contributes to soil aeration	Different extraction methods for different ecological groups of earthworms, invasive earthworm species can be harmful to ecological functioning, fewer earthworms will be active in drier soils

a no-tillage practice might not be feasible for all farms, and no-till systems may sometimes face weed and pest infestations, delayed seed germination, and high initial nitrogen input, but any reduction in tillage will improve the soil's biological health. Additionally, the maintenance of crop residues on the soil surface in conjunction with practicing reduced tillage may increase the diversity of the food web that helps suppress plant disease.

Better crop residue and tillage management will improve soil biological health and should be implemented within the context of system management practices.

Quantitative Approaches in Soil Biology

Because microbial communities are highly diverse, they pose a huge challenge to characterize and analyze. Unfortunately, there is no standard test for soil biology that can be confidently related to soil health, as we have for other soil physical and chemical properties. Several microbial-based soil health indicators have been proposed and developed over the years (Table 2), but the most daunting task is to interpret the results due to the large, expected variability in soil biological communities. For instance, soil biological activity can be measured indirectly by measuring soil enzymatic activity or measuring soil respiration over a certain period. Table 2 briefly describes some common soil-biology-based metrics of soil health.

Measuring Soil Biological Activity On-Farm

Visual inspection for the presence of earthworms, insects, and arthropods and inspecting the level of decay of the crop residue are useful to develop a sense of soil biological activities. In addition, **farmers can potentially use the Solvita® soil test kit to measure soil respiration on-farm with field soil. Solvita® is a patented soil respiration measurement system.** In the Solvita® test, field soil is collected and sieved on site with a simple garden sieve to homogenize the soil. Dry soil is remoistened after placing a measured amount into either a jar provided with the kit or in Mason jars with rubber seals. A low-level CO_2 gel attached to a stick is placed into the soil and the lid of the container is sealed at room temperature for 24 hours to allow the gel to absorb CO_2. After 24 hours, the gel color is measured for microbial respiration as compared to potential results as summarized in Table 3 for estimated microbial activity. The amount of active carbon that is metabolized from organic matter is reflected as microbial activity on the CO_2 gel.

Things to Consider

Although comprising a small portion of the soil (< 0.05% dry weight), soil biota is integral to soil functionality and soil quality. Soil organisms are inherently not good or bad, and their presence and their contribution to soil health depend greatly on context. For instance, in soil health

Table 3. Interpretation of the Solvita® soil respiration test in a jar at 68 to 72ºF.

Color 0-1.0 Blue-Gray	Color 1.0-2.5 Gray-Green	Color 2.5-3.5 Green	Color 3.5-4.0 Green-Yellow	Color 4.0-5.0 Yellow	Color 5.0-6.0 Bright Yellow
Very Low Activity (depleted soil)	Low Activity (low biological activity and organic matter is low)	Medium Low Activity (low to moderate biological activity and signs of more organic matter accumulation)	Ideal Activity (active biological communities and optimum organic matter supply)	Medium-High Activity (active biological communities and soil with high organic matter content)	Very High Activity (very active biological communities in soil with high organic matter turnover)
Estimated Emissions (Flux) of CO_2-C (lb/acre)					
0.5-1	**1-5**	**5-15**	**15-25**	**25-60**	**60-160**

(Adopted from Solvita Instructions: Natural Soil Respiration, SOP Version 2021:3.0)

assessments, the fungi: bacteria ratio may be a useful indicator of healthy soil, while greater bacterial diversity may suggest soil conditions for enhanced nutrient cycling. However, fungal and bacterial dominance and diversity are strongly correlated with soil pH, and a shift in soil pH may not always be beneficial, especially when a crop's optimal pH range is considered. In assessing soil health, less than 20% of commonly used soil health indicators (Lehmann et al., 2020) are biological indicators. This suggests that there is a need to develop and use more microbial metrics and measurements to improve future soil health assessments.

Summary

In summary, the soil biological parameters/ metrics should be used wisely and should always be correlated with other chemical and physical soil health parameters to fill the gap that chemical and physical soil health parameters cannot provide. Furthermore, soil microbial matrices dealing with soil health should acknowledge that an ideal microbial community does not exist, rather the microbial community consists of a diverse set of microbial populations that change depending on temporal and spatial variability, agronomic management, cropping systems, and plant species. Thereby, building soil biological properties for optimal soil health is a feedback system where farmers should rely on long-term biological goals based on a set of agronomic management practices.

Management Practices to Improve Soil Biology

- Add organic matter on a regular basis (cover cropping, manure, compost)
- Reduce soil disturbance (reduced tillage, no-till, etc.)
- Introduce plant diversity in agroecosystem management (for instance, crop rotation in row cropping, grass waterways, and nutrient buffer strips in grazing pastures)
- Leave crop residue on the ground.

References

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