Biological Soil Health Indicators

The soil is a gigantic reservoir of biodiversity within which the interactions between microbes, animals, and plants provide many benefits for human well-being. Living soils are crucial because soil biodiversity provides disease control and influences the quantity and quality of the food we eat, the air we breathe, and the water we drink (Wall et al., 2015). Besides the effect of soil organisms on human life, they play a central role in soil functioning and ecosystem services provisioning.

Assessing soil biological indicators of soil health is key to understanding the soil's living component. Soil microbes play crucial roles in the decomposition of soil organic matter, nutrient cycling, soil pollutant degradation, and the formation and stability of soil aggregates. Soil organisms also respond rapidly and are very sensitive to changes in tillage and cropping systems, natural disturbances, and chemical contaminants. Most of the indicators will reflect the quantity and diversity of living organisms, such as fungi, bacteria, and earthworms, as well as their bioproducts (Figure 1).

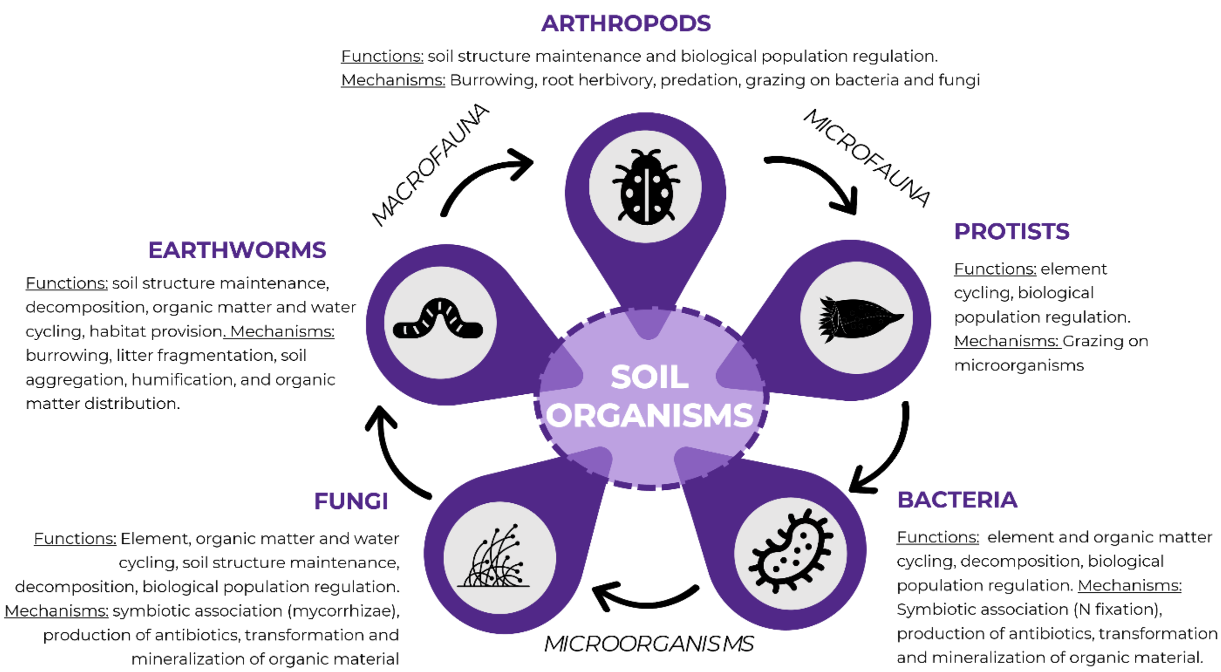

Figure 1. Main soil organisms groups and their soil functions and involved mechanisms.

Soil biological indicators can relate to soil properties at two levels: 1) Individual, population, and community level; and 2) Ecosystem level. Most individual, population, and community-level indicators are associated with soil organisms' presence, richness or abundance, microbial biomass and ratios, and community composition (Bünemann et al., 2018). At the ecosystem level, the indicators are linked to soil respiration, nitrogen mineralization, denitrification, nitrification, protein synthesis, enzymatic activity, and soil organic carbon. Generally, biological indicators that tell us about soil processes mediated by soil organisms are the most revealing about soil functions. It is important to state that there are limitations in directly measuring soil organisms as indicators of soil health. Thus, biological dynamics properties are often measured as alternatives to processes mediated by soil organisms. Besides the soil microbial community composition measured by phospholipid fatty acids, the most frequently used biological soil health indicators proposed by the Soil Microbial Agroecology Lab at Kansas State University are enzymatic activity, soil organic carbon, soil respiration, and potentially mineralizable nitrogen (Figure 2).

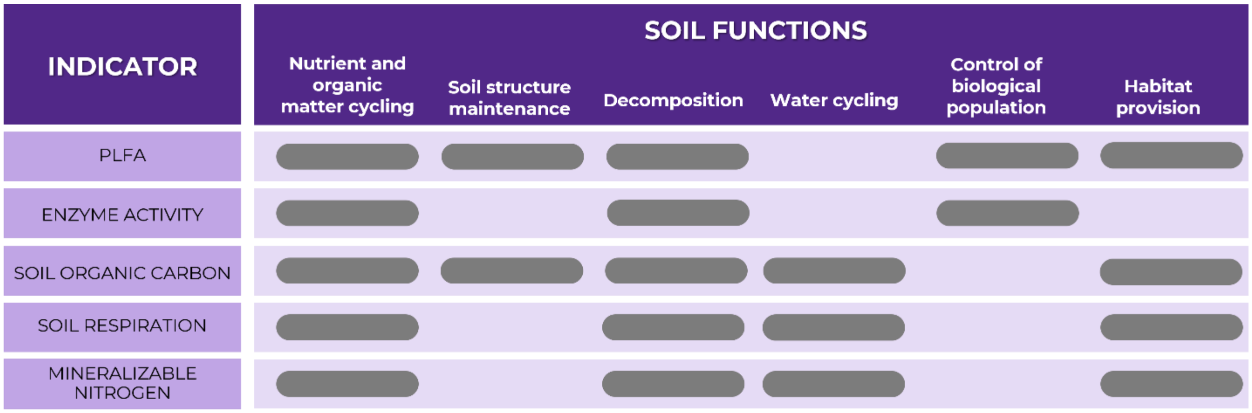

Figure 2. Soil biological indicators and related soil functions.

PHOSPHOLIPID FATTY ACID (PLFA)
It is a technique used to assess the soil microbial community composition. Phospholipid fatty acids are a key component of microbial cell membranes. The analysis of PLFAs extracted from soils can provide information about the overall structure of the living microbial biomass. Through the variation in the phospholipid composition (monounsaturated, polyunsaturated, cyclopropyl, iso, anti-iso, etc.) in different microbial groups, we can figure out who is there and how many microbes we have in terms of mass. In other words, each microorganism has a phospholipidic signature. Some microbial groups we can identify include saprophytic fungi, arbuscular mycorrhizal fungi (AMF), gram-positive bacteria, gram-negative bacteria, and actinomycetes. PLFA is a very sensitive soil health indicator and can be used to evaluate the short-term effect of land management on soil health.

Saprophytic fungi feed on dead plant and animal remains. Many are extremely beneficial, breaking down high-carbon organic material (grasses) into humus, minerals, and nutrients that plants can access. They are also critical for improving soil aggregation through their hyphy and mycelia work. Saprophytic fungi tend to be more drought resistant than bacteria.

Arbuscular mycorrhizal fungi form a mutualistic symbiosis with the roots of 70-90% of land plant species. The spores present in the soil germinate and form arbuscular structures inside the cells through an infection process in the root system. Once associated, plants and AMF can exchange nutrients and improve plant nutrient uptake (phosphorus and nitrogen). Likely saprophytic fungi, AMF is a key organism for improving soil aggregation. Hyphae of AMF are considered primary soil aggregators, and there is a positive correlation between AMF hyphae and aggregate stability in agroecosystems. Arbuscular mycorrhizal fungi also release a glycoprotein called glomalin into the soil, acting as a cementing agent between soil particles that form aggregates.

Bacteria (gram-positive, gram-negative) are fast-growing microorganisms that grow in many different environments. Bacteria play a starring role in microaggregates formation due to the sugar compounds that they release and coat the surface of soil particles. Most bacteria generally do better in well-oxygenated soil with a pH of around 7 (neutral). Bacteria provide large quantities of nitrogen to plants by fixing atmospheric nitrogen (i.e., plants do not fix nitrogen, bacteria do). Many bacteria also secrete enzymes in the soil to turn phosphorus soluble and plant available. Bacteria can also become pathogens to plants, thus the importance of having a diverse microbial community to promote auto predation. Actinomycetes are classified as bacteria but are very similar to fungi. They have filamentous growth, are important enzyme producers, and degrade resistant plant material like grasses (e.g., wheat, rye, sorghum, and corn straw).

ENZYME ACTIVITY

Extracellular enzymes are excreted by soil microorganisms such as fungi and bacteria. They are helpful as soil health indicators because they are responsible for critical soil biogeochemical processes such as carbon, nitrogen, phosphorus, and sulfur cycling. Enzyme activity can be measured through enzyme assays that measure soil metabolic activity. The most valuable and measured enzymes are β-glucosidase (βG), N-acetyl-β-glucosaminidase (NAG), acid/alkaline phosphatase (AlkP/AcdP), and arylsulfatase (ARS).

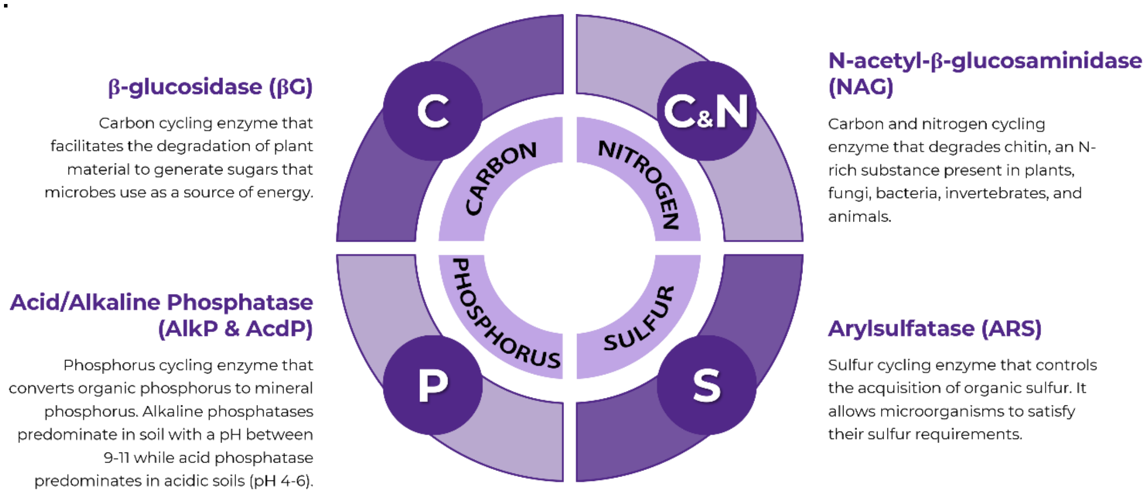

Figure 3. Enzymes and the biogeochemical cycles.

SOIL ORGANIC CARBON (SOC)

Carbon is the fundamental building block of all life on earth. The level of SOC in soils is a function of climate, topography, biology (plants and microorganisms), parent material, and time (Rice et al., 2022). The vegetation affects carbon levels due to its biomass composition. In general, high residue-producing annual crops such as corn, wheat, and grain sorghum replenish the supply of carbon to the soil. Low residue-producing crops, such as cotton and soybeans, tend to deplete soil organic carbon levels. Long-term

SOC maintenance and build-up in this scenario depend on diverse and intense cropping systems. Soil organic carbon is the most important gear of the soil engine. Physically, SOC increases water infiltration, reduces compaction, and improves soil aggregation. Chemically, SOC increases the cation exchange capacity, which is essential for the retention of many nutrients. Biologically, SOC is the source of energy for most soil microorganisms.

SOIL RESPIRATION

Soil respiration or carbon dioxide (CO_2) evolution is a measure of soil biological activity. Most of the CO_2 released from soils to the atmosphere comes from microorganisms, living roots, and macroorganisms that decompose straw, protein, and sugars to acquire energy for subsistence. Overall, the activity of soil organisms is considered positive for soil health. A high soil respiration rate indicates efficient decomposition of organic residues into available nutrients for plant growth. However, it is not to be confused with high microbial activity and respiration due to soil disturbance (i.e., tillage). Soil tillage rapidly increases microbial activity due to the greater availability of organic carbon previously locked inside soil aggregates. Some bacteria are favored by available carbon and are fast-growing, increasing CO_2 losses in tilled soils. Finally, soil respiration as a soil health indicator must be used with care due to its high spatial and temporal variability. Soil moisture and temperature are some factors that control soil respiration and may make soil respiration vary from one day to another.

POTENTIALLY MINERALIZABLE NITROGEN (PMN)

Potentially mineralizable nitrogen is a measure of the soil's organic nitrogen that can be easily mineralized. In other words, it is the conversion of organic nitrogen to mineral (i.e., inorganic) nitrogen that plants can take up. The soil's ability to provide plant-available nitrogen indicates how healthy the soil is. Have you ever observed that crops can still grow when synthetic nitrogen (e.g., UAN, urea, anhydrous ammonia, etc.) is not applied to the soil? That is a result of nitrogen mineralization by soil microorganisms.

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