Soil Microorganisms as the Nutrient Engine: From Biology to Plant Uptake

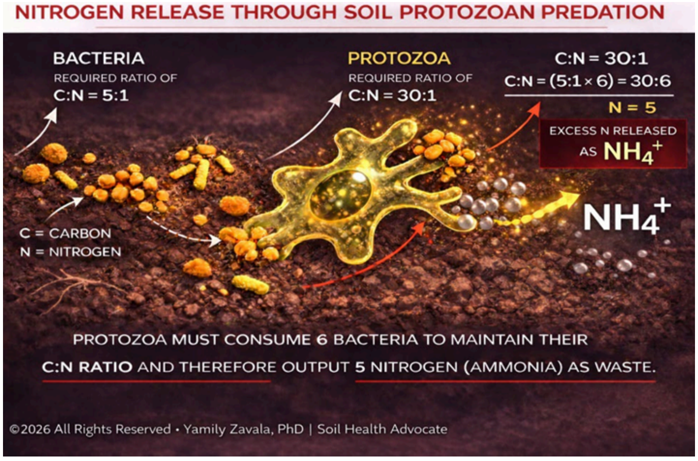
March 5, 2026, Dr. Yamily Zavala

Biology As the Key to Unlocking Nutrients

Soil fertility is often measured mainly through macronutrients like nitrogen (N), phosphorus (P), and potassium (K), while the biological processes that make these nutrients available are frequently overlooked. Soil microorganisms act as a “living nutrient engine,” unlocking nutrients that may otherwise remain tied up in organic matter, microbial biomass, or mineral bonds in the soil. Without strong biological activity, many nutrients, including nitrogen, phosphorus, and micronutrients, remain unavailable to plants, and organic residues decompose slowly, which can sometimes be observed in fields where crop residues persist for several years.

Microbial Interactions Drive Nitrogen Cycling

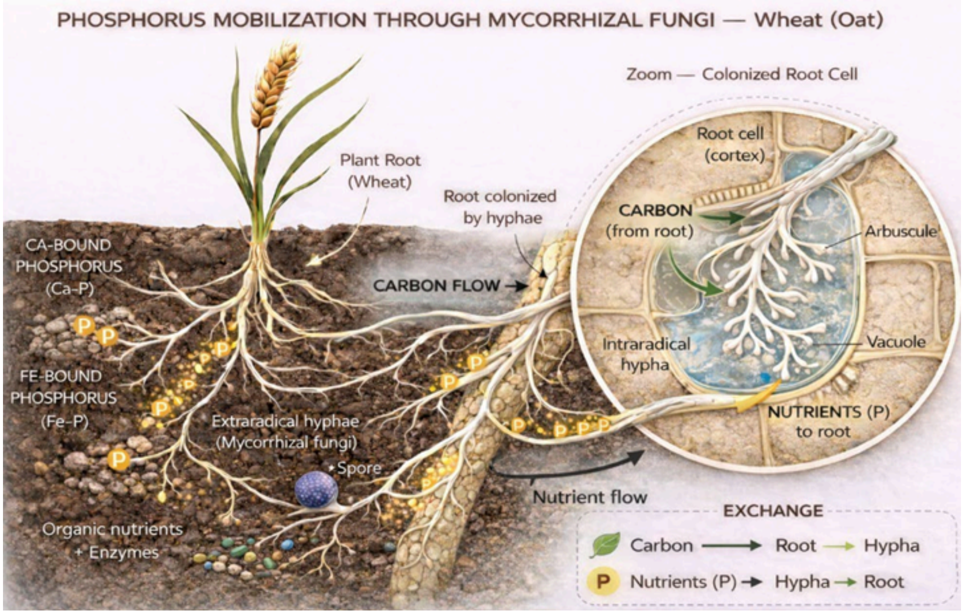
Bacteria store nutrients, such as nitrogen, within their biomass while decomposing organic material. Protozoa and nematodes then graze on these bacteria, releasing excess nitrogen in plant-available forms, such as ammonium. This occurs because protozoa require a different carbon-to-nitrogen ratio than bacteria; when they consume bacteria, they release surplus nitrogen back into the soil. This grazing process is a fundamental nutrient cycling mechanism that occurs constantly in healthy soils, helping regulate nutrient availability so that plants can access nitrogen when they need it.



This image shows how protozoa graze on bacteria in the soil and release excess nitrogen as ammonium (NH_4^+). It illustrates how microbial predation converts nutrients tied up in microbial biomass into plant available forms, supporting nitrogen cycling and crop nutrition.

The Role of Fungi in Phosphorus Availability

In many soils, phosphorus is not actually lacking but is chemically bound to elements such as calcium, iron, or aluminum, making it difficult for plants to access. Soil fungi, including mycorrhizal fungi, produce organic acids and enzymes that break these bonds and solubilize phosphorus. Mycorrhizal fungi form symbiotic relationships with plant roots, extending their hyphae into the surrounding soil to access nutrients and water beyond the reach of the root system. In exchange for carbon produced through photosynthesis, these fungi transport nutrients, particularly phosphorus, directly into the plant.

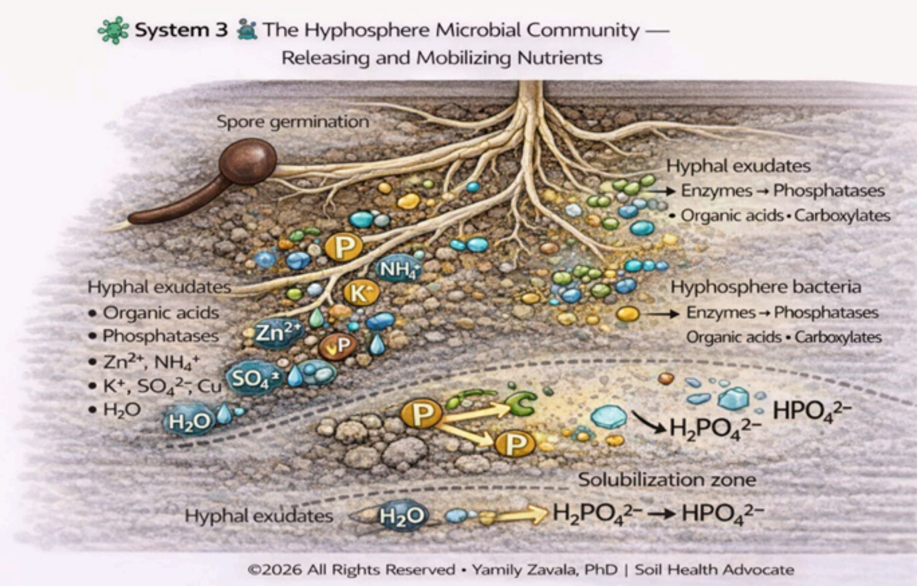


This image explains how mycorrhizal fungi extend beyond plant roots to access phosphorus bound in the soil. In exchange for plant carbon, fungal hyphae mobilize and transport phosphorus back to the root, improving nutrient uptake and root efficiency.

What Is the Hyphosphere?

The hyphosphere is the area where fungal spores germinate, just beyond the rhizosphere. It is usually associated with AMF Fungi. The hyphosphere contains a microbial community (microbial consortia). The hyphae do not work alone, they are part of a microbial community. There are five key milestones that contribute to the generation of the hyphosphere:

1. Spore Germination
    - Spores germinate and hyphae explore the soil.
2. Hyphae Exudates (1st trigger)
    - As it grows, it releases several exudates.
3. Hyphosphere Forms (A Microbial Hotspot)
    - A cluster of bacteria form around the hyphae.
4. Solubilization of bound Phosphorus
    - Phosphorus captured by hyphae and transported to plant roots.



This image highlights the hyphosphere, the biologically active zone surrounding fungal hyphae where microbes and root fungal exudates interact. It demonstrates how enzymes, organic acids, and beneficial bacteria solubilize and mobilize nutrients such as phosphorus, zinc, potassium, sulfur, and water, which are then transferred to the plant through direct root uptake and/or mycorrhizal hyphal transport.

Importance of Balance within the Soil Microbial Community

Soils dominated by bacterial activity tend to release nitrogen rapidly, which can sometimes favor weed growth early in the season. In contrast, soils with stronger fungal communities often promote more stable nutrient cycling and improved phosphorus availability, contributing to stronger root systems and overall plant resilience. A diverse microbial community therefore helps regulate nutrient supply, improve soil structure, and enhance the efficiency of nutrient uptake.

The Role of Healthy Soil Biology

Healthy soil biology enables the natural cycling of multiple nutrients, not just nitrogen and phosphorus. Active microbial and fungal communities help mobilize minerals such as sulfur, potassium, zinc, copper, and others, while also contributing to soil aggregation and carbon stability. By supporting soil biological activity, farmers can improve nutrient availability, reduce dependency on external fertilizers, and promote healthier, more resilient cropping systems.

How to Create Supportive Soil Conditions

Improving soil structure, particularly soil aggregation, is one of the most important first steps to building supportive soil conditions for microbiology. Compacted soils limit microbial activity and reduce the soil's ability to retain moisture, both of which restrict biological processes. Increasing plant diversity, such as by planting multi-species cover crop “cocktail” mixes, can help address these issues by introducing a variety of root systems and biomass into the soil.

Dr. Yamily Zavala has observed improvements in soil aggregation within just a few months after introducing diverse cover crops, which in turn creates better conditions for soil microbes and moisture retention.

How to Encourage Biological Nitrogen Cycling

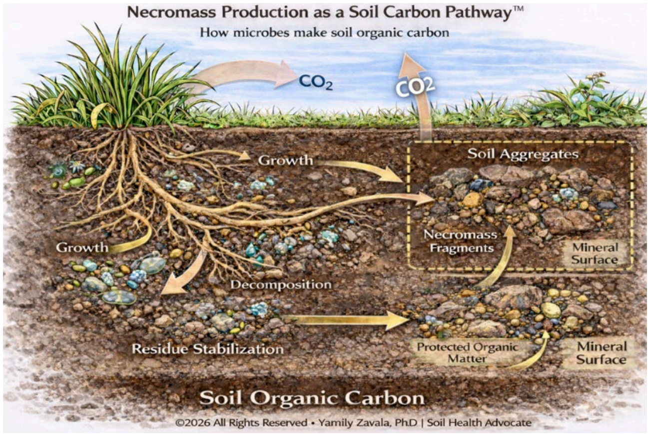
Healthy soil biology depends on both proper conditions and sufficient microbial diversity. In soils where microbial communities are weak or dormant, biological activity can be stimulated through practices such as applying compost extracts or inoculating seeds with biologically-rich materials, including compost produced through systems like the Johnson–Su bioreactor. Crop rotations that include legumes can also support nitrogen cycling by introducing symbiotic nitrogen-fixing bacteria. Other forms of nitrogen fixation, including free-living nitrogen-fixing microorganisms, may also contribute to soil fertility, and that maintaining balanced nutrient ratios (i.e. carbon-to-nitrogen and carbon-to-sulfur) can further support microbial processes.

The Relationship Between Bacterial- and Fungal-Dominated Soils

Shifting the balance of soil microbial communities can take time and is unlikely to provide immediate results in a single season. However, there are some examples that demonstrate how incorporating biological management practices into farming systems can gradually transition soils from bacterial-dominated to more fungal-dominated systems over several growing seasons. It is important to undertake soil benchmarking and monitoring so that farmers can track how biological communities respond to management practices in their specific local conditions.

The Role of Soil Microbes in Carbon Cycling

Plants capture carbon dioxide from the atmosphere and transfer carbon into the soil through root exudates. Soil microorganisms consume these carbon compounds, and when microbial cells die, their remains (AKA microbial necromass) become stabilized within soil aggregates. This process contributes significantly to long-term soil carbon storage and helps build stable soil structure. Microbial processes also produce a range of secondary metabolites, including compounds with antimicrobial properties that can help regulate soil ecosystems and support plant health.



This image shows how microbes convert plant carbon into soil organic carbon through the formation of necromass (dead microbial material). Plant roots feed soil microbes with carbon compounds, microbes grow and decompose organic residues, and their remains become stabilized inside soil aggregates and on mineral surfaces. This protected carbon can persist in the soil, improving structure, fertility, and long term carbon storage.

Necromass Fragmentation

Microbial cell walls break apart into smaller fragments. These fragments contain complex organic compounds such as amino sugars and peptidoglycan. Fungi is the bridge between roots and allows for nutrient exchange. This process switches diverse plants from antagonistic to synergistic.

Plant Diversity Boost Nutrient Exchange

There are great benefits of plant diversity in facilitating nutrient exchange within the soil ecosystem. Legumes fix nitrogen through symbiotic bacteria in root nodules, while other microbes solubilize nutrients like phosphorus. Mycorrhizal fungi form networks that connect plant roots and help transport nutrients across the soil. These interconnected relationships allow nutrients to move between plants and microorganisms, reducing nutrient deficiencies and supporting stronger plant growth compared with monoculture systems.

Green Manures Build Soil Organic Matter

Incorporating green manure introduces additional organic material that soil microorganisms can decompose, thereby stimulating biological activity. As microbes process this material and reproduce, their dead cells contribute to the formation of microbial necromass, which can stabilize carbon in the soil, particularly when fungal communities are present to help form and stabilize soil aggregates. However, successful carbon stabilization depends on a balanced and active soil ecosystem; without sufficient microbial and fungal activity, much of the added organic matter may simply be lost through respiration rather than being stored in the soil.

Shorty Fensky Case Study

Dr. Yamily shared an example from a farmer who grazed cattle on a diverse cover crop mix, highlighting the significant benefits observed in livestock performance. After beginning to graze the cover crop in mid-August, the farmer reported exceptionally strong weight gains in both cows and calves. In fact, the calves were sold about two months earlier than usual yet still weighed roughly 100 pounds more than calves from the previous year. This kind of improvement represents a major economic benefit and illustrates the value that diverse cover crops can provide within integrated crop–livestock systems.

Due to personal circumstances, the farmer did not plant a crop the next year, and the field became almost entirely covered in clover with very few weeds present. This outcome may have been related to a high fungal-to-bacterial ratio in the soil. In fungal-dominated systems, nitrogen tends to be immobilized within fungal biomass and released more slowly, which can reduce the availability of mineralized nitrogen in the soil. Because clover can fix its own nitrogen through symbiotic bacteria in its root nodules, it was able to thrive under these conditions while other plants that rely on available soil nitrogen struggled to compete. As the clover dominated vegetation decomposed, nutrient cycling accelerated and bacterial populations increased, which lowered the fungal-to-bacterial ratio at the end of the growing season. This demonstrated that soil microbial communities are dynamic rather than static. Their balance shifts depend on factors such as crop species, carbon inputs, seasonal conditions, and management practices. Spring samples often reflect the biological legacy of previous management, while fall samples provide insight into the current processes taking place in the soil.

Why Monitor?

There is great importance of long-term monitoring to understand how soil systems respond to management changes. Soil samples from Shorty's field had been collected from the same GPS locations over several years, allowing trends in microbial communities to be tracked over time. Additional measurements (i.e. aggregate stability) could provide further insight into how soil structure evolves alongside biological changes.

Conclusion

Plant diversity can quickly stimulate biological activity and improve soil structure. In one example, a simple cover crop mixture grown for just over two months produced visible improvements in soil aggregation compared with a nearby harvested lentil field that had bare, compacted soil. The cocktail cover crop created root systems and organic inputs that supported microbial activity and initiated the formation of soil aggregates. For Dr. Yamily Zavala, the development of soil aggregates is one of the earliest and most visible indicators that soil health is improving.

The images above show roots surrounded by newly formed soil aggregates and compare the planted area with adjacent bare soil. In a short time, the living roots activated the rhizosphere, helping begin soil aggregate formation and visibly improving the soil surface structure.