THE SOIL MICROBIOME

Sound

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Sound

INTRODUCTION

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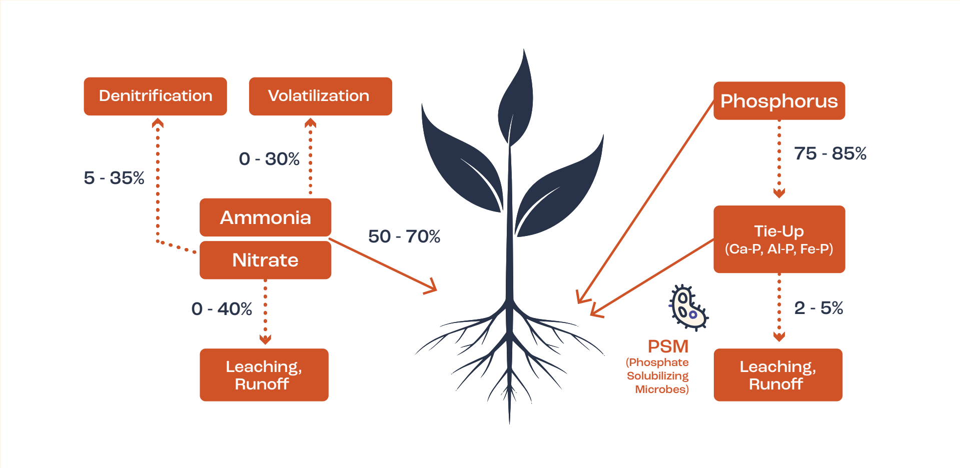
Healthy soil is a dynamic, living system of both plants and microbes. Dirt, on the other hand, is made up of stagnant, dry, dead material and provides little to a grower beyond some minimal structure. Soil can provide access to nutrients, protection from erosion, structure, water retention and much more, provided we understand a little about the ecosystem within the soil and try to maintain it.



Not all nitrogen and phosphorous is used by the plant. When nutrients are applied to the field, much is lost to the environment before it reaches the plant. Timing and weather events can lead to nitrogen losses of 30-50% from leaching, runoff, denitrification and volatilization. Additionally, about 80% of applied phosphorus quickly binds to elements in the soil such as calcium, aluminum and iron, leaving little in the orthophosphate form which is the form that plants can actually use. A healthy soil microbiome can help alleviate many of these expensive losses.

As with any complex structure, it's important to understand the key components that make up a healthy soil ecosystem, both above and below ground. Maintaining soil health means maintaining the foundational elements that can make or break the network: plants and soil microbes.

MANY MICROBES, MANY FUNCTIONS

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MICROBES:

Healthy soil contains approximately 1 billion microbes per teaspoon, and these microbes create the dynamic, living system that characterizes healthy soils. Microbes provide soil structure, influence pH, and have important symbiotic relationships with plants, providing nutrients that might otherwise be hard for the plants to access

Root exudates: *Root exudates are substances excreted by plant roots that can modify the surrounding soil pH, nutrient availability, and attract microbes. These exudates are in the form of proteins and carbohydrates, and can attract, wake up, and even grow beneficial soil microbes.*

Rhizosphere: The rhizosphere is the area extending approximately a tenth of an inch out from a plant's roots where most of the interactions between plants and the microbiome occurs. This area is rich with root exudates, soil microbes, and organic matter.

PLANTS:

Plants also play an important role in the soil microbiome. Through photosynthesis, plants turn carbon dioxide into carbon-based sugars that the rest of the microbiome needs but cannot access as easily. In exchange for these sugars, known as root exudates, plants receive important micro- and macro-nutrients from the microbes. These **root exudates** also act as chemical signals that wake up, attract and signal specific bacteria to the **rhizosphere**, or root zone.

Both plants and soil microbes profit from this symbiosis. The above-ground and below-ground parts of the microbiome have formed these mutually beneficial relationships over millions of years, signaling each other and thriving together.

THE UNDERGROUND PLAYERS:

1. **Fungi:**

   Fungi are among the smallest of the soil microbiomes, but also one of the mightiest. Mycorrhizal fungi have symbiotic relationships with plant roots and may be found either close to the roots (ectomycorrhizal) or penetrating/growing into the roots (endomycorrhizal). The fungi find, unlock, and transport nutrients, like phosphorus, to the plant in exchange for the energy provided by the plants' exudates.

MANY MICROBES, MANY FUNCTIONS

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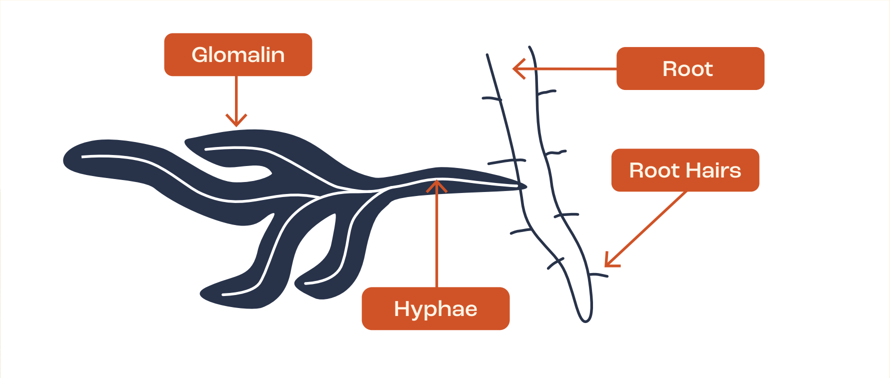
Fungi colonizing some exposed soil. Though soil does not always appear to have dense hyphae like pictured here, fungi is nearly omnipresent in most soil.

Fungal hyphae connect life in the soil, provide soil structure, and hold and carry micro- and macro- and macro-nutrients to plant roots.



Fungi project hair-like **hyphae** throughout the soil and rhizosphere, which exude **glomalin**, a sticky protein that connects life within the soil, helping hyphae hold soil particles together to form soil aggregates. Gathering soil together into aggregates helps prevent erosion and nutrient loss as a result of wind or rainfall and improves the soil's water holding capacity. The hyphae extend outward from the plant roots and can reach areas in the soil that are inaccessible to the roots alone, increasing access to water and nutrients.

Hyphae: As fungi grow, they spread through the soil as long, thread-like structures called hyphae. Hyphae transport water and nutrients throughout the fungal body, releasing the digestive enzymes that make fungi the primary decomposers in the soil food web.

Glomalin: Glomalin is a tough, sticky protein which surrounds fungal hyphae. Because it resists decay and does not dissolve in water easily, it's an excellent protector of the hyphae and prevents the loss of water and nutrients on the way to or from the plant. Glomalin plays an important role in the formation of soil aggregates by sticking together smaller soil particles.

MANY MICROBES, MANY FUNCTIONS

2

BENEFITS OF A HEALTHY BIOME

Cooperative:
All parts work together and influence each other, none can be left out.

Ecosystem Services:
- Carbon sequestration
- Nutrient cycling
- Water purification

Nutrient Factories:
A healthy, balanced population of microbes produces nutrients and processes them into plant available forms.

Farm Services:
- Increase in organic material and nutrient
- Mineralization
- Nitrogen fixation
- Improved soil structure

Plants and fungi need each other. With inefficient or overapplied nutrients, plants won't send those important chemical signals and energy through their root exudates that the fungi need. When soils become input dependent, the fungi grow weak and can no longer connect to the rest of the microbiome in the soil, including the bacteria within the soil that can unlock nitrogen and phosphorus for plants.

2. Bacteria:

In healthy soils, bacteria are concentrated around the rhizosphere and in soil organic matter. Proper soil structure plays an important role in providing habitat for soil bacteria, which can also be found in tiny spaces within the soil and in the watery films that surround soil particles.

The bacteria themselves produce a biofilm that influences soil pH, helps transfer and increase the availability of nutrients to plants and protects the bacteria from unfavorable environmental conditions in the soil.

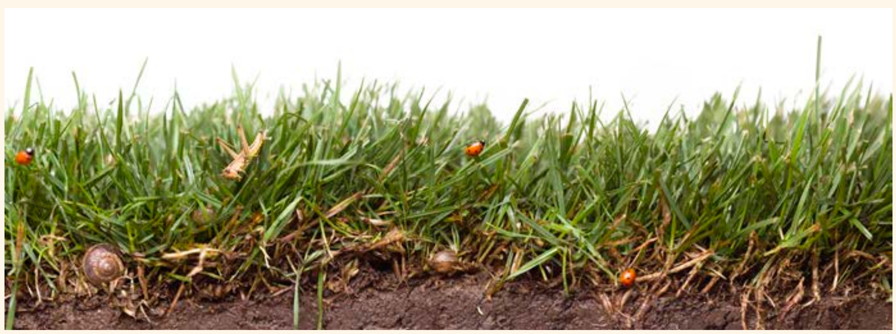
Bacteria are important decomposers of organic matter in the soil, second only to fungi. And like mycorrhizal fungi, many bacteria have symbiotic relationships with plants, feeding on plant exudates and in-turn providing nutrients to the plants. In fact, bacteria are a primary source of nutrients for plants and other soil organisms.

Aerobic soil bacteria, which grow in the presence of oxygen, are very good at providing nitrogen and phosphorus to plants. They fix atmospheric nitrogen into ammonium and solubilize phosphorus that is tied up in the soil into orthophosphates, both key forms of the nutrients that plants can access. The nitrogen-fixing bacteria require a microaerobic area of relatively low oxygen that can be found in the rhizosheath—pockets of soil stuck to plants' root hairs—and in water-stable aggregates formed by fungi. There, they use an enzyme called nitrogenase to break atmospheric nitrogen's triple bond.

Aerobic: Aerobic organisms cannot survive without oxygen—the key ingredient for their cellular respiration. Most animals and even many microbes all require aerobic (oxygenated) environments. In contrast, some organisms are anaerobic: they respire without oxygen and survive only in oxygen-free (or anaerobic) environments.

MANY MICROBES, MANY FUNCTIONS

Two kinds of nitrogen-fixing bacteria may be found in the soil: free-living nitrogen-fixing bacteria or symbiotic nitrogen fixing bacteria. The free-living bacteria fix atmospheric nitrogen for themselves directly and a plant-available form is released when the bacteria are consumed by fungi, protozoa, or other bacteria. Symbiotic bacteria, or rhizobacteria, fix nitrogen from within plant roots, forming an intimate carbon-for-nitrogen exchange relationship. Some bacteria may even colonize fungal hyphae, which can help transport nutrients to plants' root zone.



Arthropods in the soil are what we commonly call insects and bugs. They serve an important role in breaking down and aerating soil.

3. Nematodes, Protozoa and (Micro) Arthropods:

These microorganisms are likely to be found in healthy soil systems because they feed on bacteria, fungi, and each other. Knowing the benefits of bacteria and fungi in the soil, this may not sound beneficial, but it's actually an important way of mineralizing and releasing plant-available nutrients.

Because **protozoa** and **nematodes** need less nitrogen than bacteria do, when they consume bacteria they release excess nitrogen as ammonium. As long as fungal and bacterial populations are also present in the soil, this nitrogen can then be transported back to plants. As part of this cycle, protozoa and nematodes both regulate and stimulate the growth of bacterial populations. Some of these organisms also feed on fungi, mineralizing nutrients held within the fungi and releasing them back to plants.

Nematodes: Nematodes are blind, microscopic roundworms that live in the soil and can mineralize nutrients stored in bacteria and fungi. Some nematodes parasitically attack roots, but many others consume fungi, bacteria, and other members of the soil food web like protozoa, slugs, or grubs.

Protozoa: Protozoa are tiny, single-celled creatures that consume bacteria or fungi in the soil and by doing so, mineralize soil nutrients like nitrogen and make them available to plants. Some species may also keep harmful nematode populations in check. Protozoa need moisture and oxygen to survive.

MANY MICROBES, MANY FUNCTIONS

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Micro- and macro-**arthropods** feed on protozoa, fungi, and bacteria—and because they eat, they also excrete. As part of this biological process, nutrients within these microbes are mineralized and returned back into the soil in plant available forms.

A nematode under a microscope.

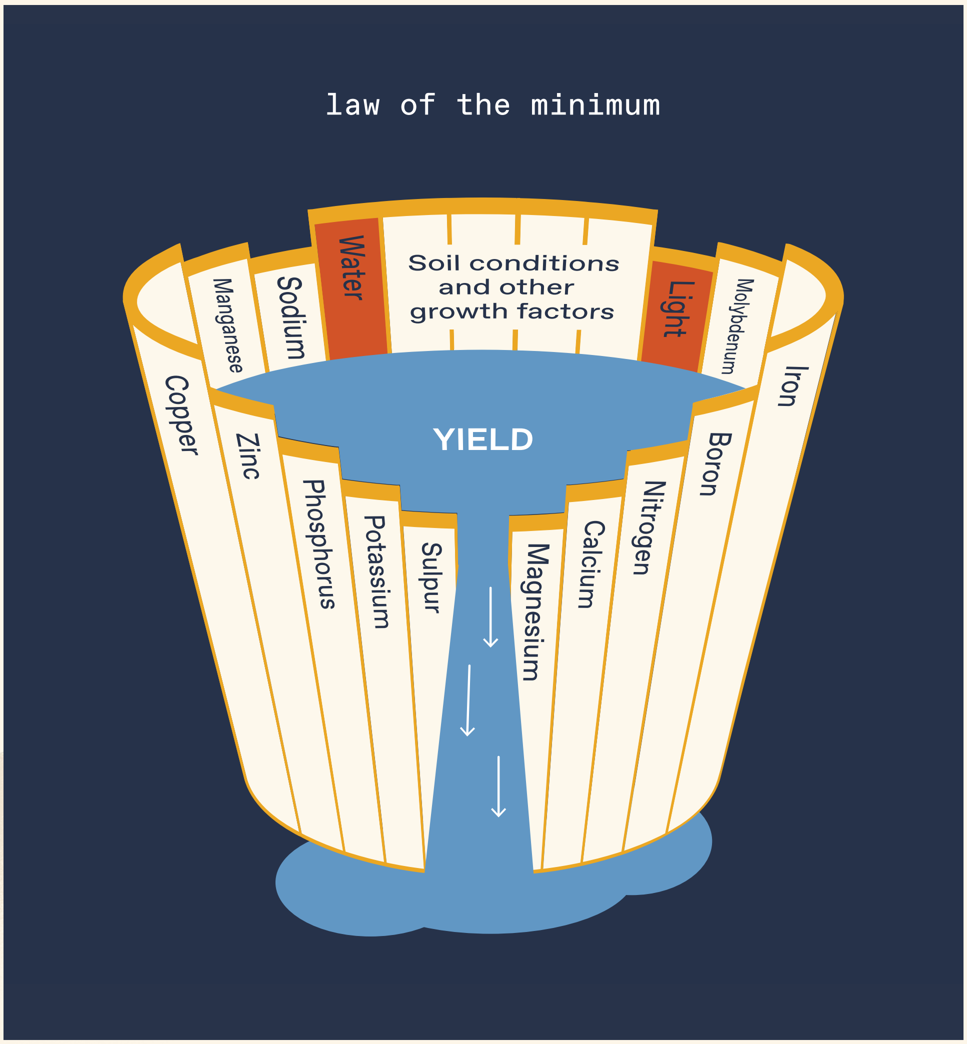
Soil compaction, poor soil structure, and a lack of bacteria and fungal populations can all have negative impacts on these microbes. Good soil management practices, on the other hand, can have a meaningful and positive influence on the soil food web.

(Micro)Arthropods: Arthropods are invertebrate organisms with exoskeletons and segmented bodies; they include larger creatures like shrimp and scorpions as well as microscopic organisms like dust mites. Growers are most concerned with the bugs and insects that are some of the larger organisms in the soil food web. In the soil, these micro- and macro-arthropods may shred larger pieces of organic material, which promotes bacterial and fungal activity. They also consume other members of the soil food web, add organic matter through their waste, and mix and aerate the soil.

ON THE FARM: CULTIVATING A HEALTHY MICROBIOME

3

A diverse and healthy soil microbiome can be a powerful asset for growers by providing crops with in-season access to key nutrients, minimizing soil loss to erosion and maintaining soil structure for sturdy root growth. But different on-farm practices will have different effects on soil health; understanding these impacts is key to leveraging the benefits of the microbiome as much as possible and improving ROI.



LIEBIG'S LAW OF THE MINIMUM

Liebig's Law of the minimum states that yield is determined by whichever factor necessary for plant growth is most limiting, which can include water, sunlight or individual macro- and micro-nutrients. If a soil is deficient in magnesium, for example, all other nutrients may be abundant, but yield will not increase. The best way to safeguard yield is for growers to balance their crops' needs and ensure there are as few limiting factors as possible.

ON THE FARM: CULTIVATING A HEALTHY MICROBIOME

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THE INEFFICIENCY OF FERTILIZER APPLICATIONS

A grower's operation is not a closed loop system; factors beyond our control, like weather and soil chemistry, all impact nutrient availability.

In a perfect world, 100% of the nutrients growers apply to their field would be used by the plant to grow bigger and produce higher yields, but unfortunately, some portion never makes it to the plant. How much of an applied nutrient is actually used by a crop is called "nutrient use efficiency," or **NUE**.

NUE: Nutrient use efficiency, or NUE, is a measure of how much of an applied nutrient is actually used by a crop. Ideally, all of the fertilizer applied to a field would be used by the plant, but some amount is lost or becomes locked in the soil. By monitoring NUE, growers may be able to find opportunities to lower input costs while maintaining yields.

On average, between 30 to 50% of applied nitrogen and 75 to 80% of applied phosphorus never make it to the plant and are wasted.

Nitrogen is generally lost in one of three ways:

Volatilization: Several factors can increase the loss of nitrogen through volatilization, including high soil pH, windy and/or hot weather conditions, and surface application of nitrogen without incorporation into the soil. Even when incorporated though, some loss to volatilization is likely.

Denitrification: When there is sufficient nitrogen and low oxygen conditions, such as in poor draining soils, soil microbes may use nitrate as a source of oxygen and release nitrogen gas, resulting in denitrification. This is especially a risk when nitrogen is over applied.

Leaching: This is the loss of nitrogen via runoff. Soil particles do not hold nitrate well—instead, water can easily move nitrate through the soil and into surface water. Not only is this an expensive loss for growers, but high nitrate levels in surface water can contribute to harmful algal blooms and can seriously affect human health when in drinking water.

HEALTHY SOIL OUTCOMES:

- Increase field resilience to weather events
- Decrease loss of topsoil to erosion and runoff
- Increase plant nutrient availability
- Increase water-use efficiency
- Increase yield
- Decrease inputs

Phosphorus is primarily lost through soil tie up. Negatively charged orthophosphates can form strong bonds with soil particles and elements like calcium, aluminum and iron, making them unavailable to plants.

RESTORING BALANCE IN THE SOIL

4

In the search for a more regenerative and resilient operation, there is no definitive place to start and no end state. Each growers operation is unique and each will be an ongoing project. However, there are four good categories to start with: reduced tillage, cover crops, targeted nutrient application and monitoring NUE.

1. **Reduced Tillage**
   Whether or not a grower can go completely, there are significant benefits to be gained from reducing tillage in general. First, it can provide a benefit to soil organic matter content. In soil, organic matter is created from the top down, which means that burying or tilling in organic material is less effective than leaving it on the surface to break down naturally.

Fields using reduced tillage retain a layer of organic matter on the surface instead of having it buried beneath the soil.

Second, soil structure, especially at the surface, can benefit greatly from reduced tillage. Untilled soils have higher water retention and reduced runoff and erosion because the beneficial structures created by the microbiome are left undisturbed. And by running fewer vehicles across the field, growers can also reduce compaction.

Finally, reducing tillage improves soil carbon retention and carbon sequestration. Increased soil organic material represents a food source for many members of the soil microbiome. The more organic matter and the larger the microbiome population, the more carbon is sequestered in the soil instead of being lost to oxidation.

2. Cover Crops

As long as living roots are in the soil, growers benefit from the interactions within the soil microbiome. Cover crops provide an opportunity to maintain soil structure and microbial health outside the cash crop's growing season.

Depending on which cover crop a grower chooses, there may be an opportunity for the plants to take up excess nitrogen on the field and store it in organic matter until it decomposes later to benefit the cash crop. Growers can also plant nitrogen-fixing cover crops to increase nutrient availability.

Introducing cover crops also helps growers move away from monocultures and toward polycultures. Because different plants release different hormones to attract different microbes, introducing different crop varieties (even just as cover crops) can improve soil health.

A cover crop in early stages at a farm in Iowa.

3. Targeted Nutrient Application

The four Rs of fertilizer application are key to efficient fertilizer application: right place, right time, right amount, and right source. By applying as little nutrient as possible–only what the plants need, when they need it—growers can maximize their nutrient use efficiency (NUE), benefit soil health, and reduce input costs.

To reduce loss, some growers may use nitrogen stabilizers or split apply by making two or more application passes in a season instead of front-loading fertilizer application. Banding nitrogen can also help reduce nitrogen application while ensuring crops have access to the nutrients

Soil samples can help growers understand what is in the soil and respond appropriately, but attention should also be paid to uptake; there may be plenty of nitrogen in the soil, is it getting into the plant? Regular tissue testing can help reveal what may be preventing nutrients from getting to the crop, allowing growers to respond proactively.

4. Monitoring Nutrient Use Efficiency (NUE)

By monitoring their nutrient use efficiency (NUE), growers can get a sense of how well their nutrient application is working and whether there's an opportunity to reduce costs and improve soil health.

A grower's last pounds of nitrogen are often negative in terms of profit ability, as any yield increases are often not enough to offset the input cost. Understanding NUE can help growers assess which on-farm practices are providing the best ROI and track their progress towards reducing inputs and improving soil health.

HOW TO CALCULATE NUE

Pounds of nitrogen
[divided by] = NUE
Number of bushels

Example:

200 lbs
[divided by] = 1.25
160 bu

5 CONCLUSION

A robust and healthy soil microbiome is one of a growers biggest assets, yet it is often underutilized. Taking advantage of the benefits to soil structure, plant nutrition, and farm resilience requires an understanding of how the soil food web functions as a system and a willingness to work with the soil. Integrating regenerative tools like a microbiome activator, reduced tillage and targeted nutrient application can help growers reduce their reliance on individual inputs. By balancing their operation on a diverse network of beneficial practices and factors, growers can reduce input costs, increase resiliency and maintain yields; the secret to this success is within the soil.

RESOURCES

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Agronomy Fact Sheet, "Nitrogen Basics – The Nitrogen Cycle," Cornell University Cooperative Extension
www.cceonondaga.org/resources/nitrogen-basics-the-nitrogen-cycle

This fact sheet is part of an Agronomy Fact Sheet Series from the Cornell University Cooperative Extension. It covers the basics of the nitrogen cycle as it applies to agriculture. It includes information on the most plant available forms of nitrogen and the most common ways nitrogen is lost to the environment.

Agronomy Fact Sheet, "Phosphorus Sources for Field Crops," Cornell University Cooperative Extension.
www.cceonondaga.org/resources/phosphorus-sources-for-field-crops

Another fact sheet from Cornell University Cooperative Extension's Agronomy Fact Sheet Series, this one provides information on different phosphorus sources for field crops. In addition to descriptions of the most common phosphorus sources used in the state of New York, it also includes a table comparing the advantages and disadvantages of different phosphorus fertilizers.

Don Comis, "Glomalin: Hiding Place for a Third of the World's Stored Soil Carbon," Agricultural Research, September 2002.
www.agresearchmag.ars.usda.gov/2002/sep/soil

Glomalin holds a huge amount of stored carbon and plays an important role in soil texture and soil organic matter content. This article, published by USDA, can help growers understand this key component of the soil microbiome and better preserve and promote soil health.

Jeff Lowenfels & Wayne Lewis, Teaming with Microbes (Portland: Timber Press, 2006).

Although this book is primarily aimed at organic gardeners, it offers an accessible and in-depth exploration of a variety of soil microorganisms. For growers looking to expand their understanding of the soil food web, this is a good introductory resource.

RESOURCES

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Sound Agriculture, “How to Gain Access to the Soil’s Phosphorus Vault,” April 14, 2021.
www.sound.ag/blog/how-to-gain-access-to-the-soils-phosphorus-vault

Phosphorus often forms strong bonds with other elements in the soil, becoming locked up and inaccessible to growers and their crops. This blog explores the mechanisms of phosphorus tie up and potential solutions growers can use to gain access to the soil’s phosphorus vault.