The Soil is Alive!

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1. Introduction

In most ecosystems, more life and diversity exists underground than above. The soil is home to a vast array of organisms, including bacteria, cyanobacteria, algae, protozoa, fungi, nematodes, and mites, insects of all sizes, worms, small mammals and plant roots.

Soil organisms play critical roles in plant health and water dynamics. Some of the processes soil organisms contribute to are nutrient cycling, nutrient retention, water infiltration and water-holding capacity, disease suppression, and degradation of pollutants. They also increase the biological diversity of the soil and improve soil structure.

Soil biological processes are responsible for supplying approximately 75% of the plant available nitrogen and 65% of the available phosphorus in the soil. Like all organisms, those inhabiting your soil need food and a favorable environment. Adequate organic matter content, ample aeration, moderate moisture, neutral pH, and warm temperatures all favor increased microbial activity.

By maintaining a high soil organic matter content you can build habitat and food for a diverse community of soil organisms. Not only does organic matter provide good habitat, but it also is of great benefit to chemical and physical soil characteristics. Moisture, pH, nutrient supply, and the biological community are all more stable, or “buffered,” as soil organic matter increases. Organic material also helps to maintain soil porosity, which is essential because most beneficial soil microbes and processes are aerobic, requiring oxygen.

2. The Root Zone

Most biological activity takes place in the top 8-12 inches in the soil profile. The rhizoshpere, or rooting zone, is an area of intense microbial activity and is integral to plant and soil relationships.

Plant roots leak energy-rich carbon compounds, sugars, amino and organic acids called exudates. Every plant species leaks a unique signature of compounds from their roots. Different microbes are attracted to different chemical exudates. The plants grown play a large role in determining the microbial community in the soil below.

3. Bacteria

a. Rhizobium

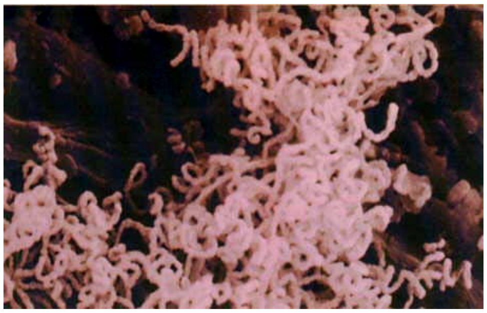
b. Nitrifying Bacteria

c. Denitrifying Bacteria

Bacteria are the smallest and most numerous of organism in the soil. Collectively there are billions of individuals in an ounce of soil. Some experts think that less than half of the species of bacteria, and therefore their functions, have been identified.

Most bacterial species are decomposers that live on simple carbon compounds, root exudates and plant litter. They are the first on the scene when nutrients and residue are added to the soil. They convert these compounds into forms readily available to the rest of the organisms in the food web. Actinomycetes are an example of microbial decomposers (Photo 1). They grow hyphae like fungi, but are closer to bacteria in their evolutionary history. Actinomycetes arrive later in the decomposition process, and are responsible for the “earthy” smell of freshly tilled soil.

Photo 1. Actinomycetes. Photo courtesy of Soil Biology Primer.



3a. Rhizobium

Other bacterial species form partnerships with plants. The most well-known of these are the nitrogen (N) fixing bacteria, rhizobium, that form symbiotic relationships with legumes, such as alfalfa, soybeans, edible beans, and clover. Rhizobium infect the roots of the host plant (Photo 2) and convert atmospheric nitrogen (N_2) into plant-available amino nitrogen (NH_2). They can supply the plant with all of its nitrogen needs. In return, the host plant supplies the rhizobium with simple carbohydrates. The plant can give up to 20% of its supply of carbohydrates to the bacteria. However, if there is a sufficient supply of nitrogen in the soil to meet the plant’s needs, the plant will not engage in the relationship with the bacteria.

Photo 2. Rhizobium bacteria nodules on a soybean plant. Photo courtesy of Stephen Temple.

A healthy, well-nodulated legume crop can supply its own N needs, but extra N is produced which carries over to the next crop. This results in a “nitrogen credit” that is an important factor in making N fertilizer recommendations. It may be difficult to account for all of the sources that contribute to this credit. One source is nitrogen mineralized from the old roots and leaves of the legume. Another source is the beneficial microbial community created by the legume. Table 1 shows the nitrogen credits that can be expected from different legumes.

Table 1. Nitrogen credits from different legume species in the first year of corn following a legume (10).

Legume Crop	**1st Year Nitrogen Credit**
	------- lb./acre -------
Soybeans	40
Harvested Alfalfa	
4 or more plants/ft^2	150
2-3 plants/ft^2	100
1 or less plants/ft^2	40
Red Clover	75

For each legume species there is a corresponding rhizobium**.** For example, the species of rhizobium for soybeans is *Bradyrhizobium japonicum* while the species for alfalfa is *Sinorhizobium meliloti***.** To effectively inoculate the soil, you must use the rhizobium specific to the legume grown. When a legume is introduced into a soil that has not been previously cropped to that species, it is unlikely that the soil will contain sufficient numbers of the correct rhizobia. In these cases a yield response to seed inoculation is likely. Where such inoculation is properly carried out, senescence of the nodules at the end of the growing season will return large numbers of rhizobia to the soil. This should ensure that inoculation in future years will be unnecessary. However, there have been benefits from inoculation if the crop has not been grown in the last 3-5 years in that field.

Rhizobium are easily applied to the seed and the preferred inoculant for any legume is a sterile-peat based culture. However, inoculants may also be supplied in a non-sterile peat, as a liquid or frozen concentrate, or as a clay-based or granulated peat preparation.

Generally, in the US, we include more than one strain in an inoculant, but in Australia, Canada and France the inoculant usually contains only a single strain. Control of inoculant quality is also more formalized in Australia and Canada than in the U.S. For more information on Rhizobium inoculants visit http://www.rhizobium.umn.edu/.

3b. Nitrifying Bacteria

Nitrifying bacteria, *Nitrosomonas* and N*itrobacter*, convert ammonium (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-). Nitrate is the preferred form of nitrogen for row crops.

However, nitrate is also the form of nitrogen that is most easily leached out of the root zone.

We recommend that fall applications of anhydrous ammonia be made only after the soil temperature at a 6-inch depth is 50^{o} F or below. Nitrifying bacteria have very low activity below this temperature, therefore, over-winter leaching losses of nitrate are reduced. In addition, the very low vapor pressure of ammonia below 50^{o}F virtually eliminates direct loss of ammonia during or after application. Table 2 lists the time it takes nitrifying bacteria to convert different N fertilizers to nitrate-N.

Table 2. Rate of conversion of different fertilizer sources to nitrate-N (7).

Fertilizer Material	**Conversion Time to Nitrate**
Ammonium Sulfate 10-34-0, MAP, DAP	1-2 weeks
Anhydrous Ammonia	3-8 weeks
Urea	1 ½ -3 weeks
Ammonium Nitrate	50% is nitrate: 0 weeks 50% is ammonium: 1-2 weeks
UAN	50% is urea: 1 ½- 3 weeks 25% is ammonium: 1-2 weeks 25% is nitrate: 0 weeks

3c. Denitrifying Bacteria

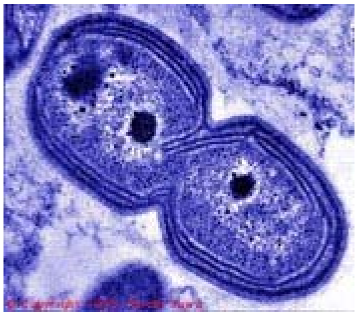
Some bacteria can live without oxygen or in anaerobic conditions. Denitrifying bacteria are an example of anaerobic bacteria that convert NO_3^- to nitrous oxide gas (N_2O) and then to nitrogen gas (N_2). Once the nitrogen is in a gaseous form, it is no longer available for plant uptake and will escape back to the atmosphere. There are 13 different species of bacteria responsible for this process. They become active when the soil has at least 50% of its pore space filled with water and are most active when the soil is saturated. Denitrifying bacteria under saturated conditions can convert 2-4 pounds of nitrate to a gaseous form per acre per day. There are commercial products available to reduce the potential for nitrogen loss from either volatilization or leaching. Below, the two most popular choices are described.

N Serve

The goal for all fall applications of N fertilizer should be to keep as much nitrogen as possible in the ammonium (NH_4^+) form going into the winter. With this strategy, only small amounts are present in the nitrate (NO_3^-) form and, thus, not subject to spring losses caused by leaching and denitrification.

Nitrapyrin, known commercially as N-Serve, selectively inhibits *Nitrosomonas* bacteria (Photo 3), which in turn slows or stops the conversion of ammonium to nitrite. N-Serve is typically added to anhydrous ammonia and liquid fertilizers to prevent the conversion of ammonium to nitrate.

Photo 3. Nitrifying bacteria cross section. Photo: Mary Ann Bruns, Center for Microbial Ecology, Michigan State University.



An Illinois study found that the earlier ammonia is applied in the fall, the more ammonia is converted to nitrate, increasing the potential for leaching (Table 3). Adding a nitrification inhibitor decreased the conversion rate but did not stop it entirely.

Table 3. Rate of conversion of anhydrous ammonia to nitrate by May 25, 2004 in northern Illinois. Source: Robert Hoeft, University of Illinois.

Application Date	Ammonia Without N Inhibitor	Ammonia With N Inhibitor
November 1, 2003	85%	55%
December 1, 2003	60%	45%
March 15, 2004	50%	20%
April 1, 2004	35%	15%

Another study was conducted at Waseca, MN to look at the effects of a nitrification inhibitor on corn yield over a 14-year period. Average corn yields showed that yield from spring-applied anhydrous ammonia by itself and fall-applied anhydrous ammonia with N-Serve was equal. However, the yield from fall applied nitrogen <u>without</u> N-Serve was lower for only 6 out of the 14 years. Therefore, there is no guarantee that use of N-Serve with 82-0-0 in the fall will increase yields. Loss of nitrogen is a complex relationship and not an exact science. It is based on the timing of nitrogen application, soil temperatures, rainfall totals and intensity, and soil texture. Both of these studies stress that the use of N-Serve must be viewed as an insurance policy - not a guarantee.

Agrotain

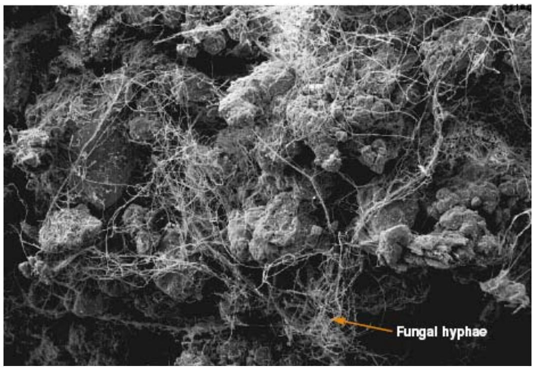
Agrotain is a urease enzyme inhibitor that is designed to delay ammonia volatilization when applied with urea ammonium nitrate (UAN) or urea. This delay allows more time to get the urea incorporated into the soil through rainfall before N losses occur. Agrotain has the greatest benefit in reducing volatilization when urea or UAN is surface-applied or where limited or no soil incorporation occurs, such as in a no-till system. Varsa et al. (14), found that in most studies Agrotain in combination with urea gave greater yield increases (average 14 bu/ac) than did Agrotain used with UAN (average of 7 bu/ac). The greatest yield benefit from Agrotain was observed when applied with urea to corn in a corn-soybean rotation (30 bu/ac). Yield decreases with application of Agrotain also occurred; yield reductions of 10 bu/a or more were seen in 7% of the sites. Consistent crop yield increases are not expected every year or on all fields. Benefits will likely occur 30 to 40% of the time; with negative impacts on yield 5 to 10% of the time. Overall, these data highlight that when conditions for N loss exist, Agrotain can help prevent N loss. However, yield gains will not necessarily be realized every year (7).

4. Fungi

a. Arbuscular Mychorrhizae

Fungi are a critical contributor to decomposition and nutrient cycling. Fungal activity is often slower to develop than bacteria and is more active on relatively high carbon to nitrogen ratio (C:N) and lignin-containing materials, such as corn residue. Fungi, more so than bacteria, enhance soil physical structure and add chemical compounds that bind soil aggregates and serve as building blocks for organic matter (Photo 4).

Photo 4. Fungal hyphae binding soil particles together into aggregates. Photo courtesy of Gupta Vadakattu, CSIRO group.



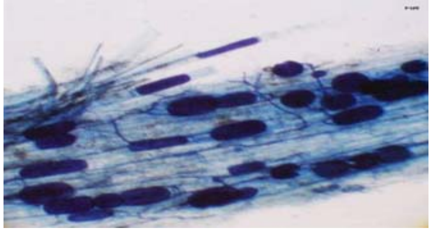
Although most fungi are beneficial, there are several species that are notorious as pathogens. These include the fungi S*clerotinia* (White Mold), *Fusarium*, *Pythium*, *Phytophthora*, and *Rhizoctonia* (Photo 5).

Photo 5. White mold infection on soybean. Photo by X.B. Yang, University of Minnesota.

4a. Arbuscular Mychorrhizae

One particularly beneficial and important type of fungi is Arbuscular Mycorrhizae (AM). AM fungi form a mutually beneficial relationship with 80% of all land plants including most agricultural crops (Photo 6). AM fungi are critical in the early establishment and growth of corn and most cereal crops. They are also important to sunflower, soybeans, flax and potatoes.

Photo 6. Endotrophic mychorrizae infecting a plant root. Photo by Marcia Wicklow - Howard, Boise State University



Mycorrhizal hyphae are 1/10th the size of root hairs and they extend throughout the soil mobilizing nutrients for the plant (Table 2). In exchange, the fungi receive food from the plant in the form of carbohydrates. Similar to the relationship between a leguminous plant and a bacterial rhizobium, colonization of plant roots by AM will be inhibited if the plant has sufficient levels of soil phosphorus.

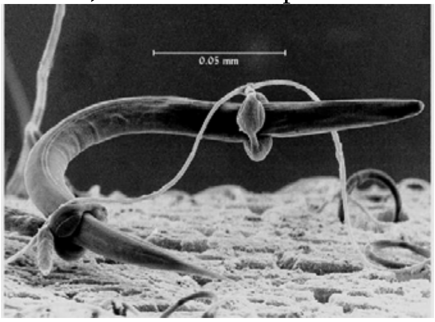
Table 2. Nutrients taken in by plants that are infected and are not infected with AM when no phosphorus is added to corn (8).

Element	**No Mycorrhizae**	**With Mycorrhizae**
	--------Micrograms/plant--------	
Phosphorus	750	1340
Potassium	6,000	9,700
Calcium	1,200	1600
Magnesium	430	630

Zinc	28	95
Copper	7	14
Manganese	72	101
Iron	80	147

Due to the hyphal density of the fungi on the plant root, AM are known to increase resistance of the host plant to root diseases by acting as a physical barrier. Photo 7 shows the direct effect of hyphae on a nematode. Additionally, AM can increase water efficiency and drought tolerance in times of low soil moisture.

Photo 7. A nematode being trapped by the hyphae of fungi. Photo courtesy of George Barron, Univ. of Guelph.



Fungi need oxygen, nutrients, neutral pH, and a host to survive. Crops that are non-hosts and therefore do not support AM establishment are canola, sugarbeet, mustard, lupines and other brassicas. Frequently saturated soils or black fallow will dramatically decrease the number of AM. Other agents that will decrease their populations are ammonia present in alkaline soils, aluminum, and possibly tannins from leaf litter.

Mycorrhizal Inoculants

Similar to rhizobium, AM fungi inoculants often show benefits to crops when the correct species or strains are present at low populations in the soil. Generally, inoculated organisms will not last long if the environment is not suitable. If the environment is suitable, the organisms are probably there anyway. Good organic matter content along with good moisture and aeration are all that most beneficial microbes will need.

Unlike rhizobium, AM are not easily applied to the seed. Mycorrhizae cannot be grown in artificial medium and must be cultured on plant roots. Therefore, the seed is coated with clay granules that contain the appropriate strain of AM. Because of this process, inoculation of AM is difficult and economical only for horticulture crops, turf grass, or high value crops.

5. Nematodes

Nematodes are microscopic, worm-like organisms that are very abundant in the soil (Photo 8). Nematodes are beneficial because they enhance the rate of nutrient cycling by grazing on bacteria, other microorganisms, or by eating organic matter and debris. A few nematodes are plant parasites, such as the soybean cyst nematode. Root-feeding nematodes use their stylets to puncture the thick cell wall of plant root cells and siphon off the internal contents (Photo 9).

Photo 8. Soil nematode.

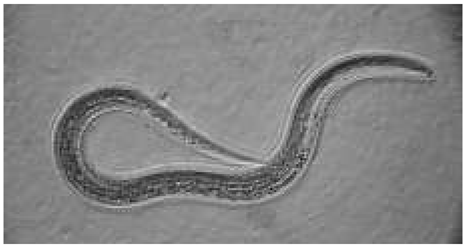


Photo 9. Root feeding nematode. Photo by Elaine R. Ingham.

There are beneficial nematodes that feed on bacteria and fungi and not plant roots. Bacteria and fungi are high in protein that in turn is high in nitrogen. When these nematodes eat bacteria or fungi they digest the protein and excrete nitrogen into the soil in a form that becomes available to plants (2).

Nematodes are a biological control agent of armyworms, root weevil, black cutworm, grubs, Japanese beetles, ants, fleas, and over 250 other soil dwelling pests. When nematodes come into contact with their prey, they attack by entering through body openings or simply by boring through the body wall. Once inside, the nematode releases a bacteria that kills the host organism within 24-48 hours. Such nematodes will feed and reproduce before exiting in search of fresh prey.

Beneficial soil nematodes are usually more abundant in crop management systems that include multiple crop sequences, reduced cultivation, and the addition of organic amendments. Infective juveniles are compatible with most, but not all, agricultural chemicals under field conditions. Many chemicals recognized to be toxic to nematodes have only a transient effect, and nematodes recover quickly after exposure. For more information on nematodes and commercial nematode pest application go to: http://www.nysaes.cornell.edu/ent/biocontrol/pathogens/nematodes.html

6. Management That Decreases Microbial Populations

Some fertilizers and agrichemicals have a negative impact on soil microbes. Anhydrous ammonia, some nematicides, and ammonia-rich and sulfur-rich fertilizers can directly harm soil life or indirectly hamper their growth by decreasing soil pH (acidification).

Increased pest and pathogen problems are often caused by insufficient rotation interval between crops. This is at least partially due to reduced biological diversity and weakened communities of beneficial organisms. If the soil microbes are not working for you they are more likely to work against you. Soil biota includes hundreds of pathogens, which are more likely to dominate the soil community if beneficial organisms have declined. When beneficials dominate the community, they suppress pathogens by competition and predation, and act as a physical protective barrier for plant roots.

Tillage directly affects soil porosity and the placement of residues. Porosity determines the amount of air and water the soil can hold. Placement of residues affects the soil surface temperatures, rate of evaporation and water content, nutrient loading, and rate of decay. In other words, tillage collapses the pores and changes the water holding, gas, and nutrient exchange capacity of the soil. Reducing soil disturbance increases the diversity and population of soil organisms. These soils release nutrients gradually and have better soil structure than full width tillage systems (2).

7. Management That Increases Microbial Populations

A more diverse soil community results in a more flexible soil. This means a soil has the ability to successfully grow a number of crops and is resilient in drought, low nutrient conditions and after a disturbance. Agricultural practices such as tillage, crop rotations and fertilizer inputs affect the numbers, diversity and functioning of the soil community (2).

Organic matter from roots, plant biomass, manure, and compost provide the food energy to support the biological community. Cover crops and green manure crops increase the length of time that plants are actively growing in a soil, providing a steady influx of food for soil microbial populations. Cover crops also aid in reducing soil erosion. Diverse crop rotations can also help disrupt some pathogen cycles.

To promote soil biodiversity:

- add organic matter regularly (cover crops, green and livestock manures)
- diversify the type of plants across the landscape (crop rotation, grass waterways, and CRP)
- maintain residue cover
- avoid excessive soil disturbance (intensive and secondary tillage, compaction, heavy use of pesticides)

It is important to remember the general philosophy that beneficial soil organisms “need to be needed.” That is, if the farm system depends on and supports their activities, more biomass and positive activities will develop. If the farm system depends solely on chemical inputs instead of biological inputs, beneficial biomass and activities will decline.

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