Benefits of a healthy foodweb

A healthy foodweb occurs when:

1. All the organisms the plant requires are present and functioning.
2. Nutrients in the soil are in the proper forms for the plant to take-up. It is one of the functions of a healthy foodweb to hold nutrients in non-leachable forms so they remain in soil, until the plant requires the nutrients, and then the plant "turns-on" the right biology to convert the nutrients into forms the plant can take-up (but which are typically very leachable).
3. The correct ratio of fungi to bacteria is present, and ratio of predator to prey is present, so soil pH, soil structure, and nutrient cycling occur at the rates and produce the right forms of nutrients for the plant.

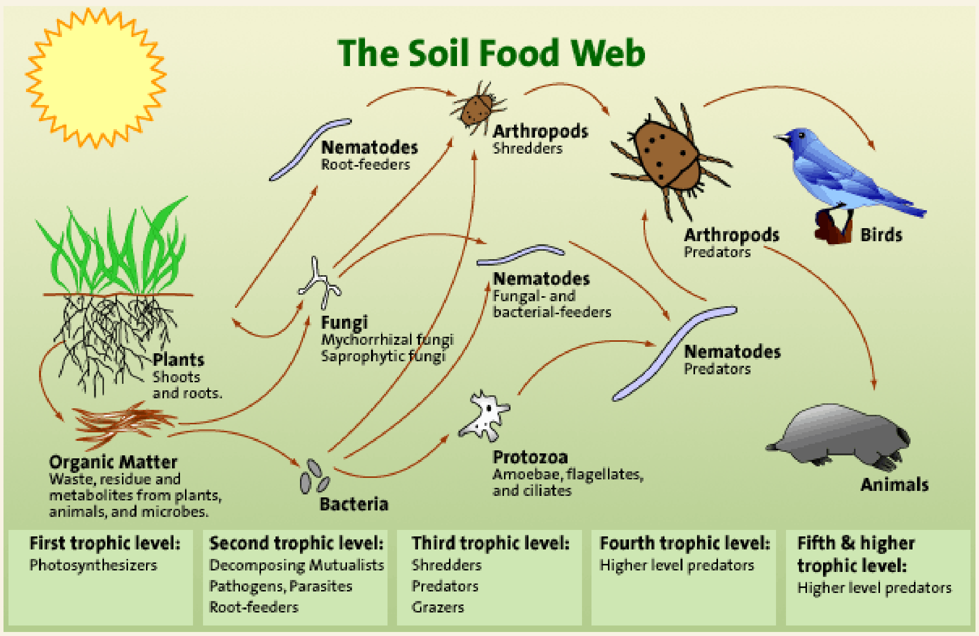
The functions of a healthy foodweb are:

1. Retention of nutrients so they do not leach or volatilize from the soil. Reduction or complete deletion of inorganic fertilizer applications is possible.
2. Cycling nutrients into the right forms at the right rates for the plant desired. The right ratio of fungi to bacteria is needed for this to happen, as well as the right numbers and activity of the predators.
3. Building soil structure, so oxygen, water and other nutrients can easily move into the soil and into deep, well-structured root systems. Current concepts of plant root systems as being at the surface of the soil is the result of current agricultural and urban practices, not a real condition of plants. Roots should go down into the soil for at least several to 10's and perhaps 100's of feet, but the compaction that humans impose on soil results in toxic materials being produced, preventing good root penetration. The only way to deal with this is to have the proper biology build the structure in the soil again, so oxygen and water can move into the soil. When the biology is functioning properly, water use is reduced, the need for fertilizers is reduced, and plant production is increased.
4. Suppression of disease-causing organisms through competition with beneficials, by setting up the soil and foliar conditions to help the beneficials instead of the diseases.
5. Protection of plant surfaces, above or below ground by making certain the foods the plant surfaces release into the soil are used by beneficial, not disease organisms, making certain that infection sites on plant surfaces are occupied by beneficial, and not disease-causing organisms. And by making certain predators that prefer disease-

Example: Ciliates are aerobic organisms, but prefer to consume anaerobic bacteria. Indicates problems with the movement of oxygen into the soil - Needs to be fixed - need good air/gas exchange.

causing organisms are present to consume disease-causing organisms.
6. Production of plant-growth-promoting hormones and chemicals can result in larger root systems, although whether forcing larger root systems on plants is a positive results needs to be understood.
7. Decomposition of toxic compounds

Organisms exist in populations that are balanced according to optimal growth conditions for your type of plant



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12-Step Approach to Understanding the Soil Foodweb

(Use this information to interpret your soil testing lab results)

Step One

Bacteria must be present to perform their functions of competing with disease-causing organisms, retaining nutrients and making micro aggregates to improve soil structure. The "correct" density of bacteria or amount of bacterial activity has just begun to be established, based on observation of what these levels are in different soils, climates, conditions, disturbances and plant species. Seasonal variations and the requirements of different plants appear to be the most important relative factors. Again, the values for active bacteria and total bacteria are given for the season, plant type, soil type and climate in the row marked "desired range".

1. When total bacterial biomass is too low, bacteria have to be added back to the soil, compost, compost tea or to the water, if working in hydroponics, for example. Add them back by using a healthy, aerobic compost, compost tea or commercial inoculums
2. When total bacterial biomass is high, most of the time this means improved ability to perform bacterial functions, but if the balance between total bacteria and total fungi becomes inappropriate for the plant species, then the balance needs to be restored. However, you don't kill off bacteria if they are higher than the desired ratio, you improve fungal biomass instead (see Ratios).
3. On rare occasions, total bacteria may compete with fungi for food resources, and in this case, reducing bacterial foods may be a good idea, to allow the fungi to have a chance to grow. Too high bacterial biomass, combined with too low active bacteria biomass may indicate anaerobic conditions occurred, because the bacteria grew very fast, used up the oxygen in the medium so the aerobic organisms went to sleep, but the anaerobes grew well. This can be very detrimental to the aerobic organisms, and actually kill them.

Step Two

Feed the bacteria, if bacterial activity is too low. Just like any other creature, bacteria require food. Plant roots often supply the simple carbon substrates that bacteria require, such as simple sugars, proteins, and carbohydrates. Bacteria need N, P, K, Ca, and all the other nutrients as well, and obtain those from organic matter and from inorganic sources as well. Various species of bacteria can solubilize mineral elements from the mineral components of soil, but no one species can effectively solubilize ALL minerals. Diversity of species to obtain all the needed nutrients is required.

Diversity is key to solving nutrient availability! Bacteria need N,P,K,Ca, and all other nutrients and they obtain those from SOM and from inorganic sources as well. Various bacteria can solubilize mineral elements from the mineral components of the soil, but no one species can effectively solubilize all minerals. Diversity of species to obtain needed nutrients is required!!!

Often soil tests will indicate that some nutrient is in low supply, but merely by adding the appropriate bacterial or fungal species, these organisms will convert plant unavailable nutrients into plant available forms. Diversity is the key, however, as well as feeding that diverse set of species so they will perform their functions.

Feed diverse set of species so they perform their functions! When soil tests indicate that some nutrient is in low supply, merely adding the appropriate bacterial or fungal species will convert plant unavailable nutrients into plant available forms. Diversity is key, feed the diverse set of species so they will perform their functions.

If activity is low, then bacterial foods need to be added to increase growth rates and improve numbers. A diversity of foods needs to be added, and thus molasses is a much better choice than white sugar. Fish hydrolysate also adds fungal foods, and N and other micronutrients. Fruit juices can be used as well, but diversity is key.

If activity is higher than the desired, then try to balance the ratios of the organisms by improving the organism group that is too low.

If active bacterial biomass is low, but total bacterial biomass is high, this is a good indicator that anaerobic conditions have occurred. In rare instances, it may be because some environmental disturbance occurred that put the majority of the bacteria to sleep, but did not kill them.

Step Three

Fungi must be present to perform their functions of competing with the more difficult disease-causing organisms, retaining nutrients especially micronutrients like Ca, and making macro aggregates which form air passageways and hallways to allow air and water to move into the soil, and to allow good drainage. This is a critical step in improving soil structure, but cannot occur without the first step of good bacterial biomass.

The "correct" density of fungal biomass, or amount of fungal activity, has just begun to be established, based on observation of these levels in different soils, climates, conditions, disturbances and plant species. Seasonal variations and the requirements of different plants appear to be the most important relative factors. Again, the values for active fungal biomass and total fungal biomass are given for the season, plant type, soil type and climate in the row marked "desired range".

When total fungal biomass is too low, fungi will need to be added back to the soil, compost, compost tea or to the water, in hydroponic situations, for example. Add them back by using a healthy, aerobic compost or compost tea. Alternatively, these fungi might be found in healthy soil, especially the humus layer of a healthy forest. But be careful not to destroy that resource by removing too much, or disturbing too much.

When total fungal biomass is high, most of the time this means improved ability to perform fungal functions, but if the balance between total bacteria and total fungi becomes inappropriate for the plant species, then the balance needs to be restored. However, you don't kill off fungi if they are higher than the desired ratio, you improve bacterial biomass instead (see Ratios).

On rare occasions, total bacteria may compete with fungi for food resources, and in this case, reducing bacterial foods may be a good idea, to allow the fungi to have a chance to grow. High total fungal biomass, combined with

Fish Hydrolysate adds fungal food and N and other micronutrients. Fruit juices can be use as well - Diveristy is Key!

Fungi are the Major Holders of Calcium in the Soil!!

Fungi make macro-aggregates which form air passage ways to allow air and water deeper into the soil -
AMF follow the root down and feed associative Bacteria -Free Fixing Nitrogen Bacteria and P-Solubilizing Bacteria - they perform specific functions.

Don't kill biology - add to it!

too low active fungal biomass may indicate a fungal disease outbreak in progress. This can be confirmed by examining the roots for necrosis, galls, or other signs of fungal disease. Beneficial fungi require aerobic conditions and if oxygen falls below 5 to 6 mg oxygen per liter, then the beneficial fungi may not survive. Anaerobic bacteria attack and consume fungi in these low oxygen conditions. Disease-causing fungi are benefited by anaerobic conditions, either because they no longer have competition from the beneficials, or because they require anaerobic conditions for best growth. In either case, anaerobic conditions select for and allow the disease-causing organisms to "win" in the fight for plant tissues.

Guess what pH actinomycetes prefer?

Step Four

Just like any other creature, fungi require food. Feed the beneficial fungi, if fungal activity is too low. Sloughed root cells and dead plant tissue often supply the more complex carbon substrates that fungi require, such as cellulose, cutins, lipopolysaccharides, complex protein-sugar-carbohydrate, and lignins. Fungi are good at condensing organic matter into ever more complex forms, such as fulvic to humic acids. Fungi need N, P, K, Ca, and all the other nutrients as well, and obtain those from organic matter and from inorganic sources as well. Many species of fungi can solubilize mineral elements from the mineral components of soil, but no one species effectively solubilizes ALL minerals. A diversity of species is needed to obtain all nutrients.

Diversity of species needed! No one species solubilizes ALL minerals!

Often soil tests will indicate that some nutrient is in low supply, but merely by adding the appropriate bacterial or fungal species, these organisms will convert plant unavailable nutrients into plant available forms. Diversity is the key, however, as well as feeding that diverse set of species so they will perform their functions.

Where we are going with multi-species cover! Feed diverse set of organisms to convert unavailable nutrients to plant available!

Both bacteria and fungi are important in holding nutrients in the soil when they would otherwise leach into deeper soil layers, and into ground water. The importance of microbes in forming soil structure and preventing erosion is well-known, but in order to hold the nutrients in soil, bacteria and fungi must turn them into biomass, which is not-leachable as long as the glues and strands that the fungi and bacteria use to hold themselves on any surface are not destroyed.

Don't disturb the soil - nature doesn't use a moldboard plow or disc - do so and you destroy soil structure - copiotropic bacteria will consume all carbon in the soil - soil collapses!

If activity is low, then fungal foods need to be added to increase growth rates and improve numbers. A diversity of foods needs to be added, and thus dead leaf material is a much better choice than purified cellulose. Fish hydrolysate also adds bacterial foods, and N and other micronutrients.

Wood, sawdust, bark, paper and cardboard can be used as well, but diversity is key.

If activity is higher than the desired, then try to balance the ratios of the organisms by improving the organism group that is too low.

If active fungal biomass is low, but total fungal biomass is high, this is a good indicator that disease is either rampant, or about to be rampant. Add BENEFICIAL fungal foods and build soil structure as rapidly as possible to compete with the disease, and protect the plant roots from the disease.

In rare instances, it may be because some environmental disturbance occurred that put the majority of the fungi to sleep, but did not kill them.

Step Five

Mycorrhizal fungi are needed by some plants, absolutely critical for other plants, and are probably detrimental for other plants. You need to know what kind of plant you have, but in general, very early successional plant species, such as many (weeds, brassicas, mustards and kale crops do not require Mycorrhizal fungal and may be harmed by Mycorrhizal fungi. Annual vegetables, flowers, grasses and row crops or broad acre crops need vesicular-arbuscular Mycorrhizal fungi. Most evergreen plants require ectomycorrhizal fungi, and blueberry and ericoid plants require ericoid Mycorrhizal fungi.

Early successional plants do not require mycorrhizal fungi!

The percentage of the root system that must be colonized has not been fully established in the Mycorrhizal literature, mostly because determining benefit is relative. Mycorrhizal fungi can protect the roots from disease organisms, through simple spatial interference, by improving nutrient uptake, and by producing glomulin and other metabolites that inhibit disease. Stress in plants can be reduced because the Mycorrhizal fungi can solubilize mineral nutrients from plant not-available forms to plant available forms, and translocate those nutrients to the root system in exchange for sugars provided by the plant.

Bacteria associate with fungal hyphal tip - their may be 100's of hyphal tips when a mycorrhiza associates with a root - bacteria receive carbon from hyphal tip just as they would from a growing root! (Dr. Christine Jones)

Given that Mycorrhizal fungi can influence so many aspects of plant growth, and documenting all these benefits is usually extremely expensive and difficult, they have not been documented. Therefore, probably the best that can be done is to say that perhaps as low as 12% colonization might be documented to be beneficial (work by Moore and Reeves in the mid-1990's), but more likely a minimum level of 40% colonization is required, as suggested by Mosse, and St. John in various publications and comments.

Early researchers found colonization as high as 80% in root systems, but most likely because they did not differentiate false-arbuscular and vesicular structures produced by disease-causing fungi from true VAM structures. Thus, colonization is rarely as high as 80% is not commonly found now that we recognize these non-Mycorrhizal forms.

In the last 10 years, some researchers have suggested that some Mycorrhizal fungi do not produce vesicules under all conditions, and so VA Mycorrhizal fungi should be called arbuscular Mycorrhizal fungi, not vesicular-arbuscular Mycorrhizal fungi. Just be aware that sometimes, people say VAM, sometimes AM. Whatever.

If the plant does not require Mycorrhizal colonization, there probably is no reason to assess the roots for Mycorrhizal colonization. Although the Allens showed that one way for certain plants to exclude non-Mycorrhizal plants from a community was to make sure the Mycorrhizal fungi were present, because the Mycorrhizal fungi pulled nutrients from the non-Mycorrhizal plants. This is a probable mechanism for Mycorrhizal crop plants being able to out compete weeds and earlier successional plant species.

Increase Fungal activity and you reduce non-mycorrhizal plants (weeds)!

When Mycorrhizal colonization is low, or less than the desired range, given that the desired plant requires VAM or ectomycorrhizal colonization or ericoid Mycorrhizal fungi, then check how low the colonization is.

1. If less than perhaps 10 to 15%, then addition of Mycorrhizal spores would be a good idea. If it is an annual plant, placing VAM spores near or on the seed or seed pieces is the simplest way to get the roots colonized as soon as the roots area produced.
    1. With permanent turf, adding VAM spores into the compost mixed into the aeration cores gets the VAM spores into the root system without destroying the turf.
    2. With perennial plants, verti-mulching and adding the VAM or ecto- spores into the compost mixed in the vertimulch is the simplest way to get the spores next to the root system. In cases where we have added inoculum in this fashion, roots have gone from 0% colonization to 25 to 30% within a year, and to 50 to 60% in two years, with addition of humic acids through the season to help the Mycorrhizal fungi grow rapidly (see next section)

How to get mycorrhiza into permanent turf!

2. If colonization is between 15% and 40%, then all that is needed is additional fungal foods to help the Mycorrhizal fungi improve plant growth, reduce plant stress, and improve root protection.
    1. There is a dose response relationship to humic acids additions. Typically addition of 2 to 4 pounds of dry product, or 1 to 2

    gallons of liquid product per acre are adequate to improve fungal growth. But, if there are toxic chemical residues to overcome, additional humics of fulvics may be needed. It is best to check periodically to see that colonization is improving as desired.
    2. Be aware that that most humic acid products contain 10 to 12% humic acids. If the product you are considering is less expensive, please check the concentration of humic acid. Half the concentration of the humic acid means they can drop the price, but your fungi get less benefit.
    3. Check colonization periodically to make sure the fungi are growing and colonization is increasing. Weather can cause problems with colonization, and severe drought, floods, burns, compaction causing by over-grazing, heavy machinery, herds of people walking on the lawns or turf can reduce colonization. If that happens, additional applications of fungal foods will be needed to help resuscitate the damage. Fungi are just like any other organism. If they are harmed, they need care to recover. Triage for fungi includes adding foods they love (humic acid is like chocolate to a choc-a-holic, but they'll also accept any woody, wide C:N ratio fungal food), and putting on a mulch or litter layer on the soil surface.
3. If colonization is above 40%, then the plants are getting the help they need from the fungi. Periodically check to make sure nothing has harmed them.
4. What if colonization seems too high? This is extremely rare, but does happen, and seems to be associated with the fungi taking more than their fair share of the plant's resources. Stop applying fungal foods. Consider helping the bacteria compete with the fungi for a bit.

Steps Six, Seven, Eight

Flagellates (Six), Amoebae (Seven), Ciliates (Eight). These are the three groups of protozoa and they are critical in a bacterial-dominated soil, because the plants need a way to access all the wonderful nutrients tied up in the bacteria. Nutrients within the bacteria cannot be obtained by plant roots, so something has to eat the bacteria to release those nutrients. That's what protozoa do. Protozoa also help build the larger soil pores by pushing aggregates around as the protozoa search for and try to reach the bacteria tucked away around soil particles.

Have to have Protozoa to mineralize or cycle nutrients - it doesn't just happen! They also help create soil structure by pushing aggregates around - I have seen this under a microscope!

If the protozoa are too low in number, the nutrients remain tied up in bacterial and fungal bodies. Even if the bacteria and fungi die, they may not release the nutrients in their bodies until the protozoa come along. In many early microbial studies, microbiologists doing plate counts did not recognize that the protozoa were still in their "pure cultures", and it was the protozoa "mineralizing" nutrients, not the bacteria themselves. When protozoa are too low, and nematodes are too low as well, then inorganic fertilizer will have to be added in order to supply N, P, S etc to the plant. This is expensive and a large proportion of these nutrients will likely be lost from the soil, either by leaching or by volatilization. Until the protozoa are inoculated and brought to desired numbers, nutrient loss will continue to be a problem. Protozoa inocula are available in the form of good compost, good compost tea, or from a commercial source, Holmes Environmental, holmesenviro@attbi.com

Key point! Protozoa mineralize nutrients not bacteria!

If the protozoa are within the desired range, nutrients will be made available for the plants are minimal amounts over time. How much will be made available? That will be discussed in the section on Plant Available N made available to plants (see below). But reductions in fertilizer applications should be possible if protozoa are in good range.

If protozoa numbers are extremely high, or the different groups are very un-balanced, then nutrient cycling will be variable, and there may be periods when pulses of ammonium or nitrate may accumulate. These forms are subject to leaching and loss through gas production, and may result in weeds having the nitrate they need to germinate, grow and outcompete the crop or desired plant species.

If ciliates are too high, then the soil is either compacted or water-logged, and lacking oxygen. Ciliates are aerobic organisms, but prefer to consume anaerobic bacteria. They tolerate reduced oxygen conditions better than the other protozoa, so high numbers of ciliates indicate problems with the movement of oxygen into the soil, which needs to be fixed. Of course, it the soil gets too anaerobic, all three groups of protozoa will be low.

Ciliates are aerobic but prefer anaerobic bacteria!

When ciliates are high, but flagellates and amoebae are also high suggests that one of three things may be happening:

1. The sample has just become compacted, or flooded, and the anaerobic conditions have just been initiated. Generally the number of ciliates is not extremely high.
2. The sample has aggregates, which are anaerobic inside the aggregates. The high ciliate signal comes from the internal parts of those aggregates where anaerobic conditions exist, but outside those aggregates, aerobic conditions exist, and thus flagellate and amoebae numbers are typically high as well. Both anaerobes and aerobes co-exist, but in very different places within the spatial structure of this

sample. This is very typical of good worm compost, particularly worm compost high in castings.
3. The sample has been anaerobic in the past, but is just becoming aerobic. Flagellates and amoebae are growing because aerobic bacteria have begun to grow. Generally, ciliate numbers will be fairly high, while flagellate and amoebae are just barely in good range. Quite often this will result in nitrate pulses and germination of weed seeds.

When flagellates are high and amoebae low, or flagellates low and amoebae high indicates an imbalance in nutrient cycling, with pulses of nitrate being produced, resulting in weeds being able to out-compete the desired plants.

What do you feed protozoa? Bacteria. So, if you have taken care of step one and two, the bacteria should be there for the protozoa to eat.

Steps Nine, Ten, Eleven

Bacterial-feeding nematodes (9), Fungal-feeding nematodes (10) and Predatory nematodes (11). The beneficial nematodes consume their prey groups, and in the case of bacterial- and fungal-feeders, release N, P, S, and micronutrients that would now be available to plants, if the majority of the cycling occurs in the root system. These nematodes also interfere with the ability of the root-feeding nematodes finding the root. The higher number of these organisms, the more nutrient cycling is occurring.

Step Twelve

Earthworms, Micro arthropods

If earthworms and/or micro arthropods are present, then the full food web is present, and if everything is in a good biomass or numbers of individual organisms, then plant health is pretty much assured, because all the processes will be functioning.

Very Key Point - FULL FUNCTIONING
SOIL FOOD WEB -
ESPECIALLY WHEN
EARTHWORMS ARE THERE!

How much do I add to fix any group?

In any case, just an inoculum is required, since all of these organisms will multiply, resulting in increased numbers. Of course, the higher the initial number of individuals added, the faster the return to health. Addition of foods for the organisms will increase the rate of return to health as well.

If toxic chemicals are present in the soil, or litter material, then these materials have to be consumed by the organisms before the twelve step program can be performed. Addition of foods to help consumption by organisms will increase the rate of return to health.

Bacteria - add bacterial foods, such as simple sugars, simple proteins, simple carbohydrates. Molasses, fruit juice, fish emulsion and green plant material high in cellular cytoplasmic material feeds bacteria. The more kinds of sugars and simple substrates added, the greater the diversity of species of bacteria, and the more likely the full range of beneficials will be present.

Bacterial AND fungal inocula can be found in most good AEROBIC composts, or compost teas made with compost documented not to contain E. coli, or other human pathogens.

There are some "starter" bacterial inocula that are useful as well. What you need to look for are maximum diversity in the bacterial species. Unless you are trying to make fermentative compost, you need to avoid inocula containing anaerobic bacteria species.

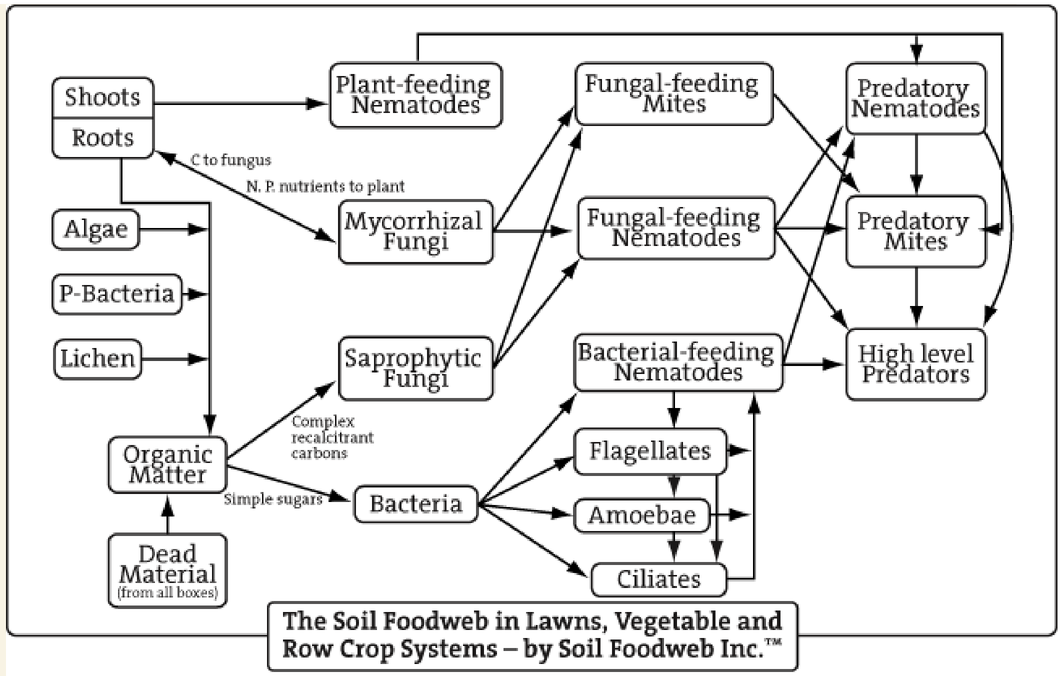
There are no fungal inocula on the market. Yeasts are rarely useful fungal species in soil, or at least there is little data to support their usefulness. Some effort needs to expended to show the veracity of this view point.

Fungi - add fungal foods, such as complex sugars, amino sugars, complex proteins, soy bean meal, fish hydrolysate, fish oils, cellulose, lignin, cutins, humic acids, fulvic acids, wood, paper or cardboard. The more kinds of fungal foods that are present, the greater the diversity of fungal species will grow.

Protozoa - consume bacteria, and thus to improve protozoan numbers, bacterial biomass needs to be enhanced. Protozoa inocula are compost, compost tea, and some commercially available protozoan cultures.

Nematodes - consume bacteria, fungi and each other. Inocula of certain entomopathogenic nematodes are available, for control of certain insect species, such as root grubs and root weevils. Compost and compost tea are the only source of inocula for the beneficial nematodes.

Mycorrhizal fungi - need roots to germinate and grow successfully. Humic acids can improve germination, but then the germinated fungus has to rapidly find a root to colonize or it will die. Spore inocula exist for all kinds of Mycorrhizal fungi. Make sure you have the kind needed for your plant. Make certain to get the spores into the root system of the plant, such as injecting the spore, or adding compost mix into the soil, filling soil cores with a mix of compost and spores.



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What food does my plant need?

In early succession, soils are strongly bacterial-dominated, because soils have not built to the point where the fungal foods, or the structure in the soil will allow them to grow as well as the bacteria.

The first organisms that enter a sterile natural parent material (sand, silt, clay alone) are the photosynthetic bacteria. In the aerobic atmosphere, these will be photosynthetic Cyanobacteria, for example. Before the Earth's oxygen atmosphere developed, the first bacteria to exist, and the first to colonize parent material in anaerobic conditions are the photosynthetic purple or sulfur bacteria (see work on mid-ocean rift bacteria).

These first photosynthetic bacteria release waste compounds, and in succession, bacteria that could use these products evolved, while today, bacteria that use these products have to reach the material, through "taxi-cabs" of various kinds, such as wind, human movement, birds, snakes, mice, or insects for examples, carrying microbes on their feet. Every day, additional species of bacteria may arrive, depending on the distance to a source of inoculum and the ability of bacteria to disperse.

Many bacteria are really bad at dispersing. They just don't grow in places where bird feet, or earthworms, or spiders come by. If they aren't picked up by something, they don't get around very well. Especially when people are doing so much to destroy the normal set of organisms in soil or on plant surfaces, dispersal to new soils is not happening adequately. When insecticides are used, insect dependent dispersal is just about nil.

Hard for bacteria to disperse by way of insects when Insects are all DEAD!

Early successional species of bacteria, or fungi, and disease-causing bacteria and fungi, have better mechanisms for dispersing. To stay alive, to maintain the species, they have to be able to find new places to grow. So, the organisms that arrive first in our agricultural soils are the diseases. They are better at dispersing than any other kind of bacteria or fungi.

As the bacterial populations increase in number, and as the number of species increases, because soil structure improves, the kinds of organic materials improve, the habitats in soil increase. And so more kinds of bacteria can find a place to live, grow and reproduce. Diversity builds. But all the nutrients will be tied up in the bacteria.

Bacteria don't mineralize nutrients all by themselves. They can't. There is no evidence that bacteria die of old age in the soil. Bacteria will become dormant, go-to-sleep, when conditions become too poor for continued growth. They don't die unless a disturbance occurs that kills them. Otherwise, they have mechanisms for surviving tough times.

Bacteria don't die of old age unless there is some type of disturbance!

Why do microbiologists say that bacteria mineralize? First, we need to understand what mineralization means. When protein is converted into carbon dioxide and ammonium or nitrate, that is mineralization. More generally, conversion of an organic material into mineral forms (carbon dioxide is a mineral form of carbon, and nitrate or ammonium are mineral forms of nitrogen) is mineralization.

What about when rock is solubilized? Rock is a mineral. You can't mineralize something that is already a mineral. Typically rock P is turned into an organic form, through the action of bacteria or fungi, and on occasion root acids, and incorporated into the biomass of these organisms. When the bacteria or fungi or plant are eaten, phosphate can be released, and since phosphate is a mineral, that would be mineralization.

But the take-home message is that soil scientists often "black-box" the processes going on in soil, and minimize the activity of the biology. They often do not take the time to learn that bacteria perform functions, but not others. Fungi do some metabolic functions, but not all things. It is critical to know what each group does. It is probably important to know what different species, or group of species do as well. Our ability to measure that level of information is limited. But differentiating bacteria from fungi is critical. They do very different things.

And up to this point in succession, fungi haven't even appeared on the scene.

At a certain point, when there is enough bacterial biomass to maintain protozoan numbers, protozoa will arrive, grow, reproduce, and maintain their populations over time. Nutrient cycling is finally present in this soil.

And now, plants can survive in this soil. But not just any plant, the plants that occupy this stage in succession are things we all would agree are weeds. The word weed has been used too generally in recent times, so let's agree that by weed, we mean something that requires high nitrate levels, poor soil structure, that produces huge numbers of seeds that disperse far and wide. We all would agree, that's a weed. And when bacterial and protozoan numbers are very out-of-whack, then the protozoa over-eat their food resources, mineralize high concentrations of N, P, S, etc, and help out the weeds that require these pulses of nutrients to germinate, and to set the stage to allow them to out-compete the later successional plant species, the things we humans like to eat.

THAT'S A WEED ALRIGHT!!

Nematodes also arrive during this time, bacterial-feeders of course, since fungi aren't present yet in high enough levels to support fungal-feeders. Root-feeding nematodes may arrive and survive, since weeds are present. Since few competitors of the root-feeders are present, if they do arrive, they can have major impacts on weeds.

The "support matrix" is now actually soil. Soil requires life to be present, not just sand, silt and clay fractions of the mineral or parent material. Organic matter is required in order to have the organisms performing their functions in the soil. Soil structure is being built, diversity is increasing, but it is all at a very early stage of development. Plant production will improve with time, but at this stage, the plants in the system are mostly weeds. But weeds leave litter on the soil surface, contribute root biomass to the soil, as well as root exudates. So, more and more food resource is made for the bacteria.

Fungi that arrive now have a food resource to utilize, to begin to build their communities, using the cellulose the plants provide. Building soil, slowly, slowly.

Very critical to understand!
Smooth out pulses of nutrients
And weeds do not out compete
Later successional plants!

As the ratio of fungi to bacteria change, the pulses of nutrients are smoothed out, and true weedy species lack the ability to out-compete the later successional plants. The early successional grass species, like Bromus, and in addition, the brassicas, the mustards, kale and cole crops do best in these soils. They develop a food web that feeds fungi a little, but mostly bacteria. But on their residues and litter, fungi get more and more food, and eventually, the soil shifts to more fungal. Not yet fungal-dominated, but more fungal relative to what came before.

And the plant species shifts, to plants that need more fungal biomass – about 2 times more bacteria than fungi, for the ryegrass related species. Some bunchgrasses, some Bermuda grass here, though many Bermuda grass species do better more bacterial. Most vegetable crop species – tomato, potato, celery, sudan grass, soybean, etc make the balance of the biology in the soil about 0.5 ratio of fungi to bacteria around their roots.

And their roots, and litter residues grow more fungi than bacteria, and again, eventually, the ratio shifts, and with it the plant species. A soil with a ratio of equal fungi to bacteria, with biomass levels above 150 ug, selects for row crops and grasses, such as corn, wheat, barley, rye, fescue, bluegrass, etc.

Equal ratio of fungi/Bacteria
selects for row crops!

But again, these plant species put more fungal foods into the soil, and the soil, slowly but surely, becomes fungal-dominated. As that threshold passes, shrubs, bushes, early successional trees win in the competition for soil nutrients. Soil pH generally shifts as well. In western soils, the soil organic matter builds, soils become more and more fungal. Late success ional systems are strongly fungal-dominated. Typical ratios of fungi to bacteria observed in systems requiring few or no inorganic chemical inputs are:

Bacterial-dominated plants (most row and vegetable crops)

Lawn grass 0.5 to 1.0	Broccoli 0.3 to 0.7	Kale 0.5 to 0.8
Carrots 0.5 to 0.8	Corn 0.8 to 1.0	Wheat 0.8 t o 1.0
Lettuce 0.5 to 0.8	Tomato 0.8 to 1.0	Tobacco 1 .0 to 3.0
Turf 0.9 to 1.5		

Fungal-dominated plants

Grape 3 to 5	Deciduous trees 10 to 100	Alder 5 to 100
Apple (orchard) 10 to 50	Pine 50 to 100	Conifer 100 to 1000

How can soil organism dominance be changed? Most simply, feed the organisms that are low in number.

Bacterial Foods are: Green, high in easy-to-use sugar and nitrogen, e.g., green grass clippings, cover crops, especially legumes, molasses, compost teas, compost made with green material (high in N and simple sugars) and manures (high N) Be careful to tie up all the manure N by adding enough plant material, or plants may be burned.

Fungal foods are: brown plant materials high in cellulose, lignin, and tannin, e.g., woody fibrous materials, like straw, sawdust, compost made with woody material and small amounts of manure. Enough N needs to be present to start decomposition, but not encourage bacterial growth. Time is needed to reach the N-release stage before putting this material on plants, or planting into such material. At first, the fungi growing on organic matter high in carbon take up N from the soil, which can stress plant growth.

Those soil organisms that make N available for plants are predators of (or eat-) fungi or bacteria. Low numbers of protozoa (bacterial-feeders), nematodes (both bacterial feeding and fungal-feeding,) earthworms, or micro arthropods can be enhanced by improving their food, i.e., bacteria or fungi. Interaction of bacteria and their predators (e.g., protozoa and bacterial-feeding nematodes), or fungi and their predators (e.g., fungal-feeding nematodes and micro arthropods), produce as much as 80 % of the plant-available N that occurs in soil.

If bacterial or fungal foods, i.e., cover crops, residues, or compost can't be obtained or grown, commercial products are available to " jump start" fungi or bacteria. If spreading organic matter is difficult, a water extract of the compost can be prepared and this "tea" can be applied through the irrigation system. Compost tea can be bacterial or fungal, depending on the compost and addition of fungal foods, unless rock dust or kelp is added.

When and how to add fungal or bacterial food

Both should be placed on the surface of the soil, although if greater bacterial activity is desired, mix lightly into the top few inches of soil. Realize that plowing and compacting kills many soil organisms, and soil structure is destroyed.

A mineral crust may then develop, decreasing water infiltration, water-holding capacity, and soil structure is destroyed. The benefit from mixing food into the soil and growing a burst of bacterial biomass may not offset all the detrimental results of the tillage. During periods of optimal moisture and temperature (spring, and fall in some areas), bacterial-food should disappear rapidly, within 2 to 9 weeks if soil organisms are diverse and healthy. Fungal-food takes a bit longer, 6 to 16 weeks for a healthy Foodweb to do it's job. If the original plant material remains identifiable, after a month or more of warm weather, some part of the Foodweb is lacking and needs to be added.

Monitor soil and compost organisms on an annual or semi-annual basis to make certain the right numbers and functions are present. Monitoring in the fall allows assessment of appropriate management through the fall into the spring when it is easiest to improve the fungal community. Organic matter additions, either as compost or as cover crops, decompose rapidly during the winter, even under the snow, if the soil Foodweb is healthy. Soil organisms growing in organic matter produce metabolic heat and will increase soil temperature in the spring. As some cover crops decompose, inhibitory compounds can be produced to so the initial flush of decomposition needs to be finished before planting the next crop. Checking the soil Foodweb in the spring allows assessment of whether beneficial are growing, or problems are developing. Assessing the Foodweb in mid-crop growth is also useful, especially for VAM colonization, pathogens, or pest problems. However, it is difficult to do much to help the current crop at mid-season, and this information is more useful determining what management is needed for the next crop.

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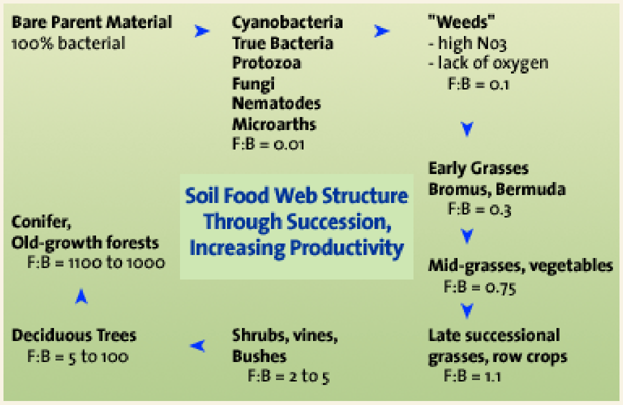
Plant Succession Diagram

As the food web in the soil becomes more complex, the ratio of fungi to bacteria increases, plant productivity increases, and vegetative communities change. It appears that "nature" drives the successional process by continuously building more and more complex carbon compounds. This development of complex, highly-retention organic matter in soil is driven by the kinds of plant materials that are produced by higher plants, and through an ever-more complex set of metabolites being released as the biology that uses the ever-more complex carbon substrates produced by plants decompose those materials.

Another way of saying this is that as humic materials accumulate in the soil, productivity of plants increases. But the formation of humic materials is completely dependent on the biology in the soil and on plant surfaces. So, what is the chicken, and which is the egg? As Dr. David Perry explained, it's a boot-strapping process. Nature moves towards ever-more complex systems, ever-more diverse, ever-more productive. Until a disturbance happens that destroys the complexity, reduces diversity. Whereupon, nature just starts the building process again...



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Interpreting Soil Foodweb Information

What information is given by which test?

- Active Bacteria/Active Fungi
- These tests measure the numbers and biomass of aerobic bacteria and fungi that are actively feeding and reproducing. Active bacteria and fungi rapidly enhance soil structure, nutrient retention, disease suppression and residue/pollutant decomposition.
- If your soil is deficient in disease suppression, you need to know whether it is because bacterial activity or fungal activity is lacking.
- If water puddles on the soil surface, perhaps the reason is that soil structure is not being maintained. If the roots of your plants only grow a short distance into the soil, it is a clear indication that the soil is compacted, and lacks oxygen. Bacteria and fungi need to grow into that soil, and build the hallways and passages ways to let water flow into the soil as well as allow oxygen to move into the soil.
- These tests are used to determine:
    1. Is nitrogen being retained at this time?
    2. Is this soil dominated by fungi or bacteria? Is it bacteria or fungi that are playing the greatest role in decomposition?
    3. Is there a decent set of bacteria to support protozoa and bacterial-feeding nematodes?
    4. Did addition of a product, compost, or compost tea, or some aspect of management cause a bloom of bacterial activity or

fungal activity, or kill, harm or otherwise reduce activity of the bacteria and fungi?
5. Did herbicides or other pesticides kill or stimulate significant numbers of organisms?

Total Bacteria / Total Fungi

- This test measures the total amount of bacteria and fungi in the sample. Total biomass includes the active populations determined in the previous tests, as well as all of the inactive (sleeping, moribund, semi-awake, just woken up, just about to go to sleep, not really wide awake yet, and dead but not yet decomposed) organisms.
- Total biomass assesses the amount of carbon or nitrogen held in these organisms, disease suppressiveness, potential benefit to soil aggregation, and relate to decomposition rates.
- There is a clear correlation between diversity and total bacteria or total fungal biomass. The higher the biomass present, the more diverse the bacterial or fungal populations. It's not a perfect correlation, but in general it holds.
- These tests are used to determine:
    1. Are fungi or bacteria dominant or is there equal biomass of both? Are there minimum levels of fungi, or bacteria, or high levels of both?
    2. Is there a pool of retained nitrogen in the form of organisms that can be released to plants later?
    3. Is there enough fungal biomass to immobilize solution calcium so it doesn't leach?
    4. Are fungal biomass and bacterial biomass great enough to support the organisms that graze on bacteria and fungi? These higher forms balance the population levels of bacteria and fungi and release nitrogen into the soil in the form of ammonium for plant growth.

SFI can perform morphological diversity testing. In general this is a significant improvement over plate counts, since so few species of bacteria and fungi actually grow on any plate count medium. However, it takes molecular methods to assess the full diversity of bacteria and fungi in soils. We work with other programs that are in the process of developing these methods for practical applications.

Nematode Numbers and Community Structure

- We extract all the active nematodes from 50 to 100 grams of soil or compost. We count and identify those individuals and report numbers of individuals per gram dry soil.
- Nematodes are identified to genus and placed in one of four functional group classes according to what they eat. The report differentiates root-feeding nematodes to genus. Reports list the beneficial bacterial-feeders, fungal-feeders and predatory nematodes, if any.
- Beneficial nematodes are important in preventing root-feeding nematodes from finding the roots of plants. Beneficial nematodes are a very important part of root protection, one which most agricultural soils lack.
- Identification of insect-feeding nematodes can also be performed.
- This test is used to determine:
    1. Are any root-feeding nematodes present? Are they at economic damage thresholds?
    2. Are any beneficial nematodes present?
    3. Bacterial-feeding nematodes help balance total bacteria populations and release nitrogen back to the plant.
    4. Fungal feeders balance total fungal levels, including root rot fungi, and also help release the nitrogen locked up inside fungi back to the plant.
    5. Predatory nematodes are higher-order predators that help balance all other nematodes. It is desirable to have some of these around but they are especially delicate and easily hurt by tillage.

Protozoa

- Protozoa are single celled organisms that mostly eat bacteria, although some prefer to consume pathogenic, disease-causing fungi. Protozoa are very important in recycling the nitrogen and other nutrients locked up inside the bacteria.
- Some protozoa also attack nematodes and some will attack fungi. All in all, having good populations of the right kinds of protozoa makes for a balanced soil.
- Protozoa come in three major groups, the ciliates, flagellates, and the amoebae. The relative numbers of these groups assess whether the sample is aerobic or anaerobic.
- This test is used to determine:
    1. Are enough protozoa present to cycle adequate nutrients? Will enough nutrients become plant available?
    2. Are ciliates numbers too high, indicating anaerobic conditions in the soil?

Comment [wd1]: Vampyrellids – consume fungus that causes "Take All Disease" in Wheat.

3. All three groups of protozoa help balance total bacteria populations and release nitrogen back to the plant.

Mycorrhizal fungi (VAM)

- The kind and amount of beneficial mycorrhizal colonization on the roots is determined in this test. Mycorrhizal fungi are extremely important fungi for plants that require colonization, such as most crop, vegetable, orchard and landscape trees and shrubs.
- If you have plants in the soil, you need know the percent of the root system colonized by mycorrhizal fungi. We not only assess VAM versus ectomycorrhizal colonization of the roots, track nodulation by N-fixing rhizobia, necrosis by disease-causing bacteria and fungi, but insect and soil pest feeding on the roots.
- Please remember that we need a representative sample of roots of the plant you want to know about included in the sample. It is best to send all the roots picked from the composite soil sample (see below on obtaining the soil sample).
- This test measures:
    1. Is enough of the root system protected by mycorrhizal fungi from disease-causing organisms?
    2. Is the root system colonized enough to supply nutrients at the rate the plant requires?
    3. Would the plant benefit from improved colonization?
    4. Percent of the root being attacked by disease-causing organisms.
    5. Percent of the root being attacked by root-feeding insects

Microarthropods

This test provides information on the numbers and identification to major group of the visible soil critters. The important groups are the fungal-feeding, herbivorous, and predatory microarthropods.

Generally, soils disturbed by plowing, disking, chiseling, etc will have not significant microarthropod populations for a year or more unless mulch is placed on the soil surface. Still, many predators of pests are microarthropods, and you would want to know if you have these important bio-control organisms present in your soil.

Those microarthropods that are true soil-dwellers are usually small and inconvenient to see with the naked eye. The principal role of these creatures is to recycle nutrients and make them available for plants.

Foliage Assay: Allows determination of the area of leaf surface occupied by microorganisms such as bacteria and fungi.

- The work so far performed suggests that if 70% or more of the leaf surface is occupied by beneficial microorganisms, then foliar disease can be significantly reduced. Plants with 70% or more of the leaf surface occupied by beneficial microorganisms also appear to have higher leaf tissue concentrations of important nutrients.
- More work is needed to determine which species of bacteria or fungi will be most suppressive and whether different cultivars of plants will respond in different ways.

Review the **Organism Biomass Data** table in a seperate window

Dry Weight: All three composts have moistu sre in good range. If the soil is too wet, aeration will be a problem and roots will be killed. Too dry and organisms cannot grow.

Active bacterial biomass: Control is in good range. HH is in good range, not significantly different from the control. In Biol, bacterial activity is low, resulting in poor decomposition, poor nutrient retention, a lack of soil structure building and limited disease suppression. Need to add bacterial inoculum, or bacterial foods to wake up the bacteria that are present (see total bacterial biomass).

Total Bacterial Biomass: Control has adequate total bacterial biomass but both treatments have low total bacterial biomass, for different reasons. Fungal growth is probably out-competing bacterial growth in Plus HH, while something in Bio1 is detrimental to bacteria. In all samples, sleeping, dormant organisms are present (active subtracted from total). Some unknown percentage of these dormant, sleeping organisms would grow on plate counts.

Active Fungal Biomass: Active fungi low in the control and in the Bio1 sample. Plus HH has in desired range activity. Disease suppression, nutrient retention, and soil building will be present in HH, not in the control or in the Bio1 samples. Need to add a fungal inoculum and fungal foods to these two samples.

Total Fungal Biomass: Both control and Bio1 too low, and therefore fungal diversity is lacking. Need to add fungal foods to get fungal decomposition going. Fungal foods are, for example, humic acids, many fulvic acids, dry, brown leaf materials, wood chips, sawdust, paper, cardboard. May need to add a fungal inoculum as well. The HH treatment has adequate fungal biomass, showing that just by adding humic acid that fungal biomass can be resuscitated.

Hyphal Diameter: As indicated by the footnote on the table, the diameter of the hyphae observed in these samples indicate typical soil fungi, a mix of beneficials and not-so-beneficial are present in the control and in the Bio1 treatment. In the HH treatment, this amendment has provided food for the beneficial fungi and they grew in preference to the less beneficial fungi. This is a very good result for any soil.

Sample #	Treatment	Protozoa			Nematodes
		# per gram			# per gram
		F	A	C	
91046	Control	580	2,798	84	0.07
91047	Plus HH	61	1,486	38	1.71
91048	Plus Bio 1	2,689	844	329	0.05

Protozoa: All too low, in all samples. Need to add an inoculum of protozoa, which is typically found in compost with higher moisture, compost tea, or in commercial products (see www.soilfoodweb.com for list). Note the variability in this assessment method. All three values of flagellates are probably not significantly different one for the other. How is this determined? From replicate sampling from a set of soil samples.

Nematodes: All too low numbers, low diversity. This is the hardest component of the foodweb to return to healthy conditions once the food web has been destroyed. An inoculum of beneficial nematodes is needed to re-establish this group of the soil foodweb.

Review the **Fungal to Bacterial Biomass** table in a seperate window

Total Fungal to Total Bacterial Biomass: Control and Bio1 both on the bacterial-dominated side, while HH is fungal-dominated. Need to add more fungal foods and possibly need fungal inoculum in control and Bio1 samples. Control and Bio1 samples reveal foodwebs appropriate for vegetables, annual plants. The HH sample has a ratio appropriate for bentgrass and other productive pasture or lawn grasses.

Active to Total Fungal Biomass: Only HH has decent levels of active fungi. Neither the control nor the Bio1 sample have enough active fungi to protect the plant against disease-causing organisms. An inoculum of beneficial fungi would be wise, but certainly fungal foods are needed.

Active to Total Bacterial Biomass: Both the control and HH have adequate active bacteria relative to total bacteria, but the Bio1 treatment has reduced the active bacterial component severely. This amendment is detrimental to both active and dormant bacteria,

Active Fungi to Active Bacteria: Which microbial group is winning? Bacteria are in the control, so the soil will become even more bacterial over the next few weeks. In the HH treatment, the beneficial fungi were enhanced and the ratio shows that the soul will become more and more fungal with time. In the Bio1 treatment, the bacteria were killed, so this ratio is very fungal. Because active bacteria were harmed more than the fungi, the ratio is quite skewed. Fungi will grow in this soil more than bacteria, until conditions change, but it may well be un-desirable fungi because the bacteria are not performing their jobs.

Plant Available N: Low in all three soils. Need a protozoan inoculum.

Nematodes: No root-feeders detected, but no beneficial nematodes found either. Need a beneficial nematode inoculum. Nematodes are the most difficult group to get re-established.

For additional questions, please e-mail Soil Foodweb Inc.

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The Nitrogen Cycle and the Soil Foodweb

Nitrogen Cycle and the Soil Food Web

A complete understanding of the nitrogen (N) cycle is necessary in order to comprehend why the soil foodweb is so important in being able to predict N cycling. Most people with little or no understanding of environmental microbiology do not do justice to the role of biology in N cycling. So, we need to go through this with most people.

Start with atmospheric N

The predominant form of N on this planet is nitrogen gas in the atmosphere. Seventy-five percent of the atmosphere is nitrogen gas, so the trick is getting that nitrogen into a form that plants can use.

N fixation

Back before life on Earth started, most of the N was fixed through the action of lightening, enough to get life started. After life started on earth, most of the nitrogen fixed is by microorganisms, and indeed, all N fixation requires the help of bacterial enzymes. Most people know about N-fixing bacterial genus, Rhizobium, on the roots of legumes. These bacteria make the plant form nodules to house them, allowing the bacteria to exclude oxygen, allowing the N-fixing enzymes to perform their function of converting N-gas into biomass.

But a number of other N-fixing bacteria abound in certain environments. Cyanobacteria form filaments, and are typically photosynthetic, so the bacteria fixing their own carbon from carbon dioxide also fix N inside those filaments, in many different extreme environments.

Free-living N-fixing bacteria, such as Azotobacter and Azospirillum, also fix N in the root systems of many different plants. The plant supplies the sugars that these bacteria need, in the amounts they need to perform N-fixation. So, while not truly symbionts, these bacteria usually are most active in the rhizosphere.

N is in bacterial biomass after N-fixation occurs

There is a mis-conception that Rhizobium, or the free-living N-fixing bacteria "dump" nitrate into the soil. They do no such thing. These bacteria require a great deal of energy to fix N. Fixed N does not get made into nitrate, or any other inorganic form of N. The bacteria fix N for themselves first, and is put into protein in the bacterium before anything else occurs. If the bacterial colony fixes enough N rapidly enough so the bacterial demand is met, then protein is provided to the plant, in the case of Rhizobium. The free-living bacteria are not in the plant, but in the rhizosphere, so all the fixed N remains tied up in bacterial biomass, in the form of protein mainly.

No inorganic N is dumped into the soil then, in this first step of fixing N. The plant may receive some N, but the plant isn't going to give away N for no reason. Only when the plant dies will it lose N, and that N is in the dead plant litter, roots, seed, fruit, etc. This organic matter is elevated in protein N, but that form is not usable by other plants. It has to be decomposed by bacteria and fungi before anything else can happen.

No inorganic, plant-available N is released into soil through the process of N-fixation. The dominant form of fixed N is protein. How does that form of N get converted into ammonium, nitrite or nitrate?

Bacteria don't die of old age in the soil. Neither do fungi. Empty hyphal strands may be left behind, but there is extremely little N in cellulose, or mannin, or chitin, or the other structural cell wall materials left behind as the empty tubes of fungal biomass. There is no evidence that in healthy soil any of these organisms die just because they get old. In lab cultures bacterial colonies will get old and the toxic metabolites that accumulate in the Petri dish will kill the bacteria in the colony. But that doesn't happen in the real world. Water washes away the metabolites in the real world, or another kind of bacteria, or fungus, or other organisms eats that waste metabolite. So the colony doesn't get stuck dying from it's own excrement. The major reason bacteria or fungi die in soil is because someone eats them.

The Mineralization Step

Predator-prey interactions in soil are no different than in the aboveground world with cats and mice, hunting dogs and birds, tigers and water buffalo, lions and gazelle. Bacteria get eaten by protozoa, nematodes, earthworms, microarthropods, etc. When bacteria, with a C:N of 5 get eaten by a protozoan with a C:N of 30, possibly higher, then N, P, S, etc will be released in plant available forms.

KEY POINT!!

If you are unfamiliar with these interactions, please read some of the reference materials in the reading list, or on Dr. Ingham's list of publications, or attend some of her classes, or other soil ecologist classes.

When fungi are eaten by protozoa, nematodes, microarthropods and earthworms, N is released in a mineral form into the soil. The majority of this process of making plant-available N occurs in the rhizosphere of the plant. But mineralization occurs only because of biological processes.

Want to predict how much N will be mineralized? You have to understand how much N is being tied-up by the bacteria and fungi in non-leachable forms, how much will be leached and lost from the root system, and how much prey (bacteria and fungi) will be consumed by the predators (protozoa, nematodes, microarthropods, earthworms, etc). There are different flow rates for different organisms, so the relationship is not straightforward.

C/N of nematodes/microarthropods is higher than Protozoa - the more diverse the system is the more nutrient cycling occurs - higher flow rates!

But if you do not understand biology, and do not know how much of whom is present, or how active they are, prediction of N-mineralization is impossible. It remains a black box, highly variable and head-scratching in its inability to be understood or predicted.

Initially N is in the form of ammonium

The predators of course release predominately ammonium, a nutrient that plants can take-up. But ammonium is not a good nutrient for ALL plant species. In general, ammonium is the right form of N for perennial plants, although all perennial plants that have been tested can take up nitrate and possibly a little nitrite as well.

But perennial plants growing with mostly nitrate in the root zone are HIGHLY prone to disease. Nitrate in high concentrations stresses these plants, and result in an never-ending battle with disease, requiring the use of high amounts of fungicide, nematode, antibiotic, and herbicide applications to combat the organisms being selected and enhanced by the high nitrate present.

Annual plants are best at using nitrate, although there is evidence that nitrate in high concentrations is harmful to continuing root function even with annuals. Annuals can take up ammonium, but generally help the equilibrium shift from ammonium to nitrate so the form of N they like is at least present, so they can preferentially take that form up.

High nitrate levels weaken cell walls!

How do you maintain ammonium as ammonium? Or convert it to nitrate?

Conversion to nitrite and then nitrate

In soil where the nitrifying bacteria are able to grow, these bacteria convert ammonium to nitrite and then nitrate. But nitrifying bacteria have some significant constraints on where they will grow. They need reduced oxygen conditions to do best. They typically reduce oxygen around their colony, so the bacterial individuals in the middle of the colony are in reduced oxygen conditions. Or they grow in the rhizosphere, where the rapid growth of all those other bacteria sets the stage for a small colony to be at the oxygen level they need. Nitrifiers take the hydrogen ions from ammonium and replace them with oxygen. Ammonium is first converted, by the action of bacterial enzymes, to nitrite (NO2) and then another set of bacteria converts nitrite to nitrate (NO3). It is an oxidation step of the nitrogen.

But this is not a mineralization step. Ammonium is already a mineral form of N, and so conversion to nitrite and then to nitrate is merely a shift in the form of inorganic N.

Nitrifying bacteria require particular habitats in order to grow and perform their nutrient cycling processes. These bacteria need the hydrogen ions in order to generate energy through their metabolic pathways. They remove H from the medium. What does that do to soil pH?

Remove H+ from medium - causes there to be a alkaline pH -

Nitrifying bacteria remove ammonium, and produce nitrate. They aren't taking up the N, that are just using it to deal with the electrons they need to get rid of in respiration. In order to grow and perform their function, they will drive a soil more alkaline. As they utilize H ions during metabolic functions, the soil will become more alkaline.

Some scientists say that bacteria couldn't possibly have that much effect on soil. Each individual bacterium is so small, how could bacteria have much effect on anything in soil? These people clearly don't understand soil, or how many bacteria are in soil. In a healthy soil, there are 600,000,000 individual bacteria per TEASPOON, or gram, of soil. In conventional ag soil, there may be only 1,000,000 individual bacteria per gram of soil.
Consider that the only reason there is enough oxygen in the atmosphere of this planet for aerobic organisms to function is because anaerobic bacteria produced enough oxygen as a waste product to change the composition of gases in the atmosphere. Humans exist only because those tiny creatures performed their functions.

Why is it not possible that bacteria could alter soil pH? They altered the atmosphere of this planet. Why not soil?

Consider the real world, not a greenhouse or lab soil. Nitrate doesn't exist in soil without the biology present and functioning. Without the organisms to alter the form of N, plants won't grow. Now, when people add ammonium to the soil, they alter the normal flow of nutrient cycling. When people say plants take up ammonium, what you need to say back, right away, is, "But is that the form of N that will keep that plant healthy?"

What form of N do different plants need? Some scientists say that N is N, it doesn't matter where it came from. Could that possibly be true? Think about yourself. What form of N do you need? What if you consumed your N in the form of nitrate? You'd be dead in a very short time because your kidneys would go into failure. If you didn't consume enough nitrate to kill you that way, you'd starve to death. People can take up nitrate, but it will kill us. Is the form of N important? Can people consume ammonia? You'll die even faster if you try that form of N.

Is the form of N important? Of course it is. Plants have similar requirements. If all you give a plant is nitrate, it will take up nitrate. But is that the correct form for that plant to grow without stress?
If the only thing you give your plant is ammonium, will that plant take-up that form of N? Yes, but is the plant growing in a healthy fashion? If the plant now needs fungicides, insecticides, herbicides, etc in order to grow,

this is not healthy. All inorganic N is highly leachable. Stop destroying water quality by putting these leachable forms of N in your soil or potting mixes.

Some plants do best taking up nitrate, others do better with ammonium.

Is there a generalization we can use to say what kinds of plants do best with the different kinds of N? Annual plants, in general, do better with nitrate. Perennial plants do best with ammonium. "Do best" means not stressed, less subject to disease, stronger cell walls, higher production. Annual plants can use ammonium, for example, but they are not healthy, and require much more pesticide in order to stay alive.

Nitrifying bacteria produce nitrate which is the preferred form of N for annual plants in normal soil – no inorganic fertilizer applications needed. Nitrifying bacteria require and maintain alkaline conditions. That means that terrestrial annual plants grow best in alkaline soils. And they do, in general.

The form of nitrogen is very important then, is it not? When bacteria and fungi grow in the soil, what form of N are they taking up? They probably prefer protein, but they will also take up nitrate, nitrite and ammonium – all of the inorganic forms of N can be taken up by these organisms. But not all species use all kinds of N. Presence of high concentrations of NO3 will select for certain communities of bacteria, or fungi. Nitrite selects for other species, ammonium for other species.

Nitrate selects for certain species! Ammonium selectes for certain species!

Look at a picture of the root of an annual plant taken with a microscope. In the book called "The Ultrastructure of the Root", by R. Fosterm the most noticeable thing you will see is the deep layer of "slime" present on root surfaces, and the soil around the root. Everything is embedded in the slime produced by bacteria.

Recent work from the USDA in Beltsville show that mycorrhizal fungi also produce significant glues to hold the fungal hyphae on the root, and which help form macro-aggregates in the soil. The pH of these glues are alkaline. When we deal with row crop plants, with most mid-to-early successional grasses, with most terrestrial weeds, and most early successional terrestrial plants, the pH around the roots is alkaline.

Alkaline pH

But given that the slime layer, the glue around aerobic bacterial cells is alkaline, and there are millions of bacteria per gram of healthy soil, they have to have a large role in influencing soil pH, especially if the soil is bacterial-dominated.

Don't over-extrapolate to wetland plants, riparian plants, hydroponic situations, or high production ag conditions. Different things are going on there. Think about the fact that most plants in high production ag fields are extremely sick, very stressed, and not functioning normally. If they were healthy, they wouldn't need all those pesticides, and they would be able to establish and out-compete the weeds. So, any example based on conventional ag cannot be used. Seriously different things are going on there. And pH is being jerked around all the time by high lime, or gypsum or anhydrous ammonia, or other additions.

Humans alter pH with very little effort. So, you can't use pH as a meaningful measure of anything if pesticides, high level of fertilizers, or compaction have been imposed on soil. And what intensive agricultural soil has not had pesticide, herbicide, high levels of inorganic fertilizer, and severe compaction imposed on it?

But how can normal soils have lower pH than neutral? Different organism dominance. Fungi produce organic acids as major components of their metabolism, but not the STRONGLY acidic organic acids that occur in anaerobic conditions. So, when we test soils that are aerobic, and fungal-dominated, the pH is always somewhere between 5.5 and 7.

This means the nitrifying bacteria are not major players in converting ammonium to nitrate, and so ammonium stays ammonium in fungal-dominated, pH 5.5 to 7.0, healthy forest soils.

What happens in compacted soils?

Compaction destroys the air passageways and water infiltration hallways in soil. If possible, the aerobic organisms start re-building the structure immediately, but their activities may use up the oxygen faster than oxygen can diffuse into the soil. When that happens, the soil loses oxygen, and may move into the facultative anaerobic and finally into the anaerobic zone of metabolism.

How rapid is the loss of oxygen? Depends on how active the organisms are, and how limited the diffusion of oxygen into the soil. Do a soil penetrometer reading. Look how far down the roots of your plants grow.

Take a look at some of Steiner's and Pfiffer's drawings of how far down roots went into soil just a mere 50 or 60 years ago. And now look at what current soils books tell you about root depth.

Something has happened. Roots of plants today don't seem to go down as far as they used to go down.

Look at the USDA definition of soil depth. In the 1940-s and 1950's, soil was defined as material in which you can grow plants. That depth was determined by how far down roots went, and in the 1930's, that depth was defined as 4 to 6 inches. In the mid-1980's, soil depth was re-defined as going down to 12 to 18 inches. In 1994, soil was re-defined again as going down 4 ft. Below those zones, in any time period, you could not get plants to grow in ag that soil. Except for tap roots, roots would not grow deeper than those depths.

How can that be? You have to understand tillage equipment. In agriculture, up to the 1970's, most soils, especially in the Midwest were tilled with mold-board plows which turn the soil to a depth of 4 to 6 inches. With continuing tillage, the soil became so compacted at that depth that water and air could not move through it. The "soil" below that point was anaerobic, salt problems occurred. Water would hold up and not penetrate further into the soil. In the spring, that pan would prevent water from moving into the soil, and then erosion occurred, taking soil downhill.

The solution to this was an engineering approach. Have a hard pan? Break it open physically. Plow deeper. Chisel and disc plows go down to, 12 to 18 inches. The hardpan at 4 to 6 inches was broken up, but the compaction zone was then imposed at 12 to 18 inches, depending on your equipment. Within a few years, the hardpan was so bad at those depths that deeper tilling equipment was invented. We need to break open the compaction zone at 12 to 18 inches, by deep-tilling, or sub-soiling. We shatter the soil down to 4 feet, and so we develop two compaction zones. One at 4 feet, and the "normal" ones at 12 to 18 inches.

As compaction occurs, oxygen movement slows, aerobic organisms go to sleep. Anaerobic organisms start to grow. In aerobic conditions, the bacteria making alkaline slime were predominant. But as anaerobic bacteria, and yeasts (which are fungi, but are not normally functional in soil in aerobic conditions), begin to win in competition with aerobes for the food resources.

Created this situation due to tillage!

Consider the metabolites produced in anaerobic conditions. Alcohols are a major component of anaerobic conditions and are among the most phytotoxic materials that we know. In anaerobic conditions, the roots will be killed.

Unless it's a riparian or wetland plant. Then these roots have mechanisms for dealing with and getting rid of alcohol. They have the plant world's equivalent of livers. Enzymes are produced which destroy alcohol, or they pump oxygen into the root system, for example.

What else is produced in anaerobic conditions? Some very toxic organic acids, such as acetic acid, proprionic acid, butyric acid, valeric acid, and a host of other low pH organic acids, only produced in anaerobic conditions. So, what happens to soil in anaerobic conditions? The pH can fall into very low levels. These severely low pH organic acids are strictly produced by anaerobic organisms, and become the dominant determinant of soil pH when the whole soil profile, or a major part of the soil, becomes anaerobic.

Why tilled, compacted soil leads to an acid soil!!!!
These toxic organic acids are produced in anaerobic conditions!
Soil pH falls to very low levels!

Some really nasty phenols are also produced under anaerobic conditions. More killing power in these anaerobic conditions.

What happens to ammonium, or nitrate in anaerobic conditions? They are lost as volatile gas, ammonia. Ammonia is a product of anaerobic microbial metabolism. What happens to sulfur in anaerobic conditions? Lost as hydrogen sulfide. What happens to phosphate in anaerobic conditions? Lost as phosphine gas. Can't smell it, but you can see it. The anaerobic organic acids metioned above, and of course ammonia and hydrogen sulfide, you can smell. If it stinks, there's anaerobic metabolism occurring.

Can you grow plants in something where N, P, S has been lost, or at least significantly reduced? Certainly not going to grow well.

Will you be able to grow healthy plants in something where plant-toxic materials have been produced?

Can you grow plants in something where the nutrient-cycling organisms have been killed, or at least put-to-sleep by the lack of oxygen, to say nothing of the toxic effect of alcohol, low pH organic acids, and phenols, or the loss of the exudates from the root systems?

You can't grow very healthy plants when these conditions exist!!

So, at low pH, the soil is in serious trouble. Below pH 4.5, terrestrial plants are not going to do well. Riparian plants? Wetland plants – different story, as explained above.

So, closing the nitrogen cycle requires anaerobic conditions, which results in nitrate or ammonium being blown off as a gas, ammonia, nitrous oxide, or nitrogen gas. And nitrogen is back where we started – in the atmosphere, where our biggest reserve of N is.

Please see the books and CD's by Dr. Elaine Ingham to hear more about the N cycle, microorganisms, and plant growth.

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Repairing the Soil Foodweb

The soil food web is a complex, interdependent, mutually beneficial group of organisms ranging in size from bacteria, to fungi (the largest organisms on the planet) to protozoa, to nematodes, microarthropods, worms and beetles. The foodweb develops good soil structure by binding pieces of soil (clay, sand, silt, organic matter, roots) together and by building airways and passageways through the soil. Good movement of air and water are vital to the health of plants and the soil food web itself. While it seems contradictory, good soil structure both allows water to drain from too wet soil and helps soil to hold water when soils start to dry out.

When considering living organisms, it is true that "everything eats, everything excretes, and everything is food for something". Bacteria and fungi feed on plant residues, breaking them down and holding nutrients (e.g. nitrogen, calcium, iron, potassium, phosphorus, etc.) in their bodies, glued and bound to soil particles, preventing loss of nutrients through leaching. The nutrients bound in the bacteria and fungi are not available to plants, until protozoa, nematodes, small microarthropods, and earthworms consume individuals of bacteria and fungi and release nutrients in plant available forms. The nutrients are released when and where the plants need them, in the form and amounts that plants need. Plants excrete foods for bacteria and fungi from their roots, which are foods for the beneficial species, protecting the root from pathogen and pest attack.

Good explanation of how it all works!!

In the process of feeding on plant materials and each other, these organisms also produce hormones that plants need, and consume or break down pollutants in the soil. The soil food web protects all plant surfaces from disease-causing organisms and other pests, often by out-competing them for food, sometimes simply by eating them, by occupying the plant surfaces so the pathogen cannot gain access, and at other times by altering the soil conditions so the disease-organisms cannot thrive.

How soil food web prevents disease!

So much of what modern agriculture has done is to destroy these beneficial organisms in the soil, and on plant surfaces. The goal was to destroy specific pathogen and pest organisms through the use of toxic chemicals, but the beneficial, protective organisms were also killed. And the boom-and-bust-life-style, disease-causing organisms came back faster from those toxic applications. It takes a number of toxic chemical applications, and typically several different kinds of toxic chemical applications have to be made, to wipe out the whole set of beneficial bacteria and fungi, protozoa and nematodes, but it has been done. In typical conventional agriculture fields, bacterial numbers have been reduced from several thousand billion in the root zone, to only a million per gram. Species diversity has been lost, and the disease-selected, the beneficials destroyed. No wonder disease and pests are impossible to control after 30 to 50 years of warfare against the normal set of organisms in soil.

But how do you fix the problem? We didn't know we were harming things so badly, and so nearly everyone has inadvertently caused serious problems in their soils. How do we get the right biology back into the soil?

Step One: Bacterial Diversity Adequate?

Bacteria must be present to perform their functions of competing with disease-causing organisms, retaining nutrients and making microaggregates to improve soil structure. The "correct" density of bacteria, or amount of bacterial activity has just begun to be established, based on observation of what these levels are in different soils, climates, conditions, disturbances and plant species. Seasonal variations and the requirements of different plants appear to be the most important relative factors. The correct values for active bacterial biomass, and total bacterial biomass are given on a Soil Foodweb report, based on season, plant type, soil type and climate, in the row marked "desired range".

1. When total bacterial biomass is too low, bacteria have to be added back to the soil, compost, compost tea or to the water, if working in hydroponics, for example. Add them back by using a healthy, aerobic compost, compost tea or commercial inoculum.
2. When total bacterial biomass is high, most of the time this means improved ability to perform bacterial functions, but if the balance between total bacteria and total fungi becomes inappropriate for the plant species, then the balance needs to be restored. However, you don't kill off bacteria if they are higher than the desired ratio, you improve fungal biomass instead (see Ratios).
3. On rare occasions, total bacteria may compete with fungi for food resources, and in this case, reducing bacterial foods may be a good idea, to allow the fungi to have a chance to grow. Too high bacterial biomass, combined with too low active bacteria biomass may indicate anaerobic conditions occurred, because the bacteria grew very fast, used up the oxygen in the medium so the aerobic organisms went to sleep, but the anaerobes grew well. This can be very detrimental to the aerobic organisms, and actually kill them.

Step Two: Feed the Bacteria

Feed the bacteria, if bacterial activity is too low. Just like any other creature, bacteria require food. Plant roots often supply the simple carbon substrates that bacteria require, such as simple sugars, proteins, and carbohydrates. Bacteria need N, P, K, Ca, and all the other nutrients as well, and obtain those from organic matter and from inorganic sources as well. Various species of bacteria can solubilize mineral elements from the mineral components of soil, but no one species can effectively solubilize ALL minerals. Diversity of species to obtain all the needed nutrients is required.

Often soil tests will indicate that some nutrient is in low supply, but merely by adding the appropriate bacterial or fungal species, these organisms will convert plant unavailable nutrients into plant available forms. Diversity is the key, however, as well as feeding that diverse set of species so they will perform their functions.

1. If activity is low, then bacterial foods need to be added to increase growth rates and improve numbers. A diversity of foods needs to be added, and thus molasses is a much better choice than white sugar. Fish hydrolysate also adds fungal foods, and N and other micronutrients. Fruit juices can be used as well, but diversity is key.
2. If activity is higher than the desired, then try to balance the ratios of the organisms by improving the organism group that is too low.
3. If active bacterial biomass is low, but total bacterial biomass is high, this is a good indicator that anaerobic conditions have occurred. In rare instances, it may be because some environmental disturbance occurred that put the majority of the bacteria to sleep, but did not kill them.

Step Three: Fungal Biomass Adequate?

Fungi must be present to perform their functions of competing with the more difficult disease-causing organisms, retaining nutrients especially micronutrients like Ca, and making macroaggregates which form air passageways and hallways to allow air and water to move into the soil, and to allow good drainage. This is a critical step in improving soil structure, but cannot occur without the first step of good bacterial biomass.

The “correct” density of fungal biomass, or amount of fungal activity, has just begun to be established, based on observation of these levels in different soils, climates, conditions, disturbances and plant species. Seasonal variations and the requirements of different plants appear to be the most important relative factors. Again, the values for active fungal biomass and total fungal biomass are given for the season, plant type, soil type and climate in the row marked “desired range”.

1. When total fungal biomass is too low, fungi will need to be added back to the soil, compost, compost tea or to the water, in hydroponic situations, for example. Add them back by using a healthy, aerobic compost or compost tea. Alternatively, these fungi might be found in healthy soil, especially the humus layer of a healthy forest. But be careful not to destroy that resource by removing too much, or disturbing too much.
2. When total fungal biomass is high, most of the time this means improved ability to perform fungal functions, but if the balance between total bacteria and total fungi becomes inappropriate for the plant species, then the balance needs to be restored. However, you don't kill off fungi if they are higher than the desired ratio, you improve bacterial biomass instead (see Ratios).
3. On rare occasions, total bacteria may compete with fungi for food resources, and in this case, reducing bacterial foods may be a good idea, to allow the fungi to have a chance to grow. High total fungal biomass, combined with too low active fungal biomass may indicate a fungal disease outbreak in progress. This can be confirmed by examining the roots for necrosis, galls, or other signs of fungal disease.
4. Beneficial fungi require aerobic conditions and if oxygen falls below 5.5 to 6 mg oxygen per liter, then the beneficial fungi may not survive. Anaerobic bacteria attack and consume fungi in these low oxygen conditions. Disease-causing fungi are benefited by anaerobic conditions, either because they no longer have competition from the beneficials, or because they require anaerobic conditions for best growth. In either case, anaerobic conditions select for and allow the disease-causing organisms to "win" in the fight for plant tissues.

Step Four: Fungal activity adequate?

Just like any other creature, fungi require food. Feed the beneficial fungi, if fungal activity is too low. Sloughed root cells and dead plant tissue often supply the more complex carbon substrates that fungi require, such as cellulose, cutins, lipopolysaccharides, complex protein-sugar-carbohydrate, and lignins. Fungi are good at condensing organic matter into ever more complex forms, such as fulvic to humic acids. Fungi need N, P, K, Ca, and all the other nutrients as well, and obtain those from organic matter and from inorganic sources as well. Many species of fungi can solubilize mineral elements from the mineral components of soil, but no one species effectively solubilizes ALL minerals. A diversity of species is needed to obtain all nutrients.

Often soil tests will indicate that some nutrient is in low supply, but merely by adding the appropriate bacterial or fungal species, these organisms will convert plant unavailable nutrients into plant available forms. Diversity is the key, however, as well as feeding that diverse set of species so they will perform their functions.

Both bacteria and fungi are important in holding nutrients in the soil when they would otherwise leach into deeper soil layers, and into ground water. The importance of microbes in forming soil structure and preventing erosion is well-known, but in order to hold the nutrients in soil, bacteria and fungi must turn them into biomass, which is not-leachable as long as the glues and strands that the fungi and bacteria use to hold themselves on any surface are not destroyed.

1. If activity is low, then fungal foods need to be added to increase growth rates and improve numbers. A diversity of foods needs to be added, and thus dead leaf material is a much better choice than purified cellulose. Fish hydrolysate also adds bacterial foods, and N and other micronutrients. Wood, sawdust, bark, paper and cardboard can be used as well, but diversity is key.
2. If activity is higher than the desired, then try to balance the ratios of the organisms by improving the organism group that is too low.
3. If active fungal biomass is low, but total fungal biomass is high, this is a good indicator that disease is either rampant, or about to be rampant. Add BENEFICIAL fungal foods and build soil structure as rapidly as possible to compete with the disease, and protect the plant roots from the disease.
4. In rare instances, it may be because some environmental disturbance occurred that put the majority of the fungi to sleep, but did not kill them.

Step Five: Roots colonized by the “goods guys”?

Mycorrhizal fungi are needed by some plants, absolutely critical for other plants, and are probably detrimental for other plants. You need to know what kind of plant you have, but in general, very early successional plant species, such as many (weeds, brassicas, mustards and kale crops do not require mycorrhizal fungal and may be harmed by mycorrhizal fungi. Annual vegetables, flowers, grasses and row crops or broadacre crops need vesicular-arbuscular mycorrhizal fungi. Most evergreen plants require ectomycorrhizal fungi, and blueberry and ericoid plants require ericoid mycorrhizal fungi.

The percentage of the root system that must be colonized has not been fully established in the mycorrhizal literature, mostly because determining benefit is relative. Mycorrhizal fungi can protect the roots from disease organisms, through simple spatial interference, by improving nutrient uptake, and by producing glomulin and other metabolites that inhibit disease. Stress in plants can be reduced because the mycorrhizal fungi can solubilize mineral nutrients from plant not-available forms to plant available forms, and translocate those nutrients to the root system in exchange for sugars provided by the plant.

Given that mycorrhizal fungi can influence so many aspects of plant growth, and documenting all these benefits is usually extremely expensive and difficult, they have not been documented. Therefore, probably the best that can be done is to say that perhaps as low as 12% colonization might be documented to be beneficial (work by Moore and Reeves in the mid-1990's), but more likely a minimum level of 40% colonization is required, as suggested by Mosse, and St. John in various publications and comments.

Early researchers found colonization as high as 80% in root systems, but most likely because they did not differentiate false-arbuscular and vesicular structures produced by disease-causing fungi from true VAM structures. Thus, colonization is rarely as high as 80% is not commonly found now that we recognize these non-mycorrhizal forms.

In the last 10 years, some researchers have suggested that some mycorrhizal fungi do not produce vesicles under all conditions, and so VA mycorrhizal fungi should be called arbuscular mycorrhizal fungi, not vesicular-arbuscular mycorrhizal fungi. Just be aware that sometimes, people say VAM, sometimes AM. Whatever.

1. If the plant does not require mycorrhizal colonization, there probably is no reason to assess the roots for mycorrhizal colonization. Although the Allens showed that one way for certain plants to exclude non-mycorrhizal plants from a community was to make sure the mycorrhizal fungi were present, because the mycorrhizal fungi pulled nutrients from the non-mycorrhizal plants. This is a probable mechanism for mycorrhizal crop plants being able to out compete weeds and earlier successional plant species.
2. When mycorrhizal colonization is low, or less than the desired range, given that the desired plant requires VAM or ectomycorrhizal colonization or ericoid mycorrhizal fungi, then check how low the colonization is.
    1. If less than perhaps 10 to 15%, then addition of mycorrhizal spores would be a good idea. If it is an annual plant, placing

VAM spores near or on the seed or seed pieces is the simplest way to get the roots colonized as soon as the roots area produced.

   i. With permanent turf, adding VAM spores into the compost mixWed into the aeration cores gets the VAM spores into the root system without destroying the turf.
   ii. With perennial plants, verti-mulching and adding the VAM or ecto- spores into the compost mixed in the vertimulch is the simplest way to get the spores next to the root system. In cases where we have added inoculum in this fashion, roots have gone from 0% colonization to 25 to 30% within a year, and to 50 to 60% in two years, with addition of humic acids through the season to help the mycorrhizal fungi grow rapidly (see next section)

2. If colonization is between 15% and 40%, then all that is needed is additional fungal foods to help the mycorrhizal fungi improve plant growth, reduce plant stress, and improve root protection.

. There is a dose response relationship to humic acids additions. Typically addition of 2 to 4 pounds of dry product, or 1 to 2 gallons of liquid product per acre are adequate to improve fungal growth. But, if there are toxic chemical residues to overcome, additional humics of fulvics may be needed. It is best to check periodically to see that colonization is improving as desired.

   i. Be aware that that most humic acid products contain 10 to 12% humic acids. If the product you are considering is less expensive, please check the concentration of humic acid. Half the concentration of the humic acid means they can drop the price, but your fungi get less benefit.
   ii. Check colonization periodically to make sure the fungi are growing and colonization is increasing. Weather can cause problems with colonization, and severe drought, floods, burns, compaction causing by over-grazing, heavy machinery, herds of people walking on the lawns or turf can reduce colonization. If that happens, additional applications of fungal foods will be needed to help resuscitate the damage. Fungi are just like any other organism. If they are harmed, they need care to recover. Triage for fungi includes adding foods they love (humic acid is like chocolate to a choc-a-holic, but they'll also accept any woody, wide C:N ratio fungal food), and putting on a mulch or litter layer on the soil surface.

3. If colonization is above 40%, then the plants are getting the help they need from the fungi. Periodically check to make sure nothing has harmed them.
4. What if colonization seems too high? This is extremely rare, but does happen, and seems to be associated with the fungi taking more than their fair share of the plant's resources. Stop applying fungal foods. Consider helping the bacteria compete with the fungi for a bit.

Steps Six, Seven, Eight: Adequate protozoa to cycle nutrients?

Make air passageways? Flagellates (Six), Amoebae (Seven), Ciliates (Eight). These are the three groups of protozoa and they are critical in a bacterial-dominated soil, because the plants need a way to access all the wonderful nutrients tied up in the bacteria. Nutrients within the bacteria cannot be obtained by plant roots, so something has to eat the bacteria to release those nutrients. That's what protozoa do. Protozoa also help build the larger soil pores by pushing aggregates around as the protozoa search for and try to reach the bacteria tucked away around soil particles.

1. If the protozoa are too low in number, the nutrients remain tied up in bacterial and fungal bodies. Even if the bacteria and fungi die, they may not release the nutrients in their bodies until the protozoa come along. In many early microbial studies, microbiologists doing plate counts did not recognize that the protozoa were still in their "pure cultures", and it was the protozoa "mineralizing" nutrients, not the bacteria themselves. When protozoa are too low, and nematodes are too low as well, then inorganic fertilizer will have to be added in order to supply N, P, S etc to the plant. This is expensive and a large proportion of these nutrients will likely be lost from the soil, either by leaching or by volatilization. Until the protozoa are inoculated and brought to desired numbers, nutrient loss will continue to be a problem. Protozoa inocula are available in the form of good compost, good compost tea, or from a commercial source, Holmes Environmental, holmesenviro@attbi.com
2. If the protozoa are within the desired range, nutrients will be made available for the plants are minimal amounts over time. How much will be made available? That will be discussed in the section on Plant Available N made available to plants (see below). But reductions in fertilizer applications should be possible if protozoa are in good range.
3. If protozoa numbers are extremely high, or the different groups are very un-balanced, then nutrient cycling will be variable, and there may be periods when pulses of ammonium or nitrate may

accumulate. These forms are subject to leaching and loss through gas production, and may result in weeds having the nitrate they need to germinate, grow and outcompete the crop or desired plant species.

4. If ciliates are too high, then the soil is either compacted or water-logged, and lacking oxygen. Ciliates are aerobic organisms, but prefer to consume anaerobic bacteria. They tolerate reduced oxygen conditions better than the other protozoa, so high numbers of ciliates indicate problems with the movement of oxygen into the soil, which needs to be fixed. Of course, it the soil gets too anaerobic, all three groups of protozoa will be low.
5. When ciliates are high, but flagellates and amoebae are also high suggests that one of three things may be happening:
    a. The sample has just become compacted, or flooded, and the anaerobic conditions have just been initiated. Generally the number of ciliates is not extremely high.
    b. The sample has aggregates, which are anaerobic inside the aggregates. The high ciliate signal comes from the internal parts of those aggregates where anaerobic conditions exist, but outside those aggregates, aerobic conditions exist, and thus flagellate and amoebae numbers are typically high as well. Both anaerobes and aerobes co-exist, but in very different places within the spatial structure of this sample. This is very typical of good worm compost, particularly worm compost high in castings.
    c. The sample has been anaerobic in the past, but is just becoming aerobic. Flagellates and amoebae are growing because aerobic bacteria have begun to grow. Generally, ciliate numbers will be fairly high, while flagellate and amoebae are just barely in good range. Quite often this will result in nitrate pulses and germination of weed seeds.
6. When flagellates are high and amoebae low, or flagellates low and amoebae high indicates an imbalance in nutrient cycling, with pulses of nitrate being produced, resulting in weeds being able to out-compete the desired plants.
7. What do you feed protozoa? Bacteria. So, if you have taken care of step one and two, the bacteria should be there for the protozoa to eat.

Steps Nine, Ten, Eleven: Adequate nematodes numbers, and are they the right kinds to help nutrient cycling, and build passageways to let water and air into the soil?

Bacterial-feeding nematodes (9), Fungal-feeding nematodes (10) and Predatory nematodes (11). The beneficial nematodes consume their prey groups, and in the case of bacterial- and fungal-feeders, release N, P, S, and micronutrients that would now be available to plants, if the majority of the cycling occurs in the root system. These nematodes also interfere with the ability of the root-feeding nematodes finding the root. The higher number of these organisms, the more nutrient cycling is occurring.

Step Twelve: The bigger critters home?

Earthworms, Microarthropods.
If earthworms and/or microarthoropods are present, then the full food web is present, and if everything is in a good biomass or numbers of individual organisms, then plant health is pretty much assured, because all the processes will be functioning.

How much do I add to fix any group?

In any case, just an inoculum is required, since all of these organisms will multiply, resulting in increased numbers. Of course, the higher the initial number of individuals added, the faster the return to health. Addition of foods for the organisms will increase the rate of return to health as well.

If toxic chemicals are present in the soil, or litter material, then these materials have to be consumed by the organisms before the twelve step program can be performed. Addition of foods to help consumption by organisms will increase the rate of return to health.

Bacteria – add bacterial foods, such as simple sugars, simple proteins, simple carbohydrates. Molasses, fruit juice, fish emulsion and green plant material high in cellular cytoplasmic material feeds bacteria. The more kinds of sugars and simple substrates added, the greater the diversity of species of bacteria, and the more likely the full range of beneficials will be present.

Bacterial AND fungal inocula can be found in most good AEROBIC composts, or compost teas made with compost documented not to contain E. coli, or other human pathogens.

There are some “starter” bacterial inocula that are useful as well. What you need to look for are maximum diversity in the bacterial species. Unless you are trying to make fermentative compost, you need to avoid inocula containing anaerobic bacterial species.

Fungi – add fungal foods, such as complex sugars, amino sugars, complex proteins, soy bean meal, fish hydrolysate, fish oils, cellulose, lignin, cutins, humic acids, fulvic acids, wood, paper or cardboard. The more kinds of fungal foods that are present, the greater the diversity of fungal species will grow.

There are no fungal inocula on the market. Yeasts are rarely useful fungal species in soil, or at least there is little data to support their usefulness. Some effort needs to expended to show the veracity of this view point.

Protozoa – consume bacteria, and thus to improve protozoan numbers, bacterial biomass needs to be enhanced. Protozoa inocula are compost, compost tea, and some commercially available protozoan cultures.

Nematodes – consume bacteria, fungi and each other. Inocula of certain entomopathogenic nematodes are available, for control of certain insect species, such as root grubs and root weevils. Compost and compost tea are the only source of inocula for the beneficial nematodes.

Mycorrhizal fungi – need roots to germinate and grow successfully. Humic acids can improve germination, but then the germinated fungus has to rapidly find a root to colonize or it will die. Spore inocula exist for all kinds of mycorrhizal fungi. Make sure you have the kind needed for your plant. Make certain to get the spores into the root system of the plant, such as injecting the spore, or adding compost mix into the soil, filling soil cores with a mix of compost and spores.

This is just a start to understanding how to get the right biology back into the soil. You need to test your soil and figure out where your soil is, with respect to the right biology, and then make a plan on how to get the right biology back. Once you think you have achieved the goal, test again to see if you have achieved a healthy soil condition for your plants.