Working with Soil Microbiology

Robert G. Linderman
Plant Health, LLC
Corvallis, OR 97330
bob.linderman@planthealthllc.com
www.planthealthllc.com

Plant and crop performance is dependent on soil health. Growers should be interested in improving soil health/quality to maximize the growth and health of crops in order to realize maximum economic returns. The health of soil is typically gaged by the performance of the above-ground crop. However, in reality it is determined by the interaction of the soil's key components: (1) soil structure (tilth), (2) soil chemistry (pH, nutrition), and (3) soil biology. When these components are in balance, the soil is healthy and crop performance will show it.

Soil Tilth. Soil structure is referred to as tilth, and involves the physical characteristics of the soil. Soil is composed of mineral and organic components, but the remaining pore space must have moisture and air to have good tilth. Not all soils have the necessary proportions to be a healthy soil; that is 45% mineral components, 5% organic matter, 25% water, and 25% air space. A number of factors can contribute to those proportions being less than optimum, such as soil compaction, that reduces air space, due to tractor traffic and irrigation practices. Clay particles may have accumulated in layers of hardpan that can impede penetration of roots, as well as percolation of water, nutrients, and air into the crop root zone. Soil aggregates may have broken down, causing the collapse of the soil structure.

How can you improve soil structure? Cultivation may break up impervious layers, but amendments to the soil will improve the over-all structure and tilth. Amendments such as gypsum, organic matter (compost, cover cropping) will help. Microbial products containing certain bacteria can cause the soil to aggregate and thereby open up. Mycorrhizae can cause water stable aggregates to form and thereby open up air spaces that contribute to improved soil structure. As a result of these amendments, over time the soil tilth will be improved as will the root system. Roots will penetrate and explore more of the soil profile, and have the necessary air to be healthy and functional.

Soil chemistry/balanced nutrition. There are several things to think about in establishing optimum soil fertility for any crop, partly because different crops have different fertilizer/nutrient needs. But there is more to this than just adding fertilizer to supply the needed N, P, K, and minor elements. A number of questions should be answered in order to optimize soil fertility. The first is what happens to the fertilizer when added pre-plant or post-plant? Soluble inorganic fertilizers first go into the soil solution, mainly as ions that either bind to soil particles or stay in the soil solution. Some of the nutrient elements in solution may leach out due to rain or irrigation, and those may need to be replaced to maintain an optimum nutrient balance for plant needs. Organic fertilizers require microbial activity to break them down in the soil, so they are released more slowly for plant use. When to apply fertilizer depends on when the plant needs them and for what plant process. Soils that have lost some important elements by leaching need to be "remineralized" to correct any deficiencies. This could be especially true where soils are being leached to reduce soil salinity. On the other hand, applying too little water may reduce leaching of salts that may have accumulated to toxic levels. Remineralization can be accomplished by amendments with materials that are rich in the needed elements, such as rock dust/flour or kelp meal. Rock dust is finely ground from mineral deposits, and contains a wide range of mineral nutrients. Kelp meal is similarly a fortified source of many minerals accumulated by the seaweed in the ocean. These products contain a wide array of mineral elements that may correct for many deficiencies. Further, these materials are said to enhance the activities of beneficial microbes that are so important in healthy soils. Some of those microbes provide relief from the toxic effects of salinity or heavy metals. Microbial amendments may reduce soil salinity by creating better drainage so salts can be leached down the soil profile.

Another consideration is how nutrients are absorbed from soil. Nutrients must be in the soil solution to flow directly to the roots for absorption. Soil pH has a profound affect on the availability of nutrients in the solution. Some elements, such as P, Cu, and Zn are relatively immobile in soil, so they don't flow in the solution. Some microbes can help solubilize nutrients by freeing them from their binding to soil particles, usually by producing acids. If microbial activity in the root zone is high, then nutrients that might otherwise leach away before the plant can use them will be retained in the root zone. Retention of nutrients in that zone will therefore increase the "fertilizer-use efficiency". It will take less fertilizer to grow the crop because less is lost by leaching and is therefore available to be absorbed by roots and mycorrhizal fungi. Mycorrhizal fungi can mine nutrients from soils at great distances from the roots, with which they have a symbiotic relationship, and transport them to the root system. For plants that have a very course, non-fibrous root system, having functional mycorrhizae is essential. Of course, bacterial associates of the mycorrhizae play a critical part of that process as well.

Soil biology. Soil biology refers to the many kinds of organisms, in addition to plant roots, that live in soil, including soil bacteria, fungi, and various fauna such as insects nematodes, protozoans, and earthworms. Most of the microbes are relatively neutral in function, but some are deleterious (pathogens) while others are beneficial (pathogen antagonists, mycorrhizal fungi). Having sufficient soil organic matter is needed to maintain high populations of these microbes.

<u>Bacteria</u>. What do soil bacteria do? Bacteria are the most numerous of the soil components, and perform many critical functions that influence crop plant growth and health. They take up and release nutrients in the rhizosphere soil around plant roots. Some associate with the hyphae of mycorrhizal fungi, deriving nutritional support from hyphal exudates. Bacterial populations can affect soil chemistry and soil structure. Some are able to capture (fix) nitrogen (N_2) from the air and convert it into fertilizer N for plant use. Some, such as *Rhizobium*, form nodules, on roots of leguminous plants, in which that transformation occurs. Nodulating rhizobia usually occur in the same root system of leguminous plants as mycorrhizal fungi, and the two endophytes function in tandem in those roots. Some nitrogen-fixers are free-living and some associate with roots, but both provide some of the nitrogen needed for plant growth.

Some bacteria are known as plant growth-promoting rhizobacteria (PGPR) because in their presence, plant growth is enhanced. Many, if not most, PGPR are also antagonistic to soilborne pathogens, and that antagonistic function may be involved in the growth enhancement. There is evidence to support the notion that mycorrhizal fungi and these bacteria function as a microbial team. The net effect of that team effort is to protect plant roots from pathogens and thereby enhance plant growth and health.

Some rhizobacteria are strongly antagonistic to soilborne fungal pathogens, and healthy soils have a higher number of them than poor soils. Soil bacteria live on nutrients supplied by plant roots, mycorrhizal fungi, other dead microbes, and organic matter. How can you tell if your soil is highly antagonistic toward soilborne pathogens? You can determine the antagonistic potential by a number of methods. Our method is to determine the combined capacity of all the antagonistic bacteria to inhibit specific fungal pathogens. We isolate a representative group of bacteria from a soil and test each for its inhibitory effect on that pathogen in a Petri dish assay. Inhibitory bacteria form a "zone of inhibition" around their colonies in which the pathogen growth is stopped. When we sum the dimensions of all the zones, we develop the Antagonistic Potential Index (API) for that pathogen in that soil. We have shown that the API is greater in soil around mycorrhizae than in soil around roots of plants without mycorrhizae. We also have shown that the API of soil amended with compost is greater than soils that have not been amended with compost. While some bacteria inhibit the growth of pathogens, some may also inhibit sporulation as with species of *Phytophthora* or *Pythium.* If those pathogens do not produce sporangia that release swimming zoospores, root infections do not occur. Some bacteria also can induce systemic resistance in plants, thereby suppressing pathogen infection.

Soil fauna. Soil is alive with various animals, including nematodes, insects, protozoans, and earthworms, that make up part of the soil foodweb. Nematodes can be root pathogens and cause serious damage to roots and thereby impair root function. Some believe that a balanced, healthy soil will have the means to suppress nematode pathogens. Earthworms in soil are a sign of a healthy soil, and their function in improving soil tilth has been well documented. Soil insects can, in some cases, be harmful, but mainly they participate in the food chain within the soil, sometimes benefiting plant health by their actions.

Fungi. Soil fungi can also be antagonists, nutrient cyclers, and pathogens. Antagonistic fungi, such as species of *Trichoderma,* are known to suppress root infections caused by pathogenic fungi.

Fungal pathogens are well known to growers because of the damage they cause to crop plants and the economic losses they cause. Many times growers have such severe damage from soilborne fungal and nematode pathogens that they elect to fumigate the soils to rid them of the pathogens. Of course, fumigation destroys the balance we seek in building healthy soil. Some believe that if the soil is really healthy in all ways, then pathogens are not able to cause much damage. That surely will not be true for some pathogens, however.

Mycorrhizal fungi. The roots of most plants are symbiotically associated with specialized soil fungi that form mycorrhizae. The term "mycorrhiza" literally means fungus-root. The mycorrhizal association that occurs on most land plants is typified by the presence within the root cortex of distinctive fungal structures that form an interface between the fungi and plant cell contents. Mycorrhizae occur on almost all of the plants on the Earth unless they have been eliminated by man's activities. Analysis of mycorrhizal ancestry indicates that they date as far back as the origin of vascular plants (some 460 million years ago), which is consistent with the hypothesis that mycorrhizae facilitated the colonization of land by ancient plants. The evidence strongly supports the contention that mycorrhizae co-evolved with land plants such that the plant and fungal symbionts became highly dependent on each other. Some are obligately dependent on their host plant and they can only live in association with living plant roots. There are several major types of mycorrhizae, but the major types are ectomycorrhizae (that associate with pines, oaks, birches, and eucalyptus), ericoid mycorrhizae (that associate with ericaceous plants such as azalea, rhododendron, blueberries, etc.), and arbuscular mycorrhizae (AM) (that associate with most of the rest of the plants). Mycorrhizae, however, are not formed in the families of crucifers, chenopods, sedges, and carnations.

Mycorrhizal fungi are symbionts whose simple life history consists of growth and reproductive phases. The growth phase involves production of vegetative hyphae (tiny tube-like filaments) within roots, and hyphae that extend out into the soil. Some mycorrhizal fungi produce thick-walled spores either in roots or on hyphae within the soil matrix. Spore germination occurs near host roots in response to host root exudates. When mycorhizal fungal hyphae contact susceptible roots, they penetrate the root tissue and begin to grow within the root, forming specific structures to maximize the exchange of materials with their plant partner. These structures increase the exchange surface area many fold without damaging the host cells which maintain contact with the entire surface of the highly branched fungal structures. During this phase, bidirectional exchange of metabolites between the fungal and plant partners takes place: carbon from the plant to the fungus, and soil mineral elements from the fungus to the plant. This process is the very essence of the symbiotic relationship with the plant root, but there are many other plant physiological processes that become altered as a result of the association.

The mycorrhizal fungal hyphal network into the soil is a living extension of the host root that increases the efficiency of nutrient and water uptake over roots alone. The most dramatic effect of increased uptake of nutrients is with those elements that normally are relatively immobile in soil such as phosphorus (P), zinc (Zn), and copper (Cu). However, the greatly increased absorptive surface area provided by soil hyphae of mycorrhizal fungi facilitates the uptake of even relatively mobile nutrients such as N and Ca. The potential for water uptake by mycorrhizal roots is similarly increased by means of the absorptive surface area provided by soil hyphae, and that contributes to the increased tolerance of mycorrhizal plants to soil drought. Similarly, plants with mycorrhizae grown in saline soils are better able to tolerate salinity than plants without mycorrhizae. Mycorrhizae may also regulate the uptake of mineral elements (such as Mn) that may be at toxic levels in soil.

The flow of energy-rich compounds from plant roots into the soil is a fundamental process in the soil ecosystem. Mycorrhizal fungi play a major role in this process, due not only to changes in the pattern of root exudation, but also to the production of exudates by soil hyphae of the mycorrhizal fungi. These root and fungal exudates stimulate qualitative changes in the microflora in the soil surrounding and being influenced by the roots (called the *rhizosphere*). Because those changes appear to be persistent, the term *'mycorrhizosphere'* has been used to describe the new microbial composition and equilibrium around plant roots with mycorrhizae. Research has documented a significant amount of the flow of C-containing substances produced in plant leaves into roots, root and soil mycorrhizal-fungal hyphae, and the mycorrhizosphere soil. Below-ground root activity and respiration in mycorrhizal plants is five times greater than that of non-mycorrhizal plants. These results demonstrate that mycorrhizal fungi dramatically increase the flow of carbon from the plant into the soil matrix that supports microbial activity. It might appear that the carbon flowing through and exuded by mycorrhizal soil hyphae is "lost" from the point of view of the plant biomass, but I believe it is a major investment in the physical and biological health of the ecosystem.

The organic compounds in exudates from root tissue and soil hyphae of mycorrhizal fungi are the basis for the mycorrhizosphere effect. The amount and composition of those exudates accounts for the selective enrichment for specific microbes from the background soil. Some bacteria and actinomycetes occur only in the mycorrhizosphere soil (as compared to rhizosphere soil of non-mycorrhizal plants), and there is specificity of selection depending on the species of mycorrhizal fungus. Whether the specificity is due to the soil hyphae of the mycorrhizal fungus or to its alteration of the root exudation pattern has not been determined. It seems plausible, however, that the total of the resultant combination of mycorrhizosphere microbes associated with any plant species in specific soils strongly influences the plant's growth and survival in that system. Once equilibrium has been reached, there simply is no way to distinguish between effects of the mycorrhizal fungi, of their microbial associates, or their combination; the effects are simply the consequences of the mycorrhizal symbiosis.

It is commonly stated that plants with mycorrhizae tolerate diseases better than plants without mycorrhizae. However, the mechanisms of that effect are not well understood. Several mechanisms have been proposed, such as enhanced nutritional status of the host plant, competition between mycorrhizal fungi and pathogens in the roots, morphological changes in the roots that block pathogens, changes in inhibitory chemicals in roots that suppress pathogens, reduced abiotic stresses that favor pathogen infection, and changes in antagonistic potential in the mycorrhizosphere. I favor the last mechanism. Mycorrhizae have profound effects on the ecology of the mycorrhizosphere due to the induced changes in root exudation patterns as well as to the presence of the mycorrhizal fungal soil mycelium. We have shown that populations of antagonistic bacteria increase in the presence of mycorrhizae, and these microbes potentially could interact synergistically to suppress root pathogens and the diseases they cause. In soilless media, it is critical that there is a source of these antagonists, either by inoculation or by incorporation of organic amendments (such as compost) that contain a high level of antagonistic microorganisms. We have shown that amendment with composts can increase the antagonistic potential of the soil or growth medium.

A number of factors are critical to the establishment of mycorrhizae, especially in soilless growth media. High levels of soluble P in the medium can greatly inhibit AM fungi. Organic fertilizers are more compatible with AM fungi than inorganic fertilizers, unless the P level of the latter is kept low. Some peat mosses are inhibitory, while coir appears not to be. Some composts are highly inhibitory, while others are not. Some fungicides used to control soilborne pathogens are very inhibitory to AM fungi, while others are not.

One critical factor to establishing mycorrhizae quickly and effectively is the placement of inoculum. Propagules (spores) of the mycorrhizae fungi must come in contact with small feeder roots of the host plant. Time to form mycorrhizae is a function of how long it takes for the fungi to come in contact with the plant roots. The sooner the symbiotic relationship is established, the sooner the benefits can occur.

Production strategies that will enhance the potential to benefit from mycorrhizae are to: (a) inoculate with mycorrhizae fungi and other associated microbes, (b) fertilize with organic or low-P inorganic fertilizers, (c) incorporate composts to increase the microbial diversity of soilless media, and (d) do not apply fungicides that will inhibit AM fungi.

Summary of strategies for building healthy soil. Assuming the health of your soil can be improved, you should take corrective actions based on the crop to be grown and your characterization of the soil in terms of texture, chemistry, and soil biology. The main actions you could take are organic amendments, microbial inoculations, changes to fertilizer and irrigation plans, and cover cropping. Specifically, you can improve soil structure by cultivation, cover cropping, organic matter amendments, and amendment with gypsum and/or microbial solutions. You can improve soil chemistry/fertility by adjusting pH in order to increase nutrient availability; by amending with nutrient-rich materials such as compost, rock dust, or kelp meal; by applying fertilizers when needed to enhance availability when the plant needs nutrition; and by considering use of organic sources of fertilizer that will leach less than inorganic sources. You can improve soil biology by organic amendments that support the growth and activity of microbes, and by inoculations with beneficial bacteria and fungi, as well as mycorrhizal fungi. There are a number of commercial products that can be used to inoculate soils or plants to benefit plant growth and health.

There are many potential benefits from having a significant presence of mycorrhizal fungi in the soil, but there are also many reasons why organic matter is important, if not essential. Organic matter improves soil texture and water-holding capacity, and as a mulch can suppress weeds; it is a source of nutrients; and it improves the capacity for beneficial microbes to function. Soil microbes can capture nutrients, holding them in the root zone, and also can help suppress soilborne pathogens. Depending on the location and crop plants, the organic matter content of your soil can be increased by using mulches, by growing plant pre-crops or cover crops, by crop rotations, and/or by adding composts, seedmeals, or other organic waste materials to the soil.

The key to success in improving soil health is to employ multiple tactics to achieve the balance needed between the main components of soil texture, chemistry, and biology. The result should be increase crop productivity and economic sustainability.

Selected references.

Bethlenfalvay, G. J.and R. G. Linderman. eds. 1992: Mycorrhizae in Sustainable Agriculture, ASA Spec. Publ. No. 54., Amer. Soc. Agronomy Press, Madison, WI.

Linderman, R.G. 2000: Effects of mycorrhizas on plant tolerance to diseases. In: Arbuscular Mycorrhizas: Molecular Biology and Physiology. Kapulnik, Y. and Douds, D. D., eds. Kluwer Press. 345-365.

Pfleger, F. L. and R. G. Linderman, eds. 1994. Mycorrhizae and Plant Health, APS Press, St. Paul, MN.