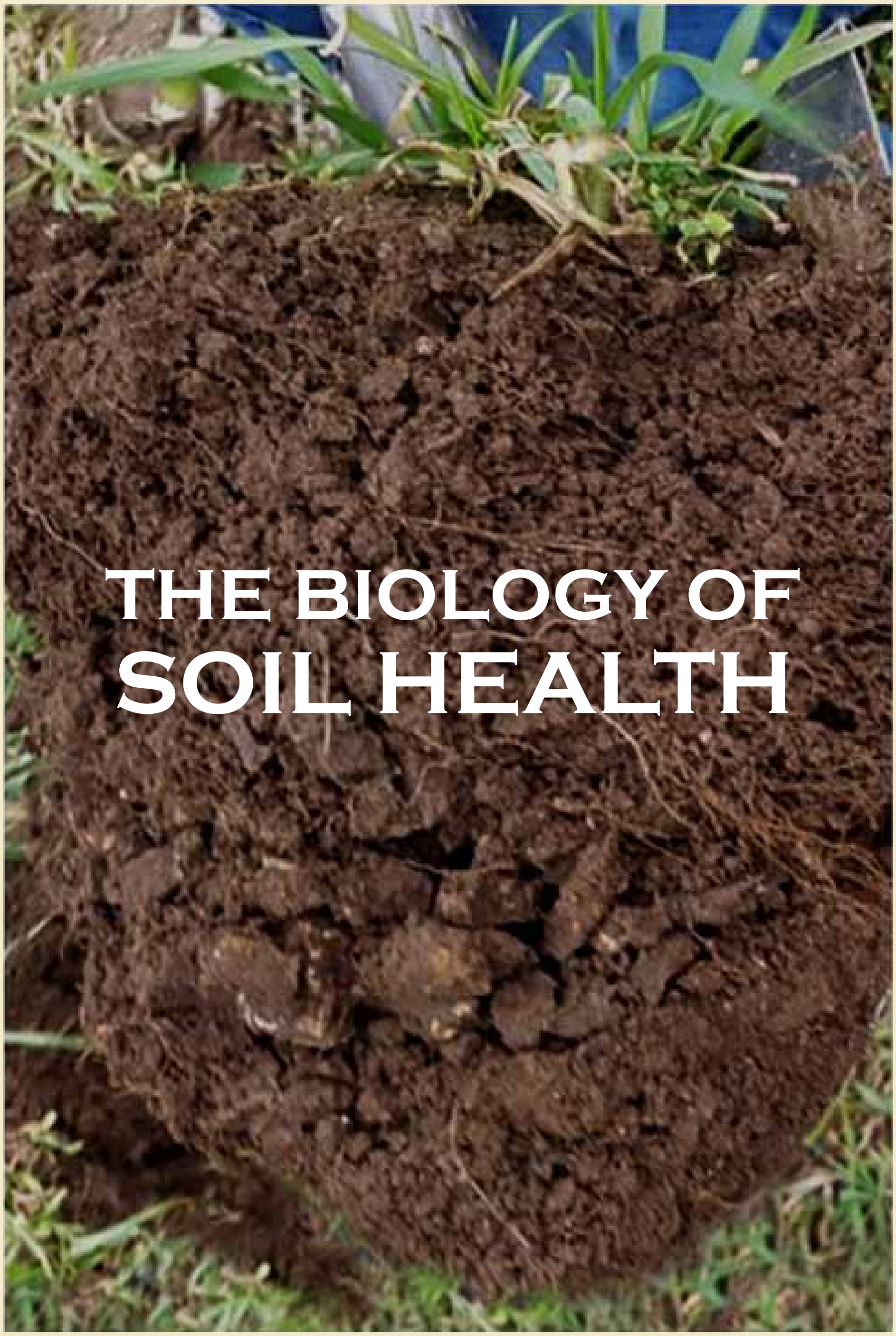
SOILS AT WORK



THE BIOLOGY OF SOIL HEALTH



Conseil canadien du COMPOST Council of Canada

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Two Excerpts from "Soils at Work: The Biology of Soil Health"

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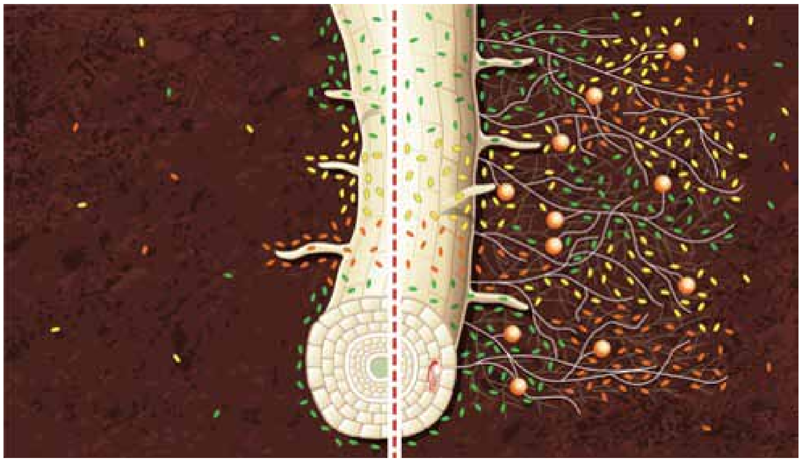
Underground Carbon Trading Systems

The older version of how plants "eat", summarized above, is certainly true. However, it is far from complete. As scientists have learned more about the soil food web and its relationship with plants, a newer understanding has developed. It turns out that microbes play very important roles, not just in liberating nutrients from organic matter and minerals, but also in getting those nutrients to the plant in a timely manner. Their work greatly enhances the relatively slow processes of interception, diffusion and mass flow. There are two main processes by which this quicker delivery is accomplished.

The Rhizosphere Effect and the Microbial Loop

The first process is the result of something scientists call the rhizosphere effect. All terrestrial plants exude carbon-rich substances from their roots into the rhizosphere (this term simply refers to the soil close to the roots). These exudates include sugars, carbohydrates, organic acids, and various other organic compounds produced by the plant from the simple sugars it created through photosynthesis. Because many of these substances are a great energy source for microbes, the rhizosphere is, to microbes, like a watering hole to desert animals – a crucial source of one of life's necessities. Accordingly, the population of bacteria and fungi are much higher around the roots of plants than they are in other parts of the soil (known as the bulk soil). This is the rhizosphere effect and this phenomenon has been well known by scientists for decades (see **Figure 29**).



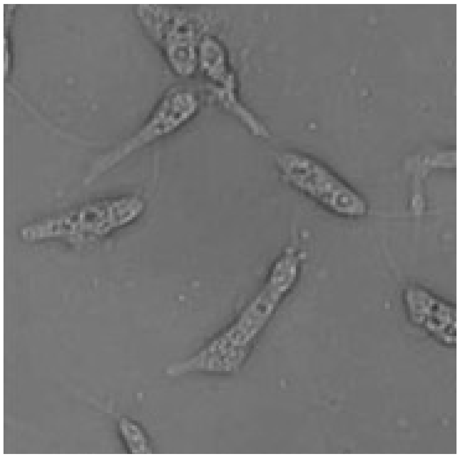
The rhizosphere effect *(Figure 29)*

While some of these root exudates have specific single-focus purposes, such as directly breaking down minerals and releasing nutrients, or attacking disease organisms, (more on these other functions in later chapters), most of them appear to have another, broader purpose: to attract and "grow" microbes in the areas directly adjacent to their roots. Plants can devote more than 40 per cent of the chemical energy they fix through photosynthesis (materials collectively known as photosynthate) to this purpose – an incredibly high level of investment on their part. Why would they do this?

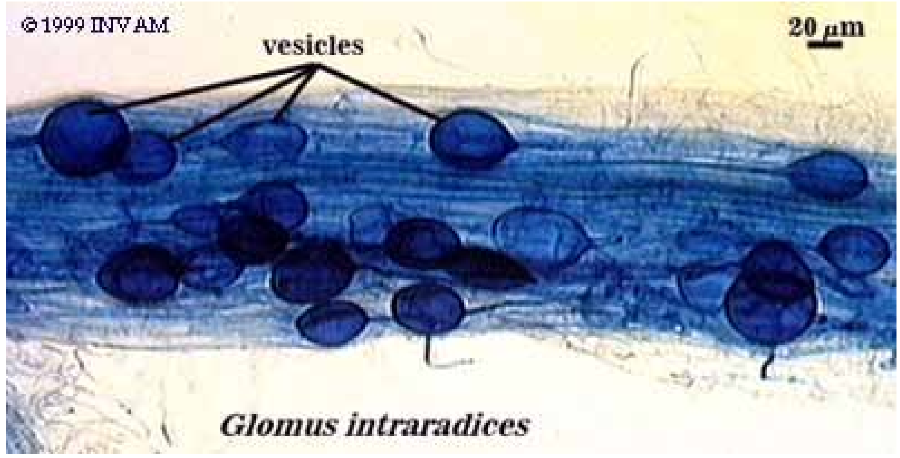
It turns out that they are essentially paying for a service – the fast, efficient delivery of nutrients to their root zones. It is similar to how we humans pay for the delivery of pizza. How does this delivery system work? As watering holes in the desert attract thirsty animals, so the exudate-rich rhizosphere attracts hungry bacteria and fungi. But they are not the only visitors. What predator doesn't know that watering holes are great hunting grounds? Because of the rhizosphere effect, microbial predators (remember the protozoa and nematodes in Chapter One?) find rich pickings in plant-root zones. As these protozoa and nematodes graze on the dense populations of bacteria and fungi in the rhizosphere, they leave their wastes behind, and these wastes are "microbial manure" -- chock full of plant-available nutrients.

In essence, plants are taking advantage of the following facts:

1. Bacteria and fungi break down soil organic matter, and many minerals as well, and absorb the nutrients in their bodies.
2. These bacteria and fungi are attracted to plant roots because of the carbon-rich exudates available there.
3. Predators, mainly the various types of protozoa and nematodes, consume bacteria and fungi to obtain these nutrients, as well as carbon (see **Figure 30**).
4. Because bacteria and fungi are nutrient-rich, relative to carbon, when compared to predators, excess nutrients are released by the predators in their wastes (i.e., microbial manures).



Predators Grazing in Rhizosphere *(Figure 30)*



Vesicular Arbuscular Mycorrhiza (VAM) *(Figure 31)*

5 The nutrients in these microbial manures are in plant-available form (soluble ions).

6 Therefore, high numbers of microbes in the rhizosphere results in high levels of nutrient availability – and these nutrients are right where the plant needs them.

This has been called the microbial loop: plants devote much of their hard-earned photosynthate (carbon compounds) to soil, in effect trading this carbon for the fast, efficient delivery of nutrients right to their door, courtesy of the soil food web.

Mycorrhizal Fungi

The second underground carbon-trading system involves the mycorrhizal fungi described in Chapter 2. These organisms establish connections with plant roots and use them to provide nutrients and water directly to the plant in return for sugars and other carbon-rich compounds. Unlike the system described above (the microbial loop), these fungi establish an actual physical connection with the roots.

There are many different species of mycorrhizal fungi. These fall into several general types, the most well-known of which are ectomycorrhizal and endomycorrhizal. The ecto type do not penetrate plant roots; they set up their trading sites on the plant root surfaces. They are associated with conifer trees and some deciduous trees, and so are of limited interest to farmers. The endo type, on the other hand, infect plant roots, setting up shop inside them.

One type of endo, known as vesicular arbuscular mycorrhiza (VAM), creates vesicles (small compartments) inside plant roots. These vesicles are typically arranged in tree-like structures (see **Figure 31**). This is where the commonly used acronym "VAM" comes from: "vesicular" is for the vesicles, "arbuscular" means tree-like, and "mycorrhiza" is the shortened form of "mycorrhizal fungi". VAM is the type of endomycorrhizal fungi found most commonly in agricultural fields.

The hyphal networks established by these fungi can be quite extensive. These networks explore and mine areas that plant roots cannot reach, greatly extending the feeding area of the plant. Most agricultural plants (e.g., corn, soy, wheat, most vegetables) establish mycorrhizal associations, although not all with the same species and not all to the same extent or degree. The main crop exception in agriculture are the brassicas, which do not establish any mycorrhizal associations whatsoever.

Mycorrhizal fungi can be extremely beneficial to farmers, as they help crops in a number of important ways. Below is a brief summary of the potential benefits:

- greater access to nutrients (particularly phosphorus, but many others as well), delivered directly to the plant
- drought protection, as the fungi also deliver water to the plant when it is most needed;
- disease suppression (see Chapter Four)
- better soil aggregation and structure (see Chapter Two)

- increased carbon sequestration (see Chapter Five)
- weed suppression.

With respect to the last point above: many annual weeds are either non-mycorrhizal or have only a weak association with these fungi. This can be a great help to farmers in managing weeds, as long as the VAM are kept alive and well in the soil. The plants that have mycorrhizal partners (the crop) have an advantage over the many weeds that do not; the latter can actually be starved of phosphorus by the fungi, who will deliver it all to their plant partners.

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4 This is not to say that plants don't use other elements – they do. However, only the nutrients listed in Table 1 are absolutely essential. Of course, scientists are always learning more about plants, and the list of essential nutrients will probably increase in number in the future, as it has in the past.

Diseases and Pests in Natural Systems

Natural Immunity

Plants have immune systems that evolved to protect them from diseases and pests. Ecosystems also have mechanisms to keep pest and diseases (and the ecosystem itself) in balance. Plant pathologists, soil ecologists, and ecosystem specialists of various kinds have observed and described these in some detail. Either or both of these systems, however, can get out of whack, allowing disease and pestilence to run amok. This happens in nature and it can and does happen in farm fields, which is of course why crop protection products have become so popular and their use so widespread. Also, as anybody who grows plants knows, it is the plants that don't get enough sun, water, or nutrition that are the first ones to succumb to disease and pest damage. Plants need to be healthy for their immune systems to work, and that health depends on a lot of factors. What we are just beginning to learn, however, is how we can manage soils so that a plant's natural protection systems are optimized, rather than ignored (or worse, compromised). This understanding is still fairly basic, from a practical perspective, but there are some important things we do know with regard to a soil's ability to protect a crop.

The Importance of Diversity

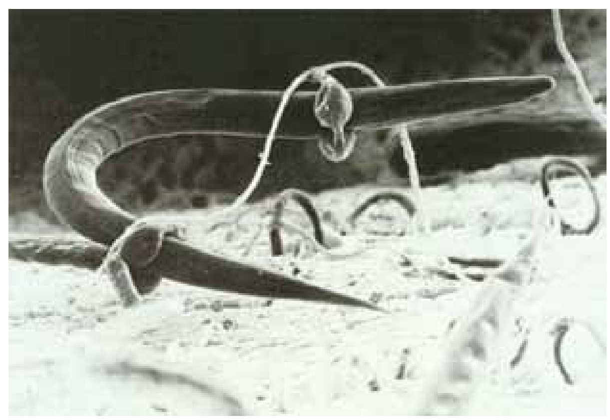
First of all, we know that diversity is a key to keeping disease organisms in check. Many microbes have weapons that they can use to battle the "bad guys" and, given a chance, they will use them. After all, it is in the interests of most soil food web entities to keep the plants in their region alive and healthy, for the plants provide them with their on-going supply of energy, via their exudates.

Beneficial microbes fight plant disease by:

- out-competing pathogenic organisms for resources
- providing barriers between pathogens and roots
- exuding anti-biotics that kill pathogens
- in some cases, consuming pathogens
- providing plants with the specific substances they need to launch their own defense mechanisms and, perhaps most amazingly
- helping plants prepare their defenses in advance of an attack by operating a below-ground communication system for disease and pest alerts (see "Mycorrhizal Fungi and Inter-Plant Communication", below).

Insect pests may also be controlled by certain organisms, for instance:

- predatory nematodes attack the larvae of some insect pests, killing them by burrowing inside and eating them alive
- these predators also prey on root-feeding nematodes, keeping those pest populations in check; and,
- certain fungi trap the root-feeding nematodes in loops made with their hyphae and then slowly absorb them (see **Figure 32**).



Nematode-trapping Fungus
(Figure 32)
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

Healthy soils are diverse soils and from what we are learning about how the soil food web works, it appears that diversity is the key to disease and pest management in natural systems. All of the disease and pest controls described above depend on the presence of a large and diverse soil food web.

Root Exudates and Disease Suppression

In Chapter Three we discussed the role of root exudates in soil fertility. By feeding bacteria and fungi in the root zone, exudates stimulate the microbial loop, resulting in improved plant access to nutrients. This is a general benefit of exudates, but it is not the only one. Plants release exudates for a variety of specific purposes as well. One of these purposes is disease suppression.

In fact, we now understand that plants are always attempting to modify the microbial population in their root zones, using both short-term and long-term strategies. In the short-term scenario, plants can release exudates that attract or grow the populations of microbes that help them fight off specific diseases (see "Bacterial Allies" below). In the longer term, plants try to mold a root-zone "microbiome" (community of microbes) that is generally suppressive of the diseases to which they are prone.

An important point to note here is that plants cannot attract microbes to their root zone if these microbes are not present in the bulk soil – a strong argument for diversity. As we will see in Chapter Seven, many soil health principles and practices are intended to stimulate and support high levels of diversity, both above and below ground. The role of exudates in building both plant and crop immunity is one important reason why.

Examples from Recent Research

Mycorrhizal Fungi and Inter-Plant Communication

A pair of recent studies have opened up a whole new direction of research into how plants defend themselves from diseases and pests. Both studies involved the role of mycorrhizal fungi (first described in Chapter One, with more detail in Chapter Three). Here is a quick review of how mycorrhiza work in general.

Mycorrhizal fungi set up trading systems with plants, where they bring nutrients and water to the plant roots in return for the sugars and other carbon-rich materials plants produce via photosynthesis. In agriculture, the common type of mycorrhiza (VAM), actually infect plant roots and create within them little compartments called vesicles, where the trading takes place. These fungi then grow their hyphae well out into the bulk soil and connect with other plant roots, as well as with other fungi. In essence, they create an underground network, which scientists refer to as common mycelial networks.

These two studies show clearly that these underground networks are used for more than carbon trading and nutrient delivery. In one study, the researchers looked at how tomato plants create a chemical that helps them fight off a specific disease that is common to tomatoes. They found evidence that non-infected plants that are close to infected plants often get started on producing the anti-pathogen chemical even before they are infected, almost as if they had been warned. The researchers wondered if there was any way in which an infected tomato plant could send a message to other plants in its vicinity, warning them of the arrival of the pathogen. They set up an experiment where they isolated the various ways in which such communication could occur – one potential way was through the air (chemical messaging) and the other two ways were via the soil. The two soil-related possibilities they looked at were: messages sent via root exudates; and messages sent through the common mycelial networks.

By carefully managing the experiment to leave only one of the three options open at a time, they were able to show without any reasonable doubt that the messages were being sent through the mycorrhizal network. This makes sense, from an evolutionary perspective. Scientists believe that terrestrial plants and mycorrhizal fungi evolved at around the same time in earth's history – around 450 million years ago. This means that they have had a long time to work out this system, which benefits both the plant (better disease resistance) and the fungi (healthier trading partners).
A similar study was done with broad beans and aphids. The latter are a major pest on broad bean crops, both directly (by sucking sap from the plant) and indirectly, as a host for a number of plant viruses. Investigators found that non-infected bean plants emit from their leaves an air-borne chemical that attracts the aphids. However, once the beans are infected by the aphids, they change their chemical signal to one that is attractive to a particular wasp species, one that preys on aphids. In other words, they send out a signal that will attract help in fighting off the aphids.

As with the tomato study described above, the researchers set up a group of bean plants in such a way that the only possible message route between the plants was the common mycelial network. They then infected some of the plants with aphids. They found, as expected, that the infected plants changed their chemical signal to one that attracts wasps and not aphids. They also found, as with the tomatoes, that the non-infected beans soon altered their chemical signal as well, making it more attractive to the wasps than the aphids. The conclusion, again, was that the mycorrhizal fungal network was passing a message between the plants connected to its network, and that the message was something like this -- "look out – aphids attacking – prepare the defenses!" (see Figures 33 and 34).

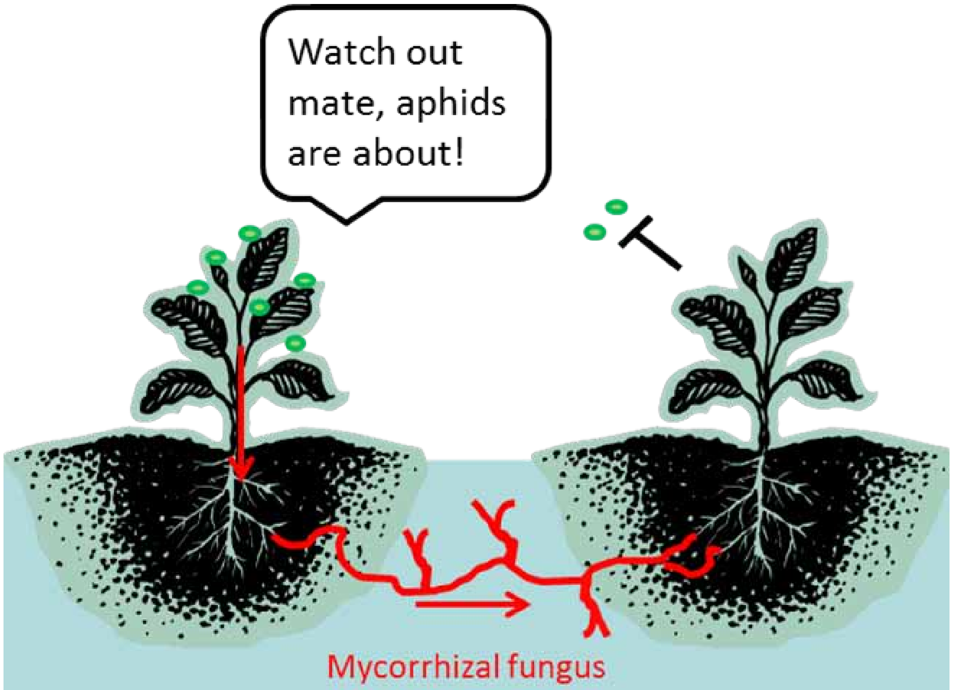


Diagram showing role of fungal networks in plant immunity *(Figure 33)*

Aphid feeding on garden pea *(Figure 34)*

Bacterial Allies

Another recent study showed clearly how plants can use their exudates to attract specific bacterial allies, who then help them to fight off disease. Some plant pathogens are able to slip through plant-leaf stomata (the leaf openings through which the plant takes in CO_2 and releases oxygen and water vapour). This is how these pathogenic bacteria are able to infect the plant (see Figure 6, Chapter One). However, the researchers knew from previous experiments that this invasion can be halted when the beneficial bacterium Bacillus subtilis is present in the soil where the plant is rooted.

To investigate how this disease resistance works, they tested approximately 3,000 plants inoculated with a common foliar pathogen, during a year-long period. They found that when a foliar pathogen attacks, the plant uses root exudates to "recruit" (that is, attract) *Bacillus subtilis*. The exudates also promote the further growth of the B. subtilis population. These beneficial bacteria then bind to the plant's roots and release substances that prompt (and assist) the plant to close its stomata, preventing further infection. This is obviously a plant-microbe partnership that has evolved over millennia – one that benefits both parties. As research continues into how plants defend themselves against diseases and pests, it is likely that many more of these partnerships will be discovered.

Again, we should make the point that this defense would not be possible if the bacteria in question were not already present in the soil – another reason to promote diversity.

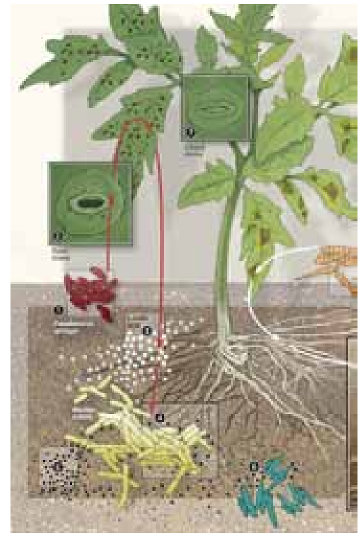
It Takes a Team

The studies above were examples of relationships between specific plants and their microbial partners. However, the use of molecular DNA-based technologies has opened up the possibility that some defense strategies are much more complicated than that. Research teams in California and the Netherlands, working cooperatively, used a technology known as the "PhyloChip" (see **Figure 35**) to look closely at the types of microbes found in soils that suppress an important disease of sugar beets. They determined that this disease, caused by a specific fungal pathogen, could be reliably controlled by a "consortium" of

PhyloChip
(Figure 35)

17 beneficial bacteria. If all of these species were present in reasonable numbers, the pathogen was not a problem; if even one was missing, the soil did not suppress the pathogen, and the beets became diseased.

As time goes on, we may find that this "team approach" is the key to many plant diseases, as well as to pest management. It would explain, for instance, why the application of compost to soils has been found to suppress disease effectively in many situations, but not consistently. Perhaps, in the cases where the disease in question was not suppressed, one or more of the key members of the microbial consortium was missing.



Plant Root Microbiome
(Figure 36)

This area of research holds enormous promise. Imagine a future where testing systems like the PhyloChip (perhaps refined to the point where farmers can employ these tools themselves) are used regularly on agricultural fields, in order to determine if the "microbe defense teams" necessary to prevent disease and suppress pests on that specific crop are present. If anything is missing, it can be added as a probiotic.

In the meantime, however, this study, like the others described above, presents another strong argument for promoting and sustaining diversity in soils. By doing so, we increase the odds that all members of any specific microbial defense team are present (see **Figure 36**).