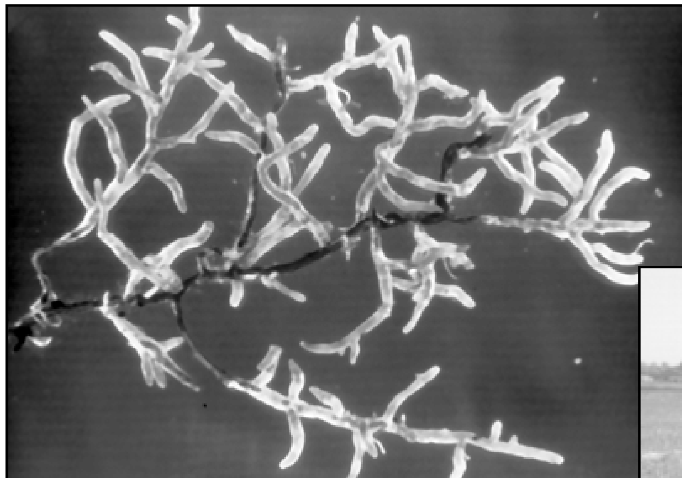
The Soil Food Web

Tuning in to the World Beneath Our Feet

by Mary-Howell R. Martens



The exchange of minerals and nutrients between plants and fungi represent a critical link to plant health and productivity. Above, ectomycorrhzial fungi, commonly associated with trees and grapes, form a protective sheath around plant roots, making soil nutrients available to the root cells and protecting the plant from pathogenic attack.

Elaine Ingham, Ph.D., has been at the forefront of educating farmers about the value of understanding soil life.

Unseen beneath our feet, there dwells a teeming microscopic universe of complex living organisms that few humans ever consider. In one teaspoon of soil alone, there may be over 600 million bacterial cells, and if that soil comes from the immediate root zone of a healthy plant, the number can exceed a million bacteria of many different species. These bacterial cells exist in complex predator-prey relationships with countless other diverse organisms. This topsoil food web forms the foundation for healthy soil, for healthy plants, and ultimately for a healthy planet. It is an essential but exceedingly delicate foundation that even the brightest scientists know very little about.

Dr. Elaine Ingham has been researching this tiny universe for nearly 20 years. She has sought to understand the importance of these organisms and the relationships that exist between them, and to elucidate the effects that various agricultural practices have on this vast network of life. For part of her Ph.D. dissertation in 1981 at Colorado State University, Dr. Ingham researched the soil food web structures in Colorado soils that were farmed with and without irrigation. She compared these results to native grassland soils. Not surprisingly, she discovered that the introduction of agricultural systems altered the species of organisms present, particularly the fungi, which are easily destroyed by agricultural pesticides. For her postdoctoral work, she compared grassland soils to high mountain meadow and pine forest soils, working across a typical successional gradient.

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Again she found great differences in species present and numbers of the typical organisms in response to other important factors in the soil.

Over the course of Ingham's education and subsequent career as a professor at Oregon State University and most recently with Soil Foodweb Inc., a research and consulting firm in Corvallis, Oregon, she has developed methods to quantify and identify the microbial populations of soils. She has learned that most traditional techniques of petri plate counts grossly underestimate both number and diversity of species present in soil, since the artificial conditions are not suitable for the growth of 99.99 percent of bacterial species and of most other organisms. To circumvent this problem, Ingham has developed effective alternative techniques based on direct enumeration methods. She uses this information to assist farmers and researchers by offering a service that assesses the health and productivity of their soil by measuring the diversity and vitality of the soil food web.

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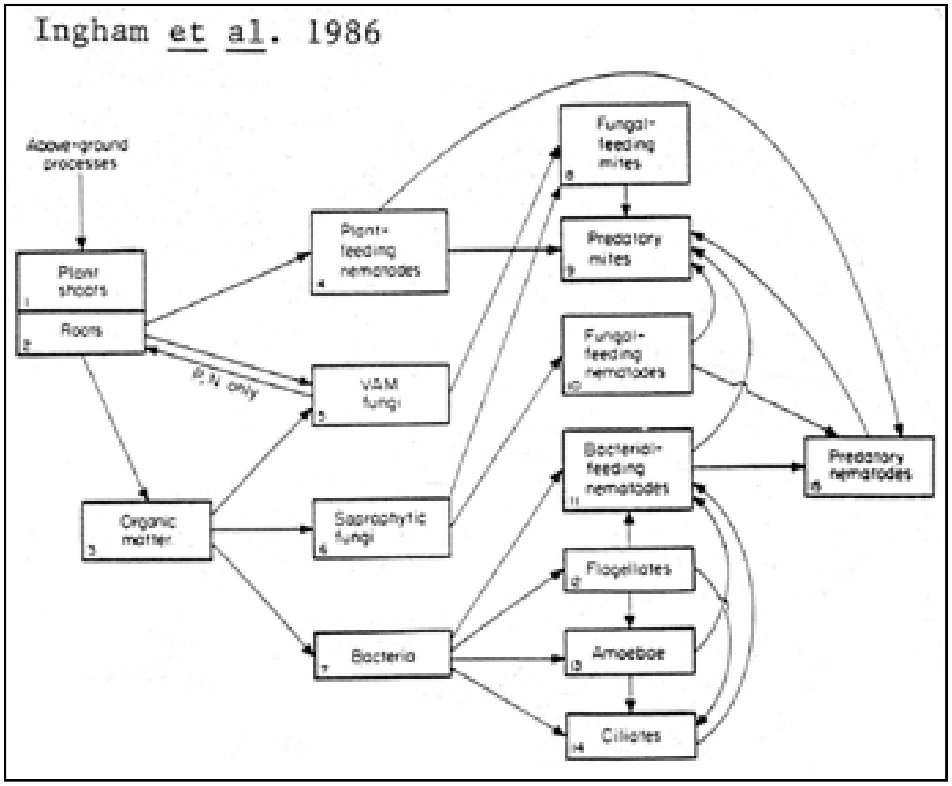
Which organisms compose this soil food web? This is not a simple question. The food web has a basic set of expected organism groups, but the numbers of organisms and different species in each group can vary significantly by soil type, climate, plants present and management. Plants and plant structures are a major component in determining the food resources in soil that will be available to bacteria and fungi. Photosynthesizing living plant material provides the initial energy to the soil food system through their roots. Living plant roots exude many types of complex high-energy nutrient molecules into the surrounding soil. Dead plant material is decomposed by bacteria and fungi, building up even greater numbers of these organisms and their metabolic products. The more diverse the initial plant population, the greater the diversity of plant products that will be released, thereby sustaining an increased variety of microbial organisms.

For a healthy soil, unaltered by the application of lethal agricultural chemicals, these "microherds" of microbes colonize the root zone, the rhizosphere, of the plant. Most are



The soil food web is the community of organisms living all or part of their lives in the soil. A food web diagram shows a series of conversions (represented by arrows) of energy and nutrients as one organism eats another.

beneficial bacteria and fungi; they do not damage living plant tissue and are critical to making essential minerals available to the plant. These microbes retain large amounts of nitrogen, phosphorous, potassium, sulfur, calcium, iron and many micronutrients in their bodies, preventing these nutrients from being leached or removed by water runoff. Ideally, they out-compete pathogenic species and form a protective layer on the surface of living plant roots. It is usually only when the beneficial species of bacteria and fungi are killed by continuous soil disturbance and toxic chemicals that pathogenic species have an advantage.

As in more familiar aboveground ecosystems, there are other organisms present that prey on these herbivores. The predators are primarily beneficial nematodes, predatory nematodes, protozoa, mites and other tiny animals which serve to recycle nutrients in the system and to keep other populations in balance. These predators, in turn, are eaten by other animals, primarily those that spend some portion of their life aboveground, such as insects, birds and small animals.

It is important to view the soil food web as a complex, whole system. When any group of organisms in the system is eliminated or damaged, the delicate balance of interrelationships can be shifted. Soil ecologists are just beginning to understand how plant production can be affected when this balance is altered. Many species of beneficial bacteria and fungi die as food supplies dwindle. Reduction in natural predators and decreased competition for certain food supplies may allow other species to grow rampantly. Plant nutrient availability often can decline, and populations of pathogens can rise. Much research is currently being done on this subject, attempting to comprehend how such changes occur.

HERBICIDES, PESTICIDES & FERTILIZERS

As part of her research, Dr. Ingham has shown that herbicides, pesticides and fertilizers have many non-target effects. The most common pesticides are fairly broad spectrum; that is, they kill much more than the target species. Residual pesticides that accumulate in soil over many years may recombine and form new, unintentional chemicals that have additional and often synergistic negative effects. Out of the 650 active ingredients used to formulate most common agricultural pesticides, only about 75 have been studied to determine their effects on soil organisms. The remaining ingredients have never been studied for their effects on the whole system or on any non-target group. Scientists don't fully understand the effect of any individual ingredient on soil life, much less the synergistic effects of the ingredients, or combinational effects with inert or soil materials. It is hardly surprising that a soil treated with numerous agricultural chemicals lacks a healthy food web. Plants growing in unhealthy soil require additional fertilizers and pesticides, furthering the deadly spiral.

As a plant grows, photosynthesis supplies much more than the individual plant's carbohydrate requirements. It has been documented that plant roots can exude over 50 percent of the carbon fixed through photosynthesis in the form of simple sugars, proteins, amino acids, vitamins, and other complex carbohydrates. The types of molecules released are specific for a variety of plants grown under certain conditions, forming in effect a unique chemical signature. As these molecules are released into the rhizosphere, they serve as food and growth stimulants for a certain mix of microbes. Dr. Joyce Loper, of the USDA Agricultural Research Service, and other scientists have shown that for each plant species, this characteristic chemical soup stimulates the development of a select, beneficial company of root-dwelling microbes. This microbial population colonizes the root zone, producing certain chemicals that inhibit the growth of pathogenic species. These organisms also are instrumental in supplying the plant's unique nutritional needs.

The residual effects of this unique microbial population in subsequent years may also help explain why certain crop rotations work better than others. It is possible that the microbial population nurtured by one crop species creates a nutritional or microbial environment that is well suited to a particular subsequent crop species but not perhaps for others. For example, it is likely that crops like broccoli, which inhibit the growth of mycorrhizal fungi, reduce the productivity of a following crop such as corn, which requires mycorrhizal fungi. While this has not been conclusively proven, it could form part of the basis for a better understanding of observable crop rotational effects.

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Certain soil amendments favor the development of a diverse microbial population. Compost in particular can improve soil nutritional availability and soil tilth because of its complex microbial population. Composts bring with them a wide array of bacteria, fungi, protozoa, nematodes and microarthropods, along with the food resources needed to feed these organisms. However, not all composts have the same beneficial effects. There are many different types of composts, as determined by their original ingredients and their degree of maturity. The greater the diversity of food resources in the original composted material, the greater the diversity of microorganisms that can grow in that compost.

In order to better understand the complex benefits of a healthy soil food web, Ingham has separated the major effects into several primary categories.

NUTRIENT CYCLING & RETENTION

Plants require many different mineral ions for optimal growth. These must be obtained from the soil. Many nutrient ions are solubilized from the parent rock material in a process known as mineralization. Bacteria and fungi produce enzymes and acids necessary to break down inorganic minerals and to convert them into stable organic forms. Other nutrients are released through the decomposition of organic matter. In all cases, a healthy, diverse microbial population will develop with rapid decomposition of organic material and will facilitate the recycling of nutrients. Organic matter is also electrically charged and therefore critical to its ability to attract and hold many different nutrient ions. The higher the organic matter in the soil, the greater the ion holding capacity, resulting in reduced leaching of either anions or cations from the soil.

It is only when a predator consumes excessive amounts of nitrogen in the dead cells that it is released into the soil solution. It is this system of nitrogen cycling that has worked brilliantly for the past million years.

Ectomycorrhizae on tree roots. This is a highly desirable colonization of tree and shrub roots that causes the very shape of the root branching pattern to change. Roots in this condition are very efficient at absorbing phosphorus, other nutrients and water, and are protected from root rot fungi and parasitic nematodes.

There is much competition for nitrogen among soil organisms. Those organisms that have the best enzymes for grabbing nitrogen are usually the winners. Bacteria possess the most effective nitrogen-grabbing enzyme system, closely followed by many species of fungi. Plant enzyme systems do not produce enzymes that operate outside the plant and cannot compete well when there is strong competition for limited nitrogen resources.

In a healthy soil, this does not mean that the plant will be deprived of adequate nitrogen. Bacteria require one nitrogen atom to balance every five carbon atoms, and fungi require 10 carbons for each nitrogen. Therefore, the predator organisms that eat bacteria and fungi get too much nitrogen for the carbon they require. Since excess nitrogen is toxic, this nitrogen is released into the surrounding soil solution, where it can be absorbed by plant roots. It is commonly assumed that when bacteria or fungi decompose, nitrogen in their cells slowly becomes available to plants in a form that is readily assimilated into the roots. However, in a healthy soil, there is little scientific evidence that bacteria and fungi simply die and decompose. If another bacteria or fungus uses the dead cells for a food source, there is no release of nitrogen. It is only when a predator consumes excessive amounts of nitrogen in the dead cells that it is released into the soil solution. It is this system of nitrogen cycling that has worked brilliantly for the past million years.

Compare this system to another familiar situation; when inorganic ammonium nitrate fertilizer is applied to agricultural soil, ammonium and nitrate ions are rapidly released into the soil solution. Nitrate ions are negatively charged and can be quite mobile. The result is that a large percentage of these nitrogen-containing ions may move rapidly out of the plant root zone and into the groundwater. This produces not only reduced plant growth but also environmental pollution. The least leachable form of nitrogen is that which is incorporated into the bodies of bacteria and fungi, resulting in good plant growth and little loss of nitrogen to groundwater or runoff.

Nitrogen is not the only nutrient effectively stored and recycled by soil microbes. Carbon is the major constituent of all cells. When soils are depleted of organic matter and healthy microbial populations, the ability of a soil to hold carbon is destroyed and it enters the atmosphere as carbon dioxide, now recognized as one of the greenhouse gases that are responsible for breaking down the ozone layer. All soil organisms have the ability to sequester carbon, but bacteria are the least efficient in this process. When bacteria consume simple sugars, proteins or complex carbohydrates, they incorporate most of the nutrients, including nitrogen, into their cell structure. However, when they consume more carbon than necessary, the excess is released into the atmosphere as carbon dioxide. Fungi require more carbon than bacteria and therefore release a much smaller quantity of carbon dioxide. When a soil is dominated by bacterial biomass, as it is in most modern agricultural systems, the ability to hold carbon in the soil is significantly reduced.

Fungal cells are responsible in a large part for storing and stabilizing much of the calcium in the soil. Ingham has shown that a soil low in fungi will permit calcium to leach away. Such a soil will require frequent applications of lime to replenish the calcium supply. A healthy fungal population can retain 95 percent of the calcium added to the soil, slowly releasing the calcium for plant use and maintaining a beneficial cation exchange capacity.

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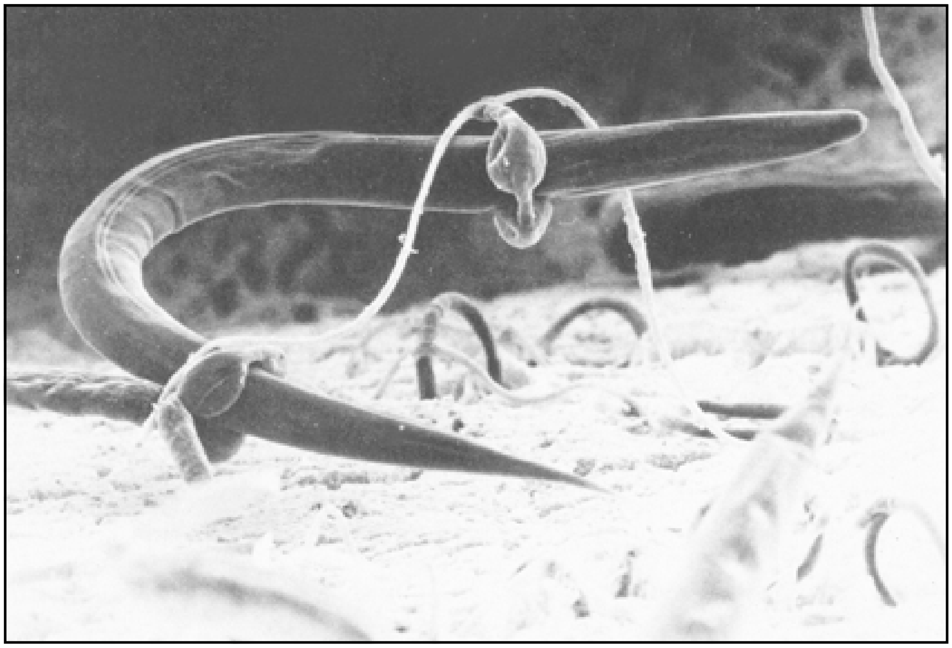

Parasitic nematodes may fall prey to certain types of fungi, which can be used as biological control agents to fight soil-borne pathogens. These predatory fungi grow through the soil, setting out traps when they detect signs of their prey.

Mycorrhizal fungi are especially effective in providing nutrients to plant roots. These are certain types of fungi that actually colonize the outer cells of plant roots, but also extend long fungal threads, or hyphae, far out into the rhizosphere, forming a critical link between the plant roots and the soil. Virtually all plant species will form beneficial mycorrhizal relationships, given the right conditions. Mycorrhizae produce enzymes that decompose organic matter, solubilize phosphorus and other nutrients from inorganic rock, and convert nitrogen into plant-available forms. They also greatly expand the soil area from which the plant can absorb water. In return for this activity, mycorrhizae obtain valuable carbon and other nutrients from the plant roots. This is a win-win mutualism between both partners, with the plant providing food for the fungus and the fungus providing both nutrients and water to the plant.

The importance of mycorrhizae in plant productivity and health has often been overlooked. Pines are not native to Puerto Rico and therefore the appropriate mycorrhizal fungi were absent in the soil. For years, people unsuccessfully tried to establish pines on the island. The pine seeds would germinate well and grow to heights of 8 to 10 cm but then would rapidly decline. In 1955, soil was taken from North Carolina pine forests, and the Puerto Rico plantings were inoculated. Within one year, all inoculated seedlings were thriving, while the uninoculated control plants were dead. Microscopic analysis showed that the healthy seedlings were well colonized by a vigorous mycorrhizal population. While the benefits of mycorrhizae is not always as dramatic, it has been well documented that mycorrhizal plants are often more competitive and better able to tolerate environmental stress.

SOIL STRUCTURE

Around plant roots, bacteria form a slimy layer. They produce waste products that glue soil particles and organic matter together in small, loose clumps called microaggregates. Threading between these aggregates and binding them together are fine, ribbon-like strands of fungal hyphae which further define and stabilize the soil into macroaggregates. It is this aggregated soil structure, which looks it a bit like spongy chocolate cake, that effectively resists compaction and erosion and promotes optimal plant and microbial growth. The structural matrix of these aggregates provides adequate pore space for easy air and water movement. Beneficial microbes, like plant roots and most other living organisms, require air and water for survival.

Water and air are held in the pores until needed, stimulating a healthy mix of beneficial organisms and facilitating root growth. Larger animals, such as earthworms, move without resistance between the aggregates, further improving soil structure and plant health.

When a fragile soil is worked with heavy equipment, aggregates are crushed, killing microbes and forcing out water and air. Plants grow with difficulty in such soil, not only because of physical resistance from the compacted soil particles, but also because the beneficial soil food web has been severely damaged. If soil is unable to hold sufficient oxygen, harmful anaerobic soil bacteria will proliferate, producing toxins that kill plant roots and other microorganisms.

In general, the largest soil organisms are the first damaged by soil compaction. These include earthworms and small insects, which are at the top of the soil food web and are essential to keeping microbial populations in balance. When these organisms are lost, an otherwise undisturbed soil will have the tendency to shift from being fungal dominated to being more bacterially dominated. This will alter nutrient availability and soil structure, effectively limiting the types of plants that can grow. Some species of anaerobic bacteria thrive in a soil deprived of oxygen and can produce chemical metabolites, such as alcohols, aldehydes, phenols and ethylene, that are toxic to plant roots and to other microorganisms. As compaction continues to eliminate pore space, plant roots have difficulty obtaining sufficient water, air and nutrients, placing them under considerable stress. This stress, added to the shift in beneficial organisms, will create a situation where plant pathogens may increase rapidly and cause serious problems.

DISEASE SUPPRESSION

Dr. Ingham and others in her field have found that plant roots, well colonized by a mixture of different bacterial and fungal species, are far more resistant to pathogenic attack. Mycorrhizal fungi form an impenetrable physical barrier on the surface of plant roots, varying in thickness, density and fungal species, according to the plant species, plant health and soil conditions.

This layer of beneficial fungi plays a powerful role in disease suppression, both through simple physical interference as well as through the production of inhibitory products.

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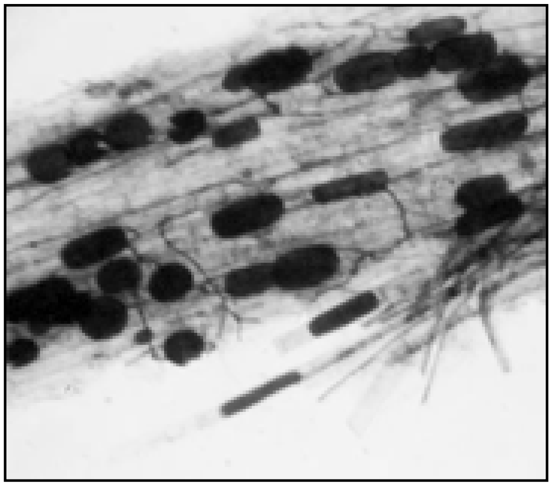
Some species of fungi that parasitize other fungi, such as Trichoderma, have been observed physically attacking and destroying pathogenic fungi. Dr. William Albrecht reported that Fusarium, a fungal species often maligned in its role in many plant diseases, can actually be one of the most common beneficial saprophytes in a healthy soil. He stated that the dividing line between beneficial symbiosis and parasitism can be very narrow. When Fusarium encounters a root that is poorly nourished or is under stress, it can become rapidly pathogenic.



Sections of plant roots that are colonized internally by beneficial symbiotic fungi. The dark structures are the portion of the VAM fungi that forms inside individual cells of the root tissue.

DECOMPOSITION OF TOXIC MATERIALS

Application of chemical salt-based fertilizers tends to change the microbial population in a soil. Many fragile species of microbes are severely damaged by the powerful osmotic effects of the concentrated fertilizers. As with soil compaction, a shift in microbial populations can occur following fertilizer application, resulting in reduced overall plant growth and an increase in plant pathogens. There are species of microbes that are able to withstand the effects of chemical fertilizers. They actually make use of the fertilizer materials for nutrition and in doing so, can change harmful compounds into ones much less damaging to soil life. The presence of ample organic matter in a soil can help to reduce the harmful effects of chemical fertilizers, possibly due its buffering action.

When pesticides and herbicides are applied to soil, they produce an immediate detectable effect, but they can have other subtle residual effects for many years. Removing such contaminants from the soil is quite difficult. A healthy soil food web can help here also, by actually breaking chemicals down into less toxic materials and also by facilitating the absorption of many pesticides in organic material, rendering them less damaging to microbes and plant roots and facilitating their eventual degradation. It is fortunate for the farmer that many types of chemicals can be degraded by certain species of microbes in the soil, if they are present.

Certain bacterial species, such as *Bacillus laterosporus*, or the fungal species Phanerochete have been noted as degraders of 2,4-D and DDT. There is currently much research being done on bioremediation, using microbes to break down various environmental toxins. In many cases, bioremediation may be preferred over more conventional treatments because it is less expensive and can be more successful in removing a wide variety of contaminants.

PRODUCTION OF PLANT GROWTH REGULATOR COMPOUNDS

In return for the release of nutritional substances from plant roots, microbes themselves produce chemicals that stimulate plant growth or protect the plant from attack. These substances include auxins, enzymes, vitamins, amino acids, indoles and antibiotics. These complex molecules are able to pass from the soil into plant cells and be transported to other parts of the plant, with minimal change to chemical structure, where they can stimulate plant growth and enhance plant reproduction. They may also play a role in enhancing the nutritional composition of the plant.

It is clear, both from studying Dr. Ingham's work and comparing it to older research, that soil ecology has been largely neglected in the era of chemical fertilizers and pesticides and that the microbial population in soil is the key factor in healthy crop production. Any practice that reduces or shifts normal microbial populations, such as the use of agricultural chemicals and excessive or inappropriate tillage, will effectively reduce crop potential. Conscientiously adopting practices that favor this unseen universe should improve plant health, yield and the nutritional benefits we may obtain from those plants.

Dr. Ingham's Soil Foodweb Inc. website, at <www.soilfoodweb.com>, hosts a variety of resources, including tips for taking samples and choosing proper tests, information on turf and landscaping, compost, product resources, as well as other related articles. Soil Foodweb Inc. is located at 1128 NE 2nd St., Ste. 120, Corvallis, Oregon 97330, phone (541) 725-5066, fax (541) 752-5142, e-mail <info@soilfoodweb.com>.