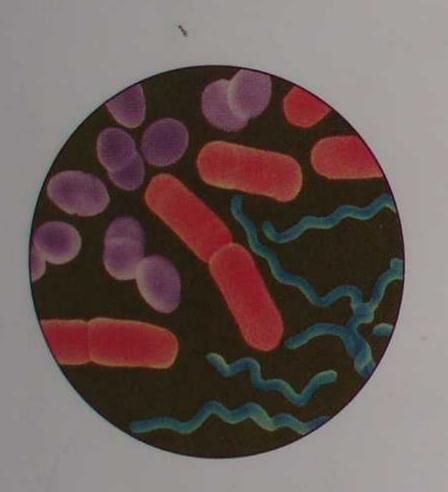
### Teaming with Microbes

A Gardener's Guide to the Soil Food Web

Jeff Lowenfels & Wayne Lewis

Foreword by Elaine Ingham



### Foreword

For today's the day the nematodes have their picnic! If you go down in the dirt today, you'd better not go alone! Sung to the tune of "The Teddy Bears' Picnic"

And so, we make up words to songs. a microscope for long hours looking at ... nothing but inert particles. up words to popular songs is always good! Soil shouldn't be so boring, but urban landscapes mean dead dirt. It means being bent over "HEN YOU ARE BORED looking at "soil" from urban lawns, making Boring.

pening. Instead, after just a few secondsmicroscope looking at micrometer after micrometer of boring—nothing hapthings! No need to invent new lyrics to old songs. No hours staring through a Real soil is active, alive, moving! Critters everywhere, doing interesting -movement, life, action!

and the nutritional content of your food, because of the loss, eventually, of the or the constant applications of toxic pesticide sprayed, mean the National line against criminals. But in soil, the levels of inorganic fertilizer being used, disturbances. In the human world, we send in the National Guard, to hold the would come back faster if your neighborhood was turned into a chemical war don't come back as fast as the bad guys. Think about your neighborhood: who were killed. A few bad guys were killed as well, but good guys are gone, and they first application, thousands of organisms that were beneficial to your plants bad situation we have today would not have developed, but typically with that beneficials in the soil. If toxic material was applied only once in your work strongly indicates that toxic chemicals destroy water quality, soil eficial biology that has been lost. Guard of the soil has been killed, too. We have to purposefully restore the benfauna that compete with the bad guys and keep them under control. the "mafia" of the soil, an urban war zone, by killing off the normal flora and things that make soil healthy. Use of toxics to any extent creates a habitat for their soils for years, without recognizing that those chemicals harm Urban dwellers and other growers have been pouring toxic chemicals on Opportunistic marauders and looters, that's who comes back in after the very life, the health, Recent

Where will the new recruits come from? You have to add them—bacteria, fungi, protozoa, nematodes, earthworms, microarthropods—back to your soil. Roots of plants feed these beneficials, but to make sure that the beneficials get reestablished, care packages may need to be delivered. Soil Foodweb, Inc., helps people rapidly reestablish the biology that creates the foothold for health to come back into these systems; and this book describes these hardworking members of the front line of defense for your plants. Where do they live? Who are their families? How do you send in lunch packs, not toxics, to help the recruits along?

Win back your soil's health. Put nothing on your soil if you don't know what it will do to the life under your feet. If there is "no information" about how something impacts the life in your soil, or if the material has never been tested to determine what it does to the organisms in your soil, don't use the material. If you have already purchased the product, test it yourself.

Toxics are sometimes necessary to roust out a particularly bad infestation or disease, but toxics should be used as a last resort, not as your first response to a wilting plant. If you use toxics, then remember to replace the good guys, and send in some food, immediately.

Reestablishing the proper biology is critical. You may lose a few battles along the way. But persevere, and you can win. Think strategically: how can you help deliver troops, foods, medicines, and bandages to the front lines of the battle between beneficials and the diseases and pests in the most effective way? The directions, at least to the best of our knowledge, are in this book.

Most people have a great deal to learn when it comes to soil. You need the information that Jeff and Wayne have put together. They also make their "lessons" about soil health enjoyable! They present what could be deadly dull and boring in a way that is exciting and understandable. Instead of your having to work for years and years, staring through microscopes, as my colleagues and I have done in our efforts to understand soil biology, this book gives you an gether in this book, in a way that allows the complex story of life in the soil to be easily understood.

I hope you will join with us and help to learn how to return health to soil, and therefore, to the food you eat. The instructions are here.

Dr. Elaine Ingham, Ph.D.
President, Worldwide, Soil Foodweb, Inc.
www.soilfoodweb.com

### Preface

of the growing season, we carpet bombed our lawns with a megadose of water-soluble, high-nitrogen fertilizer and watered like crazy; then we strafed their weeds with a popular broadleaf herbicide. Next, we attacked our vegetable gardens and flower beds with a bag or two of commercial fertilizer and leveled them with a rototiller until the soil, the color and texture of finely ground coffee, lay as smooth and level as the Bonneville Salt Flats. These things we did religiously, as did most of our neighbors. Once was never enough either. We continued to use chemical fertilizers throughout the season as if we were competing in the large-vegetable contest at the Alaska State Fair—and at the end of the season we rototilled again, for some inexplicable reason.

When necessary (and it often was), we would suit up into protective clothing—complete with rubber gloves and a face mask—and paint our birches to protect them from invading aphids by using some god-awful smelling stuff that listed ingredients no normal person could pronounce, assuming he or she took the time to read the incredibly small print on the chemical's label. Then we sprayed our spruce trees with something that smelled even worse—something so strong, one application lasted not one but two years. It was a good thing we did protect ourselves, as both spray products are now off the market, withdrawn as health hazards.

Don't misunderstand us. At the same time we were also practicing what we considered to be an "appropriate" measure of environmental responsibility and political correctness. We left the grass clippings on the lawn to decompose and tilled fallen leaves into the garden beds, and occasionally we let loose batches of lacewings, ladybird beetles, and praying mantids—our version of integrated pest management. We composted. We recycled our newspapers and aluminum cans. We fed the birds and allowed all manner of wildlife to wander in our yards. In our minds we were pretty organic and environmentally conscious (if not downright responsible). In short, we were like most home gardeners, maintaining just the right balance between better living with chemistry and at least *some* of Rachel Carson's teachings.

Besides, we were mostly using only water-soluble, high-nitrogen fertilizer. How bad could that be for the environment? It sure made the plants grow. And we really employed only one weed killer, albeit a nonselective, broadleaf one. Okay, we occasionally resorted to an insecticide too, but when we considered what was on the shelves of our favorite nurseries, these didn't amount to much in our minds. Surely we couldn't be causing harm when we were only trying to save a spruce, help a birch, or prevent noxious dandelions and chickweed from taking over the world?

Central to the way we cared for our gardens and yards was a notion shared by tens of millions of other gardeners and, until you finish this book, perhaps you as well: nitrogen from an organic source is the same as nitrogen from an inorganic one. Plants really didn't care if their nitrogen and other nutrients came from a blue powder you mixed with water or aged manure. It is all nitrogen to them.

Then one autumn, after the gardens were put to bed and we were settling in for the winter, looking for something to hold our horticultural interest for the cold months, a gardening friend e-mailed two stunning electron microscope pictures. The first showed in exquisite detail a nematode trapped by a single looped fungal strand, or hypha. Wow! This was quite a picture—a fungus taking out a nematode! We had never heard of, much less seen such a thing, and it started us wondering: how did the fungus kill its prey? What attracted the blind nematode to the rings of the fungus in the first place? How do the rings work?

The second image showed what appeared to be a similar nematode, only this one was unimpeded by fungal hyphae and had entered the tomato root. This photo raised its own questions. Why wasn't this nematode attacked, and where were the fungal hyphae that killed off the first nematode?

A foraging, root-eating nematode, trapped by a fungal hypha. Courtesy H. H. Triantaphyllou. Reprinted, with permission, from http://www.apsnet.org/, American Phytopathological Society, St. Paul, Minnesota.



While researching the answers to these questions, we stumbled upon the work of Dr. Elaine Ingham, a soil microbiologist famous for her work with the life that resides in soil and, in particular, who eats whom in the soil world. Since some organisms eat from more than one food chain or are eaten by more than one type of predator, the chains are linked into webs—soil food webs. Ingham, an excellent teacher, became our guide to the whole world of complex communities in the soil. Through her we learned that the fungus in the first photograph was protecting the plant's roots; if that wasn't enough to make us stop and think, we learned the plant attracted the fungus to its roots in the first instance! And we also learned what killed the fungus that would have prevented the nematode from attacking the tomato root.

Naturally, we began to wonder what other heretofore-unseen things were going on down there in the soil. Might the world revealed to us by tools like the electron microscopes affect how we care for the plants in our gardens, yards, and lawns? We have all been dazzled by Hubble images of deep space, incomprehensibly far away, yet few of us have ever had the opportunity to marvel at the photographs produced by a scanning electron microscope (SEM), which provide a window to an equally unknown universe literally right under our feet.

We looked for answers, and soon realized that while we were out spreading fertilizer and rototilling our garden beds by rote, an ever-growing group of scientists around the world had been making discovery after discovery that put these practices into question. Many scientific disciplines—microbiology, bacteriology, mycology (the study of fungi), myrmecology (the study of ants), chemistry, agriculture—came together in recent decades to focus jointly on understanding the world of soil. Slowly, their findings about what goes on in the soil are being applied to commercial agriculture, silviculture, and viniculture. It is time we applied this science to things we grow in our home yards and gardens.



With no fungal hyphae barring the way, a nematode penetrates a tomato root to feed. Photograph by William Weryin and Richard Sayre, USDA-ARS.

Most gardeners are stuck in traditional horticultural land, a place where a blend of old wives' tales, anecdotal science, and slick commercial pitches designed to sell products dictates our seasonal activities. If there is any understanding of the underlying science of gardening, it is almost always limited to the soil's NPK chemistry and its physical structure. As you read these pages, you will learn how to use the biology in your soils—naturally or manipulated—to your and your plants' benefit. Since chemical fertilizers kill the soil microorganisms and chase away larger animals, the system we espouse is an organic one, free of chemicals. Chemicals, in fact, are what killed off the root-protecting fungal hyphae, giving our nematode friend access to the unprotected tomato root in the second photo.

By necessity, this book is divided into two sections. The first is an explanation of soil and the soil food web. There is no getting around it. You have to know the science before you can apply it. At least in this instance, the science is fascinating, even astonishing, and we try not to make a textbook out of it. The second section is the explanation of how to work the soil food web to your soils' advantage and to yours as a gardener.

What makes this book different from other texts on soil is our strong emphasis on the biology and microbiology of soils—relationships between soil and organisms in the soil and their impact on plants. We are not abandoning soil chemistry, pH, cation exchange, porosity, texture, and other ways to describe soil. Classic soil science is covered, but from the premise that it is the stage where the biology acts out its many dramas. After the players are introduced and their individual stories told, what evolves is a set of predictable outcomes from their interrelationships, or lack thereof. In the second half of the book, these outcomes are formed into a few simple rules, rules that we've applied in our yards and gardens, as have many of our neighbors in Alaska, where we initiated these new practices. So have others, throughout the Pacific Northwest in particular, but in other parts of the world as well. We think that learning about and then applying soil science (particularly the science of how various forms of life in the soil interrelate—the soil food web) has made us better gardeners. Once you are aware of and appreciate the beautiful synergisms between soil organisms, you will not only become a better gardener but a better steward of the earth. Home gardeners really have no business applying poisons, and yet apply them they do, to the food they grow and eat (and worse, feed to their families) and the lawns on which they play.

You might be tempted to skip right to the second part of this book, but we strongly discourage doing so. It is essential to know the science to really understand the rules. Sure, it requires a bit of effort (or the chapter on soil science

does, anyway), but for too long, for too many gardeners, everything we needed to know came in a bottle or jar and all we had to do was mix with water and apply with a hose-end sprayer: instant cooking meets home gardening. Some hobby. Well, we want you to be thinking gardeners, not mindless consumers who react because a magazine or television ad says to do something. If you really want to be a good gardener, you need to understand what is going on in your soil.

So, here goes. We now know all nitrogen is not the same and that if you let the plants and the biology in the soil do their jobs, gardening becomes much easier and gardens much better. May your yard and your gardens grow to their natural glory. We know ours now do.

# he Basic Science



Dennis Kunkel Microscopy, Inc. Electron microscope photograph of organic compost humus (brown), decaying plant material (green), and some mineral particles (purple and yellow), 25x. Image copyright

### Chapter 1

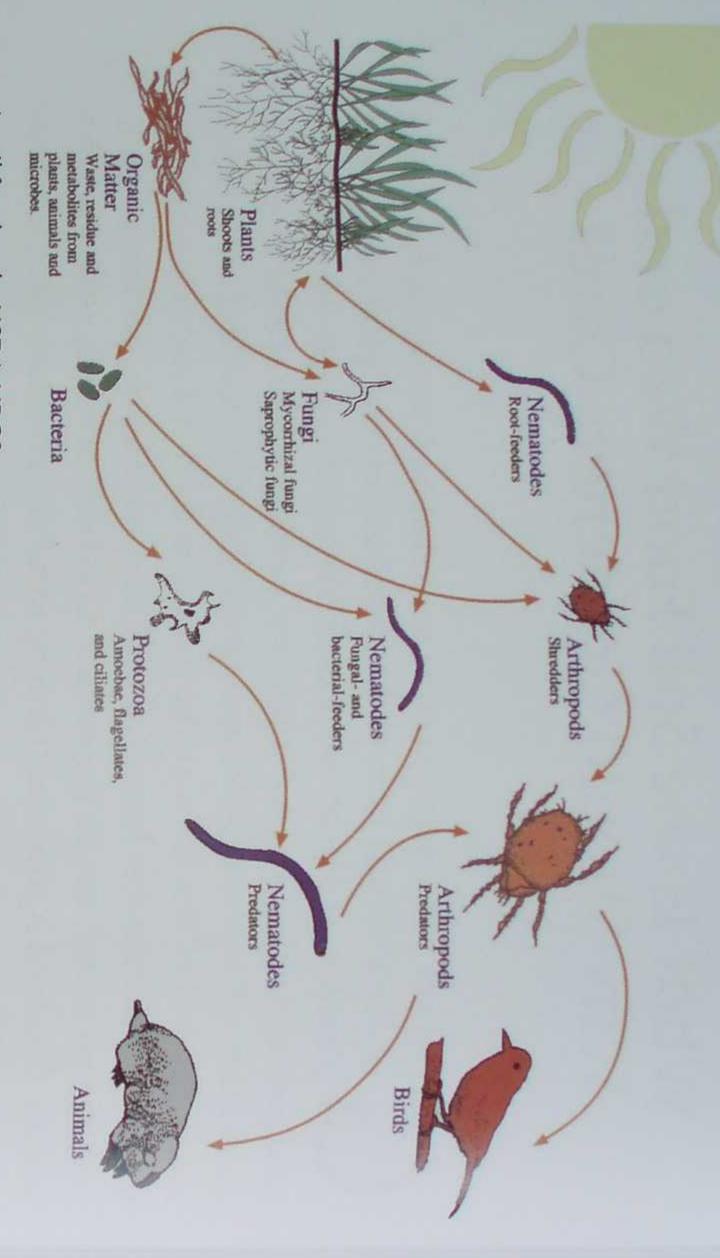
# What Is the Soil Food Web and Why Should Gardeners Care?

tion that this is so engender a reaction of satisfaction. animals. Good soil is absolutely teeming with life, yet seldom does the realizacredible two miles beneath the surface. Good soil, however, is not just and more. Most of this life is on the surface, in the first 4 inches (10 centimeacross other soil life: centipedes, springtails, ants, slugs, ladybird beetle larvae, good soil, and unless you habitually use pesticides, you should have ters); some soil microbes have even been discovered living comfortably an in-IVEN ITS VITAL IMPORTANCE to our hobby, it is amazing that most of plant life, and poor soil doesn't. You've undoubtedly seen worms in us don't venture beyond the understanding that good soil supports a few come

you use sophisticated and expensive optics. Only then do the tiny, microscopic good soil), there is a whole world of soil organisms that you cannot see unless ample, there are up to 50 earthworms in a square foot [0.09 square meters] of measured by microbial geneticists, contains a billion invisible bacteria, several that are nothing less than staggering. A mere teaspoon of good garden soil, as yards of equally invisible fungal hyphae, several thousand protozoa, and a few In addition to all the living organisms you can see in garden soils (for ex--bacteria, fungi, protozoa, nematodes-appear, and in numbers

ergy to survive. While a few bacteria, known as chemosynthesizers, something containing carbon in order to get the energy they need to sustain energy from sulfur, nitrogen, or even iron compounds, the rest have life. Carbon may come from organic material supplied by plants, waste ucts produced by other organisms, or the bodies of other organisms. The first an eat-and-be-eaten world, in and on soil. order of business of all soil life is obtaining carbon to fuel metabolism-The common denominator of all soil life is that every organism needs enprodderive to eat -it is

swallowed a fly? She then swallows a spider ("that wriggled and jiggled and tickled inside her") to catch the fly, and then a bird to catch the spider, and so on, until she eats a horse and dies ("Of course!"). If you made a diagram of Do you remember the children's song about an old lady who accidentally



A soil food web, USDA-NRCS.

probable horse, you would have what is known as a food chain. who was expected to eat whom, starting with the fly and ending wi th the im-

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set of organisms and thus a different soil food web. web of food chains, or a soil food web. Each soil environment has a different comes a series of food chains linked and cross-linked to each other, of who eats whom in and on the soil, the straight-line food chain instead be-Most organisms eat more than one kind of prey, so if you make a diagram creating a

story each tells, however, is a simple one and always starts with the plant. sets of interactions, relationships, and chemical and physical processes. The can imagine, this and other diagrams represent complex and highly This is the simple, graphical definition of a soil food web, thou organized gh as you

## Plants are in control

tems and feeding the leaves. Few realize that a great deal of the energy that redates. A good analogy is perspiration, a human's exudate. chemicals they secrete through their roots. These secretions are know Most gardeners think of plants as only taking up nutrients through from photosynthesis in the leaves is actually used by plants to n as exuroot sysproduce

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The rhizosphere is an area of interaction between the surface of a plant root and the area surrounding it.

Bacteria and other microorganisms as well as soil debris fill the area. 10,000×. Photograph by Sandra Silvers, USDA-ARS.

cellular material sloughed off as the plant's root tips grow. All this secretion of cial bacteria and fungi living in the soil that subsist on these exudates and the teins. Amazingly, their presence wakes up, attracts, and grows specific be ing mix of soil organisms, including bacteria, fungi, nematodes, protozoa ple of millimeters (1 millimeter = 1/25 inch). The rhizosphere, which can mediately around the roots, extending out about a tenth of an inch, or a even larger organisms. All this "life" competes for the exudates in the rl like a jelly or jam under the electron microscope, contains a constantly sphere, or its water or mineral content. Root exudates are in the form of carbohydrates (including sugars) and and sloughing-off of cells takes place in the rhizosphere, a zone imchangnefiprohizo-, and coulook

tracted to and consume plant root exudates. In turn, they attract and are eaten amoebae, paramecia, flagellates, and ciliates you should have studied in functions. Anything they don't need is excreted as wastes, which plant roo ogy?), who eat bacteria and fungi (primarily for carbon) to fuel their meta readily able to absorb as nutrients. How convenient that this production of plant nutrients takes place right in the rhizosphere, the bigger microbes, specifically nematodes and protozoa (remember the At the bottom of the soil food web are bacteria and fungi, which are atsite of root-nutrient bolic biolts are

surely not appreciated by and the different kinds of fungi and bacteria attracted to the rhizosphere b At the center of any viable soil food web are plants. Plants control the for their own benefit, an amazing fact that is too little understood Studies indicate that individual plants can control the numbers gardeners who are constantly interfering food ythe and Na-

trient needs of the plant and the exudates it produces. tions of rhizosphere bacteria and fungi wax and wane, depending on the nuexudates they produce. During different times of the growing season, popula-

and other nutrients as waste. todes and protozoa in the soil come along and eat the bacteria and fungi in the the nutrients locked up in the bacteria and fungi "fertilizer bags." The nemarhizosphere. They digest what they need to survive and excrete excess carbon analogy, soil protozoa and nematodes act as "fertilizer spreaders" by releasing organic matter (such as those sloughed-off root-tip cells). Carrying on the bodies nitrogen and other nutrients they gain from root exudates Soil bacteria and fungi are like small bags of fertilizer, retaining in their and other

vides the nutrients needed for plant life, and plants initiate and fuel the cycle by producing exudates. tem, the very same one that has fueled plants since they evolved. Soil life propends on the interplay between these microbes. It is a completely natural sysand bacteria (and, ultimately, nematodes and protozoa); their survival de-Left to their own devices, then, plants produce exudates that attract fungi

# Soil life creates soil structure

bodies, jointed appendages, and a hard outer covering called an exoskeleton). by plant exudates are in turn eaten by arthropods (animals with segmented The protozoa and nematodes that feasted on the fungi and bacteria attracted

Bacteria on a soil particle.
Image copyright Ann West.



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tection, and while they do, they have an impact on the soil. this eating, members of a soil food web move about in search of prey or proeach other and themselves are the food of snakes, birds, moles, and other ani-Insects, spiders, even shrimp and lobsters are arthropods. Soil arthropods ea Simply put, the soil is one big fast-food restaurant. In the course of all

cles, sticking to them and binding them together, thread-like, into aggregates. bacteria to stick to your teeth). Fungal hyphae, too, travel through soil partithink of the plaque produced overnight in your mouth, which enables mouth attach themselves, they produce a slime, the secondary result of which is that individual soil particles are bound together (if the concept is hard to grasp, Bacteria are so small they need to stick to things, or they will wash away; to

provide for the passage of air and water through the soil. structure: the activities of its members bind soil particles together even as they tion to providing nutrients to roots in the rhizosphere, also helps create soil fungi can help in this regard (see chapter 4). The soil food web, then, in addiways that allow air and water to enter and leave the soil. Even microscopic mals, move through the soil in search of food and protection, creating path-Worms, together with insect larvae and moles and other burrowing ani-

# Soil life produces soil nutrients

bers of the community. The nutrients in these bodies are passed on to other be it decaying the organism directly or working on the dung of the successful be decayed after they die. One way or the other, fungi and bacteria get involved, members of the community. A larger predator may eat them alive, or they may When any member of a soil food web dies, it becomes fodder for other memeater. It makes no difference. Nutrients are preserved and eventually are tained in the bodies of even the smallest fungi and bacteria. When these are turn, are consumed or die. the rhizosphere, they release nutrients in plant-available form when they, re-

stead, they are retained in the bodies of soil life. Here is the gardener's truth: when you apply a chemical fertilizer, a tiny bit hits the rhizosphere, where it is Not so with the nutrients locked up inside soil organisms, a state known as imsorbed, but most of it continues to drain through soil until it hits the water tal mobilization; these nutrients are eventually released as wastes, or mineralized. And when the plants themselves die and are allowed to decay, the nutrients they retained are again immobilized in the fungi and bacteria that consume them. Without this system, most important nutrients would drain from soil. ble. ab-In-

nutrient supply in the soil is influenced by soil life in other ways.

What Is the Soil Food Web?

25

example, worms pull organic matter into the soil, where it is shredded by beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles and the larvae of other insects, opening it up for fungal and bacterial beetles. This worm activity provides yet more nutrients for the soil community.

### Healthy soil food webs control disease

A healthy food web is one that is not being destroyed by pathogenic and disease-causing organisms. Not all soil organisms are beneficial, after all. As gardeners you know that pathogenic soil bacteria and fungi cause many plant diseases. Healthy soil food webs not only have tremendous numbers of individual organisms but a great diversity of organisms. Remember that teaspoon vidual organisms but a great diversity of organisms. Remember that teaspoon of good garden soil? Perhaps 20,000 to 30,000 different species make up its billion bacteria—a healthy population in numbers and diversity.

A large and diverse community controls troublemakers. A good analogy is a thief in a crowded market: if there are enough people around, they will catch or even stop the thief (and it is in their self-interest to do so). If the market is deserted, however, the thief will be successful, just as he will be if he is stronger, faster, or in some other way better adapted than those that would be in pursuit.

In the soil food web world, the good guys don't usually catch thieves (though it happens: witness the hapless nematode that started this all for us); rather, they compete with them for exudates and other nutrients, air, water, and even space. If the soil food web is a healthy one, this competition keeps the pathogens in check; they may even be outcompeted to their death.

Just as important, every member of the soil food web has its place in the soil community. Each, be it on the surface or subsurface, plays a specific role. Elimination of even just one group can drastically alter a soil community. Birds participate by spreading protozoa carried on their feet or dropping a worm taken from one area into another. Too many cats, and things will change. Dung from mammals provides nutrients for beetles in the soil. Kill the mammals, or eliminate their habitat or food source (which amounts to the same thing), and you won't have as many beetles. It works in the reverse as well. A healthy soil food web won't allow one set of members to get so strong as to destroy the web. If there are too many nematodes and protozoa, the bacteria and fungi on which they prey are in trouble and, ultimately, so are the plants in the area.

And there are other benefits. The nets or webs fungi form around roots act as physical barriers to invasion and protect plants from pathogenic fungi and bacteria. Bacteria coat surfaces so thoroughly, there is no room for others to attach themselves. If something impacts these fungi or bacteria and their numbers drop or they disappear, the plant can easily be attacked.

Special soil fungi, called mycorrhizal fungi, establish themselves in a symbiotic relationship with roots, providing them not only with physical protection but with nutrient delivery as well. In return for exudates, these fungi provide water, phosphorus, and other necessary plant nutrients. Soil food web populations must be in balance, or these fungi are eaten and the plant suffers.

Bacteria produce exudates of their own, and the slime they use to attach to surfaces traps pathogens. Sometimes, bacteria work in conjunction with fungi to form protective layers, not only around roots in the rhizosphere but on an equivalent area around leaf surfaces, the phyllosphere. Leaves produce exudates that attract microorganisms in exactly the same way roots do; these act as a barrier to invasion, preventing disease-causing organisms from entering the plant's system.

Some fungi and bacteria produce inhibitory compounds, things like vitamins and antibiotics, which help maintain or improve plant health; penicillin and streptomycin, for example, are produced by a soil-borne fungus and a soil-borne bacterium, respectively.

### All nitrogen is not the same

Ultimately, from the plant's perspective anyhow, the role of the soil food web is to cycle down nutrients until they become temporarily immobilized in the bodies of bacteria and fungi and then mineralized. The most important of these nutrients is nitrogen—the basic building block of amino acids and, therefore, life. The biomass of fungi and bacteria (that is, the total amount of each in the soil) determines, for the most part, the amount of nitrogen that is readily available for plant use.

It wasn't until the 1980s that soil scientists could accurately measure the amount of bacteria and fungi in soils. Dr. Elaine Ingham at Oregon State University along with others started publishing research that showed the ratio of these two organisms in various types of soil. In general, the least disturbed soils (those that supported old growth timber) had far more fungi than bacteria, while disturbed soils (rototilled soil, for example) had far more bacteria than fungi. These and later studies show that agricultural soils have a fungal to bacterial biomass (F:B ratio) of 1:1 or less, while forest soils have ten times or more fungi than bacteria.

Ingham and some of her graduate students at OSU also noticed a correlation between plants and their preference for soils that were fungally dominated versus those that were bacterially dominated or neutral. Since the path from bacterial to fungal domination in soils follows the general course of plant suc-

What Is the Soil Food Web?

27

cession, it became easy to predict what type of soil particular plants preferred by noting where they came from. In general, perennials, trees, and shrubs preby noting where they came from annuals, grasses, and vegetables prefer soils fer fungally dominated soils, while annuals, grasses, and vegetables prefer soils dominated by bacteria.

One implication of these findings, for the gardener, has to do with the nitrogen in bacteria and fungi. Remember, this is what the soil food web means to a plant: when these organisms are eaten, some of the nitrogen is retained by to a plant: when these organisms are eaten, some of plant-available amthe eater, but much of it is released as waste in the form of plant-available ammonium (NH<sub>4</sub>). Depending on the soil environment, this can either remain as ammonium or be converted into nitrate (NO<sub>3</sub>) by special bacteria. When does ammonium or be converted into nitrate (NO<sub>3</sub>) by special bacteria. When does ammonium or be converted into nitrate (NO<sub>3</sub>) have an alkaline pH (thanks to bacteria. This is because such soils generally have an alkaline pH (thanks to bacterial bioslime), which encourages the nitrogen-fixing bacteria to thrive. The acids produced by fungi, as they begin to dominate, lower the pH and greatly reduce the amount of these bacteria. In fungally dominated soils, much of the nitrogen remains in ammonium form.

Ah, here is the rub: chemical fertilizers provide plants with nitrogen, but most do so in the form of nitrates (NO<sub>3</sub>). An understanding of the soil food web makes it clear, however, that plants that prefer fungally dominated soils ultimately won't flourish on a diet of nitrates. Knowing this can make a great deal of difference in the way you manage your gardens and yard. If you can cause either fungi or bacteria to dominate, or provide an equal mix (and you can just how is explained in Part 2), then plants can get the kind of nitrogen they prefer, without chemicals, and thrive.

### Negative impacts on the soil food web

Chemical fertilizers negatively impact the soil food web by killing off entire portions of it. What gardener hasn't seen what table salt does to a slug? Fertilizers are salts; they suck the water out of the bacteria, fungi, protozoa, and nematodes in the soil. Since these microbes are at the very foundation of the soil food web nutrient system, you have to keep adding fertilizer once you start using it regularly. The microbiology is missing and not there to do its job, feeding the plants.

It makes sense that once the bacteria, fungi, nematodes, and protozoa are gone, other members of the food web disappear as well. Earthworms, for example, lacking food and irritated by the synthetic nitrates in soluble nitrogen fertilizers, move out. Since they are major shredders of organic material, their absence is a great loss. Without the activity and diversity of a healthy food web,

you not only impact the nutrient system but all the other things a healthy soil food web brings. Soil structure deteriorates, watering can become problematic, pathogens and pests establish themselves and, worst of all, gardening becomes a lot more work than it needs to be.

If the salt-based chemical fertilizers don't kill portions of the soil food web, rototilling will. This gardening rite of spring breaks up fungal hyphae, decimates worms, and rips and crushes arthropods. It destroys soil structure and eventually saps soil of necessary air. Again, this means more work for you in the end. Air pollution, pesticides, fungicides, and herbicides, too, kill off important members of the food web community or "chase" them away. Any chain is only as strong as its weakest link: if there is a gap in the soil food web, the system will break down and stop functioning properly.

### Healthy soil food webs benefit you and your plants

Why should a gardener be knowledgeable about how soils and soil food webs work? Because then you can manage them so they work for you and your plants. By using techniques that employ soil food web science as you garden, you can at least reduce and at best eliminate the need for fertilizers, herbicides, fungicides, and pesticides (and a lot of accompanying work). You can improve degraded soils and return them to usefulness. Soils will retain nutrients in the bodies of soil food web organisms instead of letting them leach out to God knows where. Your plants will be getting nutrients in the form each particular plant wants and needs so they will be less stressed. You will have natural disease prevention, protection, and suppression. Your soils will hold more water.

The organisms in the soil food web will do most of the work of maintaining plant health. Billions of living organisms will be continuously at work throughout the year, doing the heavy chores, providing nutrients to plants, building defense systems against pests and diseases, loosening soil and increasing drainage, providing necessary pathways for oxygen and carbon dioxide. You won't have to do these things yourself.

Gardening with the soil food web is easy, but you must get the life back in your soils. First, however, you have to know something about the soil in which the soil food web operates; second, you need to know what each of the key members of the food web community does. Both these concerns are taken up in the rest of Part 1.

### Chapter 2 Classic Soil Science

THIS WOULD BE A GOOD TIME to go outside and get a few handfuls of soil from different places in your yard. Take a good, close look at the soil. Smell it. Grind some between your fingers. Compare the samples for differences and similarities. When you repeat these observations after you read this chapter, you will have a different perspective of what is in your hands.

The typical gardener knows very little about soil and why it matters. To us, however, soil is the house in which all the organisms of the soil food web live. It is the stage for the actors that interest us. You simply have to know something about the physical nature of soil if you are to understand the biology that inhabits it and how to use this biology to become a better gardener. After all, an acre of good garden soil teems with life, containing several pounds (about 1 kilogram) of small mammals; 133 pounds of protozoa; 900 pounds each of earthworms, arthropods, and algae; 2000 pounds of bacteria; and 2400 pounds of fungi.

Most of us, if we want things to grow better, simply replace soil that is poor in quality with good soil. Experienced gardeners know good soil when they see it: coffee-colored, rich in organic matter, able to hold water yet still drain when there is too much around. And it smells good. Poor soil is pale, compacted, drains either too well and won't retain any water or holds too much water, sometimes even becoming anaerobic. It can smell bad. If you are going to use the soil food web, however, you really need to know more. Where does soil come from? What are its components? How can we agree to describe it, and how can we measure its characteristics? This knowledge will help you adjust your soils, for what determines really good soil, in the end, is what you wish to grow in it: good soil must be able to maintain a soil food web compatible with the plants it supports. Trust us—in the end, you will be glad you know a little something more about soil, something beyond its color and smell.

### What is soil, really?

Technically, soil is all the loose, unconsolidated, mineral and organic matter in the upper layer of the earth's crust. The standard comparison uses an apple to

represent the earth. Carve off approximately 75% of the skin, which represents all the water, and another 15%, which represents deserts or mountains—land too hot, too cold, too wet, or too steep to be usable for growing plants. The 10% that remains represents all the earth's soil—soils with the necessary physical, chemical, and biological properties to support plant life. When we take into account the footprints of cities, roads, and other man-made infrastructure (these, incidentally, usually are sited on some of the very best soils), the surface area of usable soil is further reduced.

For the moment, the thing that concerns us is the tiny strip of apple skin that represents the soil in our gardens and yards. How did it get there? What is it? Why does it support plant growth?

### Weathering

Your yard's soil is in large part a product of weathering. Weathering is the sum impact of all the natural forces that decay rocks. These forces can be physical, chemical, or biological.

To begin, the mere action of wind, rain, snow, sun, and cold (along with glacial grinding, bumps along river beds, scrapes against other rocks, and rolls in ocean waves and stream currents) physically breaks rocks down into tiny mineral particles and starts the process of soil formation. Water freezes in rock cracks and crevices and expands, increasing its volume by 9% (and exerting a force of about 2000 pounds per square inch) as it turns to ice. Hot weather causes the surfaces of rock to expand, while the inner rock, just a millimeter away, remains cool and stable. As the outer layer pulls away, cracks form, and the surface peels off into smaller particles.

Chemical weathering dissolves rock by breaking the molecular bonds that hold it together through exposure to water, oxygen, and carbon dioxide. Some materials in rock go into solution, causing the rock to lose structural stability and making it more susceptible to physical weathering (think of a sugar cube dropped into a cup of tea and then stirred). Fungi and bacteria also contribute to chemical weathering by producing chemicals as they decay their food (fungi produce acids, and bacteria alkaline substances); besides carbon dioxide, microbes produce ammonia and nitric acids, which act as solvents. Rock material is broken down into simpler elements. Although there are almost 90 different chemical elements in soil, only eight constitute the majority: oxygen, silicon, aluminum, iron, magnesium, calcium, sodium, and potassium. All have an electric charge on a molecular level, and in different combinations these form electrically charged molecules that combine to form different minerals.



The acids produced by the yellow lichen on this rock are slowly contributing to its conversion into soil. Photograph by Dave Powell, USDA Forest Service, www.forestryimages.org.

Biological activity, too, causes weathering. Mosses and lichens (or, more precisely, the fungi in them) attach themselves to rocks and produce acids and chelating agents that dissolve little bits of rock to use as nutrients, resulting in small fissures that fill up with water. Freeze and thaw cycles further break apart the parent material, and the roots of larger plants penetrate crevices and widen them, forcing rocks apart.

### Organic matter

Weathering breaks rock down into mineral components of one sort or another. Soil, however, needs to be able to support plant life—and that requires more than just minerals. On average, good garden soil is 45% mineral in nature and 5% organic matter, built up as organisms above and in it go about their daily business. As plants and animals on the surface die and are decayed by bacteria and fungi, they are ultimately converted into humus, a carbon-rich, coffee-colored, organic material. Think of the end product of composting. This valuable material is humus.

Humus consists of very long, hard-to-break chains of carbon molecules with a large surface area; these surfaces carry electrical charges, which attract and hold mineral particles. What's more, the molecular structure of the long chains resembles a sponge—lots of nooks and crannies that serve as veritable condominiums for soil microbes. Once you've added humus and other organic matter, such as dead plant matter and insect bodies, to weathered minerals, you have a soil almost capable of supporting trees, shrubs, lawns, and gardens—but not quite.

### Air and water

Minerals and humus make up the solid phase of soil, but plants require oxygen and water—the gaseous and liquid phases—as well. The voids between individual mineral and organic particles are filled by air or water (and sometimes both).



Humus has a rich, coffee color and is full of organic material. This handful is about 55% organic matter. Courtesy Alaska Humus Company, www.alaskahumus.com.

Classic Soil Science

33

Water moves between soil pore spaces in one of two ways: by the pull of gravity or by the pull of individual water molecules on each other, or capillary action. Gravitational water moves freely through soils. Picture water being poured into a jar of gravel: gravity pulls the water to the bottom as the jar fills poured into a jar of gravel: gravity pulls the water. As the water fills the up. Large pores promote the flow of gravitational water. As the water fills the pores, it displaces and pushes out the air in front of it. When the water flows through, it allows a new supply of air to move in. When gravitational water hits roots, which act like sponges, it is absorbed.

Smaller soil pore spaces contain a film of capillary water that is not influenced by gravity and is actually left behind after gravitational water passes through. The liquid is bonded together by the attraction of its molecules for each other (a force known as cohesion, but let's not complicate things) and to surrounding soil surfaces (a force known as adhesion). This creates a surface tension, causing the water to form a thick film on the particle surfaces. Capillary water can "flow" uphill. It is available to plant roots after gravitational water has passed by and as such is a major source of water for plants.

Hydroscopic water is a thinner film of water, only a few molecules thick, which, like capillary water, is attached to extremely small soil particles by virtue of electrical properties. This film is so thin that the bonds between water molecules and soil particles are concentrated and extremely hard to break. Roots cannot absorb it, therefore, but this film of water is critical to the ability of many microbes to live and travel. Even when conditions are dry, the soil particulate surface holds some hydroscopic water; it is impossible to remove it from soil without applying lots of heat and actually boiling it off.

Just about half the pore spaces in good soil are filled with water. The other half are filled with air. Water movement pushes stale air out and sucks in air from the surface, so adding water means an exchange of air occurs, which is important. If a healthy soil food web is in place, the metabolic activity of soil organisms uses the oxygen and creates carbon dioxide. The presence of carbon dioxide is a good sign that the soil contains life; however, the carbon dioxide must be exchanged with fresh air to keep life going.

In some soils, the pore spaces are cut off in lots of places, and air is not exchanged when water flows. In fact, water may not flow at all. These soils have very poor porosity—that is, they lack adequate space between the soil particles. All the oxygen in the soil can be used up by aerobic metabolic activities, resulting in oxygen-less, anaerobic conditions. Organisms that can live in such conditions often produce alcohols and other substances that kill plant root cells.

### Soil profiles and horizons

Soils are exposed nonstop to the forces of weathering. Rain, for example, will cause some soil minerals and organic matter to leach out as the water moves down through the soil. This material may hit an impervious barrier and become concentrated in a certain zone or layer. The size of particles may cause a particular material to be concentrated or be filtered. Eventually, over time, distinct layers and zones of different material are formed. These can be seen, like the rock strata in the Grand Canyon's walls, as you dig down through the soil. A soil profile is a map of these layers, or horizons.

Soil scientists have attached a letter or combination of letters (and even numbers) to each horizon that appears in any typical soil profile. For the gardener (thankfully), the top horizons, the O and A, are really the only ones that count. The Oi horizon contains organic material that can still be specifically identified (with a bit of training that's beyond the scope of this book); this is fibric soil. The Oe horizon has experienced more decay, and while the materials are identifiable as plant matter, you cannot tell which specific plants are involved, even with training; this is humic soil. Finally, the Oa horizon is where the organic material has decomposed so much that you cannot tell its origin. It could be from plants or from animal matter. This is sapric soil. All this is somewhat useful information if you want to know if your soils will create more decay by-products (like nitrogen) because the process that converts the soil to humus isn't complete; or if your soil has been decayed to the point where it basically just houses microbes that cause decay.

The A horizon lies under the O horizon. Here humus particles accumulate as water runs through the O horizon above and pulls organic particles downward. Water flowing through this horizon carries lots of dissolved and suspended materials. This A horizon has the highest organic matter content of any of the soil horizons and the highest biological activity. This is where the roots grow.

Several other soil horizons follow and, eventually, bedrock. You would need a backhoe to trench through all the horizons under your yard, something that is clearly not worth the effort. Often one or more horizons are missing, worn or transported away by weathering forces, and just as often it is too hard to see any distinction between layers.

The important thing is to make sure your gardens and yard have good soil—the proper mixture of minerals, organic matter, air, and water—in the top layers, in the area where plants grow. If not, you will have to add to what you do have or replace it entirely.

### Soil color

Color can be an easy indicator of what is in your soil, as soil color is sometimes dependent on the soil's specific mineral and organic components. Weathering, oxidation, reduction actions of iron and manganese minerals, and the biochemistry of the decomposition of organic matter are the primary factors influencing soil color.

Organic components in soil are very strong coloring agents and produce dark soils; these can accumulate or can dissolve and coat other particles of soil with black color. When iron is a component of soil, it rusts, and soil particles are coated with red and yellowish tints. When manganese oxide is a major component of soil, its particles take on a purple-black hue. The presence of these colors usually indicates good drainage and aeration.

Gray soils can indicate a lack of organic material. They also often indicate anaerobic conditions because the microbes that survive in such conditions often use the iron in the soil, rendering it colorless in the process. Similarly, magnesium is reduced to colorless compounds by other types of anaerobic soil microbes.

Soil scientists use color charts to identify, compare, and describe soil conditions. For the gardener, however, color plays less of a role. For us, good soil is the color of dark coffee—again, mostly because of its organic components.

### Soil texture

Soil scientists describe the size of soil particles in terms of texture. There are three categories of soil texture: sand, silt, and clay. All soil has a specific texture that enables one to judge its propensity to support a healthy soil food web and thus healthy plants.

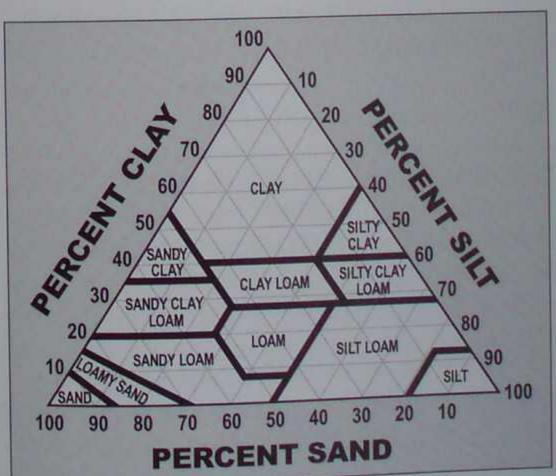
Soil texture has nothing to do with composition. If you think the term "sand" applies only to quartz particles, for example, you would be wrong. True, most sand particles are mineral quartz, but all sorts of rock can be weathered into sand: silicates, feldspars (potassium-aluminum silicate, sodium-aluminum silicate, and calcium-aluminum silicate), iron, and gypsum (calcium sulfate). If the sand comes from ground-up coral reefs, it is limestone. Most silt particles, too, are mineral quartz (only they are much smaller in size than those found in sandy soils), and silts can have the same non-quartz constituents as sand. Clays, on the other hand, are made up of an entirely different group of minerals, hydrous aluminum silicates, with other elements, such as magnesium or iron, occasionally substituting for some of the aluminum.

So, the key point for the gardener is that texture has to do with size of particles only, not the composition of these particles. What size particles, then, constitute sand, slit, and clay?

Start with sand. You've undoubtedly been to a beach and know that sand particles can be seen with the naked eye. They range in size from 0.0625 to 2 millimeters in diameter. Anything much bigger has far too much space between individual particles to be of any use to gardeners except as gravel for a path. Sand particles are just small enough to hold some water when aggregated, but most of it is gravitational water and readily drains out, leaving lots of air and only a little capillary water. Moreover, the particles of sand are big enough to be influenced by gravity, and they quickly settle to the bottom when mixed in water. As to texture, soils with large proportions of sand in them are gritty when ground between the fingers.

Next in texture size is silt. Sand particles can be seen with the naked eye, but you will need a microscope to see individual silt particles. Like sand, these consist of weathered rock, only much, much smaller in size—between 0.004 and 0.0625 millimeter in diameter. The pore spaces between silt particles are much smaller and hold a lot more capillary water than sand does. Like sand, particles of silt are also influenced by gravity and will settle out when put in water. The texture of silt when rubbed between fingers is that of flour.

Clays are formed during intense hydrothermal activity or by chemical action, that of carbonic acid weathering silicate-bearing rocks. Clay particles are readily distinguished from silt, but this time an electron microscope is



A diagram of soil textures. Courtesy Tom Hoffman Graphic Design.

Classic Soil Science

37

needed—these particles are that small, the smallest that make up soil, 0.004 millimeter across or less. Clay particles are "plastic" and somewhat slippery when rubbed between fingers. This is because clay particles absorb and hold lots of water, which is why they are known as hydrous silicate compounds. Besides siliwater, which is why they are known as hydrous silicate compounds. Besides siliwater, which is why they are known as hydrous silicate compounds and iron as well. For comparison, let's put things into a more familiar perspective. If a clay

For comparison, let's put things into a more than the process of a delay particle were the size of a marigold seed, a silt particle would be a large radish, and a sand grain would be a large garden wheelbarrow. Another way to look at a soil texture is to visualize a gram (about a teaspoon's worth) of sand, spread soil texture is to visualize a gram (about a teaspoon's worth) of sand, spread out one-particle deep; this would cover an area about the size of a silver dollar, out one-particle deep; this would cover an area about the size of a silver dollar, let you were to spread an equal amount of clay one-particle thick, you would need a basketball court—and some of the stands surrounding it, at that.

What difference does texture make? The size of the particles has everything to do with their surface area and the surface area of the pore spaces between individual particles. Clay has tremendous surface area compared to sand. Silt is in between. Clay has smaller pore spaces between particles, but many more pore spaces in total, so the surface area of the pore spaces in clay is greater than silt, which is greater than sand. Incidentally, organic matter, usually in the form of humus, is comprised of very minute particles that, like clay, have lots of surface area to which plant nutrients attach, thus preventing them from leaching out. Humus also holds capillary water.

All soils have different textures, but any can be put into a specific category, depending on how much sand-, silt-, and clay-sized grains they contain. The ideal garden soil is loam, a mixture with relatively equal parts of sand, silt, and clay. Loam has the surface area of silt and clay, to hold nutrients and water, and the pore space of sand, to aid drainage and help pull in air.

### Sample your soils

Good garden soil contains 30 to 50% sand, 30 to 50% silt, and 20 to 30% clay, with 5 to 10% organic matter. You can find out how close your soils come to this ideal, loam. All it takes is a quart jar, two cups of water, and a tablespoon of a water softener, such as Calgon liquid. You will also need soil from the top 12 inches (30 centimeters) of the areas you want tested, be it your vegetable garden, flower bed, or lawn.

Mix each soil sample with two cups of water and a tablespoon of water softener. Put it in the jar, close the jar, and shake it vigorously, so that all the particles become suspended in the water. Then put the jar down and let things settle. After a couple of minutes, any sand particles in your soil will have settled

out. It takes a few hours for the smallest silt particles to settle on top of this sand. Much of the smallest clay-sized particles will actually stay in suspension for up to a day. Organics in the soil will float to the top and remain there for an even longer period.

Wait 24 hours and then measure the thickness of each of the layers with a ruler. To determine the percentages of each, divide the depth or thickness of each layer by the total depth of all three layers and then multiply the answer by 100. Once you know what percentages of each material are in your soil, you can begin to physically change it if need be. How to do this is discussed in the second half of the book.

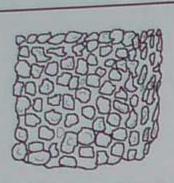
### Soil structure

Individual particulate size, or texture, is obviously an important characteristic of soils, but so is the actual shape these particles take when grouped together. This shape, or soil structure, depends on both the soil's physical and chemical properties. Factors that influence soil structure are particle orientation, amount of clay and humus, shrinking and swelling due to weather (wetting and drying as well as freezing and thawing), root forces, biological influences (worms and small animals), and human activity. Soil structure types, or peds, fall into several distinct categories.

When you look at your garden soils, you don't see individual particles but rather aggregates of these particles. The biology in the soil produces the glues that bind individual soil particles into aggregates. As they go about their day-to-day business, bacteria, fungi, and worms produce polysaccharides, sticky carbohydrates that act like glues, binding individual mineral and humic particles together into aggregates.

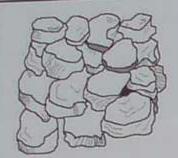
Let's start with bacteria. The slime they produce allows them to stick to particles as well as to each other. Colonies are formed, and these too stick together, as do the particles to which the bacteria are attached. Fungi also help create soil aggregates. A group of common soil fungi, in the order Glomales, produces a sticky protein called glomalin. As the fungal strands, or hyphae, grow through soil pores, glomalin coats soil particles like super glue, sticking these particles together into aggregates or clumps. These aggregates change the soil pore space, making it easier for the soil to hold capillary water and soluble nutrients and recycle them slowly to plants.

Worms process soil particles in search of food. Individual particles of minerals and organics are ingested and ultimately excreted as aggregates; these are so large, they are readily identified as worm castings. Consider, too, the impact



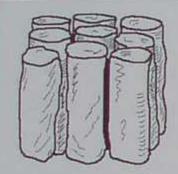
### GRANULAR

Resembles cookie crumbs and is usually less than 0.5 cm in diameter. Commonly found in surface horizons where roots have been growing.



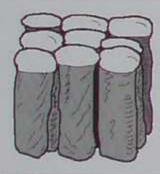
### **BLOCKY**

Irregular blocks that are usually 1.5 - 5.0 cm in diameter.



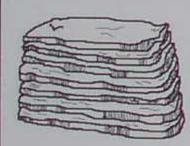
### **PRISMATIC**

Vertical columns of soil that might be a number of cm long. Usually found in lower horizons.



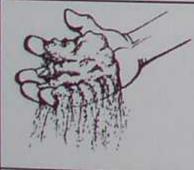
### COLUMNAR

Vertical columns of soil that have a salt "cap" at the top. Found in soils of arid climates.



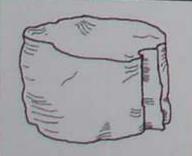
### PLATY

Thin, flat plates of soil that lie horizontally. Usually found in compacted soil.



### SINGLE GRAINED

Soil is broken into individual particles that do not stick together. Always accompanies a loose consistency. Commonly found in sandy soils.



### MASSIVE

Soil has no visible structure, is hard to break apart, and appears in very large clods.

Soil structure peds. Courtesy Tom Hoffman Graphic Design.

of soil organisms as they make their way through the soil. Each group of animals has various body widths. As they move, they create spaces in and between soil particles and aggregates. By way of comparison, imagine that a bacterium 1 micrometer in diameter (1 micrometer = ½25,000 inch) is the width of a piece of spaghetti. Fungal bodies are generally wider, 3 to 5 micrometers. Nematodes (5 to 100 micrometers on average) would be the size of a pencil, perhaps even one of those thick ones; and protozoa (10 to 100 micrometers) would be the diameter of an American-style hot dog. Continuing to use our scale, soil mites and springtails, at 100 micrometers to 5 millimeters, would have the diameter of a good-sized tree. Beetles, earthworms, and spiders (2 to 100 millimeters) would have the diameter of really large trees. Imagine how each opens up soil particles as they go about their daily activities.

Finally, electrical charges on the surfaces of organic matter and clay particles attract each other in addition to chemicals (calcium, iron, aluminum) in water solution, acting as bonding agents that hold together soil particles.

Why are we going over this soil structure stuff? Because soil structure is a key characteristic of good growing conditions. If there is adequate soil structure, there is ample drainage between aggregates, but also plenty of plant-available capillary water. The air circulation necessary for biological activity is sufficient. And, perhaps most important, if there is adequate soil structure, there is space for soil biology to live. Good soil structure withstands torrential rains, the drying of desert-like droughts, herds of animal traffic, and deep freezes. Water and nutrient retention is high. Life in and on it thrives.

Poor soil structure results in a lack of water retention, and soil collapses under all the abovementioned environmental and man-made pressures. Little life is in it, and the serious reduction in fertility drives people to resort to chemical fertilizers in increasing amounts.



Microscopic view of a fungus growing on a corn root. The round bodies are fungal spores, the threads are fungal hyphae, and the green color is from dyetagged glomalin, the glue that holds soil particles together. Photograph by Sara Wright, USDA-ARS.

### Cation exchange capacity

All tiny particles, not just humus, carry electrical charges. These particles are called ions. Ions with a positive (+) charge are called cations and negatively charged (-) ones, anions. Positively charged particles are electrically attached to negatively charged particles. This is exactly what happens when opposite ends of magnets attract each other. When a positively charged cation attaches itself to a negatively charged anion, the cation is "absorbed" by the anion. Even microorganisms in the soil are small enough to carry and be influenced by electrical charges.

Sand particles are too large to carry electrical charges, but both clay and humus particles are small enough to have lots of negatively charged anions that attract positively charged cations. The cations that are absorbed by clay and humus include calcium (Ca<sup>++</sup>), potassium (K<sup>+</sup>), sodium (Na<sup>+</sup>), magnesium (Mg<sup>++</sup>), iron (Fe<sup>+</sup>), ammonium (NH4<sup>+</sup>), and hydrogen (H<sup>+</sup>). These are all major plant nutrients, and they are held in the soil by two components of good soil. The attraction of these cations to the clay and humus particles is so strong that when a solution containing them comes into contact, the attraction is satiated and only about 1% of the cation nutrients remains in solution.

There are anions in soil as well. These include chloride (Cl $^-$ ), nitrate (NO $_3^-$ ), sulfate (SO $_4^-$ ), and phosphate (PO $_4^-$ )—all plant nutrients. Unfortunately, soil anions are repelled by the negative charge on clay and humus particles and therefore stay in solution instead of being absorbed. These plant nutrients are often missing from garden soils, as they are easily leached away in the soil solution when it rains or soil is watered: nothing is holding them on to soil surfaces.

Why does this matter? The surfaces of root hairs have their own electrical charges. When a root hair enters the soil, it can exchange its own cations for those attached to clay or humus particles and then absorb the cation nutrient

| SOIL TEXTURE          | CEC (MEQ/100G) |
|-----------------------|----------------|
| Sands (light colored) | 3–5            |
| Sands (dark colored)  | 10–20          |
| Loams                 | 10–15          |
| Silt loams            | 15-25          |
| Clay and clay loams   | 20-50          |
| Organic soils         |                |
| Carl                  | 50-100         |

Cation exchange capacities for various soil textures. Courtesy Tom Hoffman Graphic Design.

involved. Roots use hydrogen cations (H<sup>+</sup>) as their exchange currency, giving up one hydrogen cation for every cation nutrient absorbed. This keeps the balance of charges equal. This is how plants "eat."

The place where the exchange of a cation occurs is known as a cation exchange site, and the number of these exchange sites measures the capacity of the soil to hold nutrients, or the cation exchange capacity (CEC). A soil's CEC is simply the sum of positively charged nutrient replacements that it can absorb per unit weight or volume. CEC is measured in milligram equivalents per 100 grams (meq/100g). What the gardener needs to know is that the higher the CEC number, the more nutrients a soil can hold and therefore, the better it is for growing plants. The higher the CEC, the more fertile the soil. You can order a CEC test to be run by a professional soil lab.

The CEC of soil depends, in part, on its texture. Sand and silt have low CECs because these particles are too big to be influenced by an electrical charge and hold nutrients. Clay and organic particles impart a high CEC to soils because they do carry lots of electrical charges: the more humus and, to a point, clay present in soils, the more nutrients can be stored in the soil, which is why gardeners seek more organics in their soils.

There are limits to a good thing. Don't forget that clay particles are extremely small; too much clay and too little humus results in a high CEC but little air in the soil, because the pore space is too small and cut off by the clay's platy structure. Such soil has good CEC but poor drainage. Thus it is not enough to know the CEC alone; you have to know the soil texture and mixture.

### Soil pH

Most of us have a basic understanding of pH as a way to measure liquids to see if they are acid or not. On a scale of 1 to 14, a pH of 1 is very acidic and a pH of 14 is very alkaline (or basic), the opposite of acidic. The pH tells the concentration of hydrogen ions (H<sup>+</sup>, a cation) in the solution being measured. If you have relatively few hydrogen ions compared to the rest of what is in solution, the pH is low and the solution is acidic. Similarly, if you have a lot of hydrogen ions in solution, then you have a solution with a high pH, one that is alkaline.

As a gardener, you (fortunately) don't need to know much more about pH. You do need to understand, however, that every time a plant root tip exchanges a hydrogen cation for a nutrient cation, the concentration of hydrogen ions in the solution increases. As the concentration of H<sup>+</sup> goes up, the pH goes up the soil is increasingly alkaline. Things usually balance out, however, because root surfaces also take up negatively charged anions, using hydroxy (OH<sup>-</sup>)

anions as the medium of exchange. Adding OH<sup>-</sup> to the solution lowers the pH (that is, soil is increasingly acidic) because it lowers the concentration of H<sup>+</sup>. Fungi and bacteria are small enough to have cations and anions on their surfaces, electrically holding or releasing the mineral nutrients they take in from decomposition in the soil. This, too, has an impact on the pH of the soil.

Why is pH a consideration when we talk about the soil food web? The pH created by nutrient-ion exchanges influences what types of microorganisms live in the soil. This can either encourage or discourage nitrification and other biological activities that affect how plants grow. As important, each plant has an optimum soil pH. As you will learn, this has more to do with the need of certain fungi and bacteria important to those plants to thrive in a certain pH than it does with the chemistry of pH.

Knowing your soil's pH is useful in determining what you want to put into your soil, if anything, to support specific types of soil food webs. And knowing the pH in the rhizosphere helps determine if any adjustments should be made to help plant growth.

The rest of Part 1 covers the biology that lives in the soil. You have to appreciate the soil first, however.

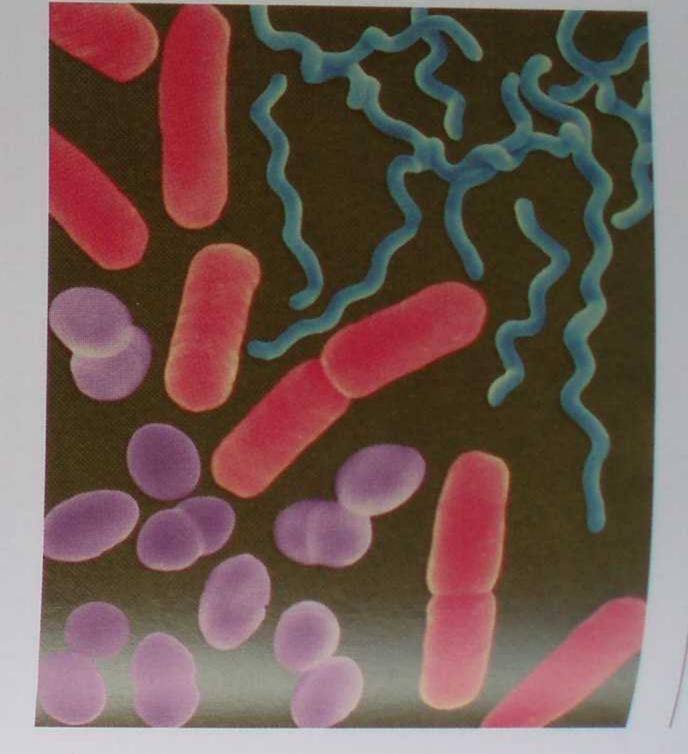
### Chapter 3 Bacteria

Bacteria are everywhere. Few gardeners appreciate that they are crucial to the lives of plants, and fewer still have ever taken them into consideration. Yet no other organism has more members in the soil, not even close. In part, this is because these single-celled organisms are so minuscule that anywhere from 250,000 to 500,000 of them can fit inside the period at the end of this sentence.

Bacteria were the earliest form of life on earth, appearing at least 3 billion years ago. They are prokaryotes: their DNA is contained in a single chromosome that is not enclosed in a nucleus. Their size, or more precisely their lack thereof, must be the main reason our familiarity with bacteria is usually limited to the diseases they cause and the need to wash our hands before eating. Most baby boomers used a standard-issue 1000 power microscope to study microorganisms, but bacteria are too small to see in any detail at this power. School microscopes have gotten better, and some lucky students now do get a closer look, literally, at bacteria. The three basic shapes, all represented in the soil, are coccus (spherical or oval), bacillus (rod-shaped), and spiral.

Bacteria reproduce, for the most part, by single cell division; that is, one cell divides and makes two cells, they each divide again, and so forth. Amazingly, under laboratory conditions, one solitary bacterium can produce in the vicinity of 5 billion offspring in a mere 12 hours if they have enough food. If all bacteria reproduced at this rate all the time, it would take only a month or so to double the mass of our planet. Fortunately, soil bacteria are limited by natural conditions, predators (protozoa chief among them), and a slower reproductive rate than their laboratory cousins; for example, bacteria must have some form of moisture for the uptake of nutrients and the release of waste. In most cases, moisture is also required for bacteria to move about and to transport the enzymes they use to break down organic matter. When soils become too dry, many soil bacteria go dormant. Bacteria, incidentally, rarely die of old age, but are usually eaten by something else or killed by environmental changes and then consumed by other decomposers, often other bacteria.

photo composite of the three basic shapes of bacteria: coccus, bacillus, and spiral, 800×. Image copyright Dennis Kunkel Microscopy, Inc.



# Primary decomposers

and are themselves decayed. leased (mineralized) only when the bacteria are consumed or otherwise die ents. These nutrients are then held immobilized inside the bacteria; they are remal material in order to ingest nitrogen, carbon compounds, and other nutriin our own wastes in a matter of months. Bacteria decompose plant and aniorganic matter, second only to fungi. Without them, we would be smothered Despite their tiny size, bacteria are among the earth's primary decomposers of

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digest than the more complex carbon compounds of other plant material. composing young, still-fresh plant material, which composters call green maing on what is available and where they are located. Most, however, do best deterial. Green material contains lots of sugars, which are easier for bacteria to than do bacteria. Composters call this brown material, and until it is broken down into smaller carbon chains, other members of the soil food web more readily di Different kinds of soil bacteria survive on different food sources, igest this , depend-

of proteins that assist in this molecular transport. On the inside of they take in food directly through their cell walls, which are composed, in part, more tiny pieces of organic matter. How do they do this? The short answer is rium's cell wall is a mixture of sugars, proteins, carbons, and ionswall. Nature likes to try to keep things balanced; normally, water would flow from the dilute solution without into the more concentrated one within Given their diminutive size, bacteria must ingest what are necessarily even out of equilibrium with the less concentrated mixture outside the cell -a rich soup a bacte-(a spe-

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act as osmotic barriers. cial form of diffusion known as osmosis), but in the case of bacteria, cell walls

passed from its source to the fire: these proteins pass "buckets" of nutrients is to think of an old-fashioned fire bucket brigade, in which the water was brane transport different kinds of nutrient molecules. One way to imagine this as molecular pumps and use energy to suck or push their target through the eral ways. In the most important, active transport, the membrane proteins act Molecular transport across the cellular membrane is accomplished in sev--nutrients in, waste products out. Different proteins in the mem-

use. Once inside the bacteria, the nutrients are locked up. pieces and then transport these through their cellular membranes, ready for stand that bacteria break up organic matter into small, electrically charged tainly be aware of and appreciate how bacteria feed but only needs to undertrons located on both sides of the membrane surface. The gardener should cer-Active transport is a fascinating but complicated process fueled by y elec-

base of the soil food web food pyramid. eating bacteria. If there aren't sufficient numbers of bacteria in the soil, lations of these members of the soil food web suffer. Bacteria are part Other members of the soil food web obtain their energy and nutrients by popuof the

## Feeding bacteria

nutrition from the cells sloughed off during root-tip growth. But not all soil populations of them concentrate in the rhizosphere, where bacteria also find cules, many of which consist of chains of smaller molecules in repetitive patubiquitous as bacteria. All organic matter is made up of large, complex bacteria live in the rhizosphere, for, fortunately, organic matter is almost as Root exudates are favorite foods for certain soil bacteria, and as a result, huge certain points of these chains, creating smaller chains of simple sugars and bacteria need to sustain themselves. fatty and amino acids. These three groups provide the basic building that usually contain carbon. Bacteria are able to break the bonds blocks along mole-

gether and to digest their food. All this is done outside the organism adapted over the millenia to attack all manner of organic and even inorganic ingestion. Untold numbers of enzymes are employed by bacteria, who have matter. It is an astonishing feat that bacteria can employ enzymes to break <sup>0</sup>rganic matter, while at the same time not impacting their own cell membrane. Bacteria use enzymes both to break the bonds holding organic char before ins todown

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### Air and no air

meaning they can live in aerobic conditions if they must but prefer anaerobic environments. and other bacteria normally found in the mammalian gastrointestinal tract (think vomit), ammonia, and vinegar. The notorious Escherichia coli (E. coli) anaerobic decay include hydrogen sulfide (think rotten eggs), butyric acid terial genus Clostridium, for example, does not need oxygen live in the absence of oxygen; indeed, most cannot live in its invade and destroy the inside soft tissue of decaying matter. By-products of There are two main groups of bacteria. The first, anaerobic bacteria, are able to (and thus in poorly made, manure-based composts) are facultative anaerobes, presence. The bacto survive and can

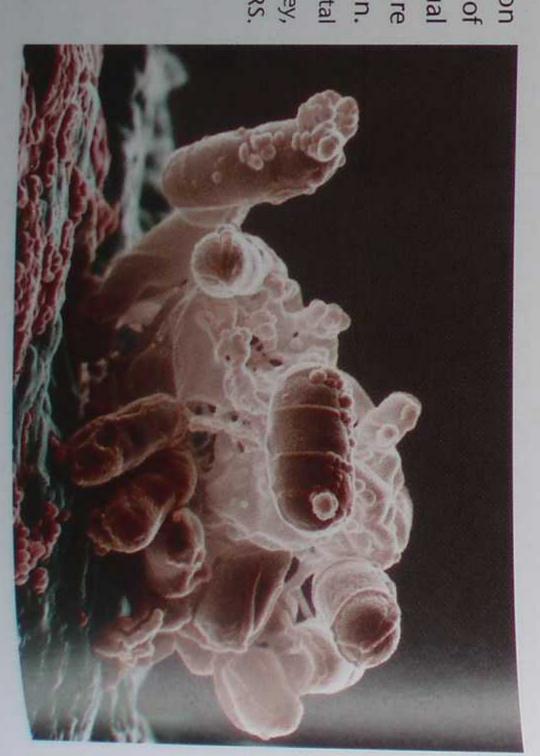
aerobic bacteria, the other major group of bacteria: those that require air. anaerobic conditions foster pathogenic bacteria and, worse, kill off beneficial member when composting and gardening with the soil food web because perhaps in the garden but certainly in the refrigerator. These are smells to re-Most gardeners have smelled by-products of anaerobic decomposition,

ically the bacterial genus Streptomyces) produce enzymes that include volatile tions if they must, most cannot. Aerobic bacteria are not normally known to chemicals that give soil its clean, fresh, earthy aroma. Anyone who has garcause bad smells. In fact, the actinomycetes (of order Actinomycetales, specifdened recognizes this smell, the smell of "good soil." While some facultative aerobic bacteria are able to live in anaerobic condi-

use their branching filaments to connect soil particles so they, along with the aments, almost like fungal hyphae. Some scientists believe Streptomyces species Actinomycetes are different from other soil bacteria: they actually grow fil-

Low-temperature electron micrograph of a cluster of *E. coli* bacteria. Individual bacteria in this photo are oblong and colored brown.

Photograph by Eric Erbe, digital color by Christopher Pooley, USDA-ARS.



bacteria, from acidic to alkaline. gal cell walls and in arthropod shells. These are not normal foods of other baccarbon compounds, the former found in plant wall cells and the latter in funteria. Actinomycetes are also adapted to live in a wider range of pH than other zoan ciliates, which would engulf and ingest them. Actinomycetes are particusoil particles, become too big to be eaten by their natural predators, the protolarly adept at decaying cellulose and chitin—two difficult-to-digest ("brown")

## Decay of cellulose

in a hit-and-miss manner. lulose, as opposed to the random release of enzymes by other bacteria who eat breaking enzymes that they release only when they come into contact with plants. Specialized bacteria, like the aptly named Cellulomonas, carry cellulosethe mass of plant bodies, and hence half the mass of organic matter created by glucose, is the molecular material that gives plants structure. It constitutes Cellulose, a complex carbohydrate made up of long chains of carbon-based half cel-

tough brown component of barks and woody materials, is a much more comlignin, another prevalent, molecularly complex plant material. Lignin, the plex organic molecule than cellulose, made up of chains of interlinked alcofor fungi to decay. hols; these are resistant to the enzymes produced by most bacteria and are left Most bacteria reach their limit when it comes to the noncarbohydrate

### Element cycling

in the soil food web play a crucial role in recycling three of the basic elements ide) is a major by-product of aerobic bacterial metabolism. Carbon tied up in needed for life: carbon, sulfur, and nitrogen. For example, CO2 (carbon diox-One way of looking at decay is to view it as nature's recycling system. Bacteria ally consumed and then recycled back to CO2. in higher plants converts the CO<sub>2</sub> into organic compounds, which are eventuplant and animal biomass is cycled into  ${
m CO_2}$  gas during decay. Photosynthesis

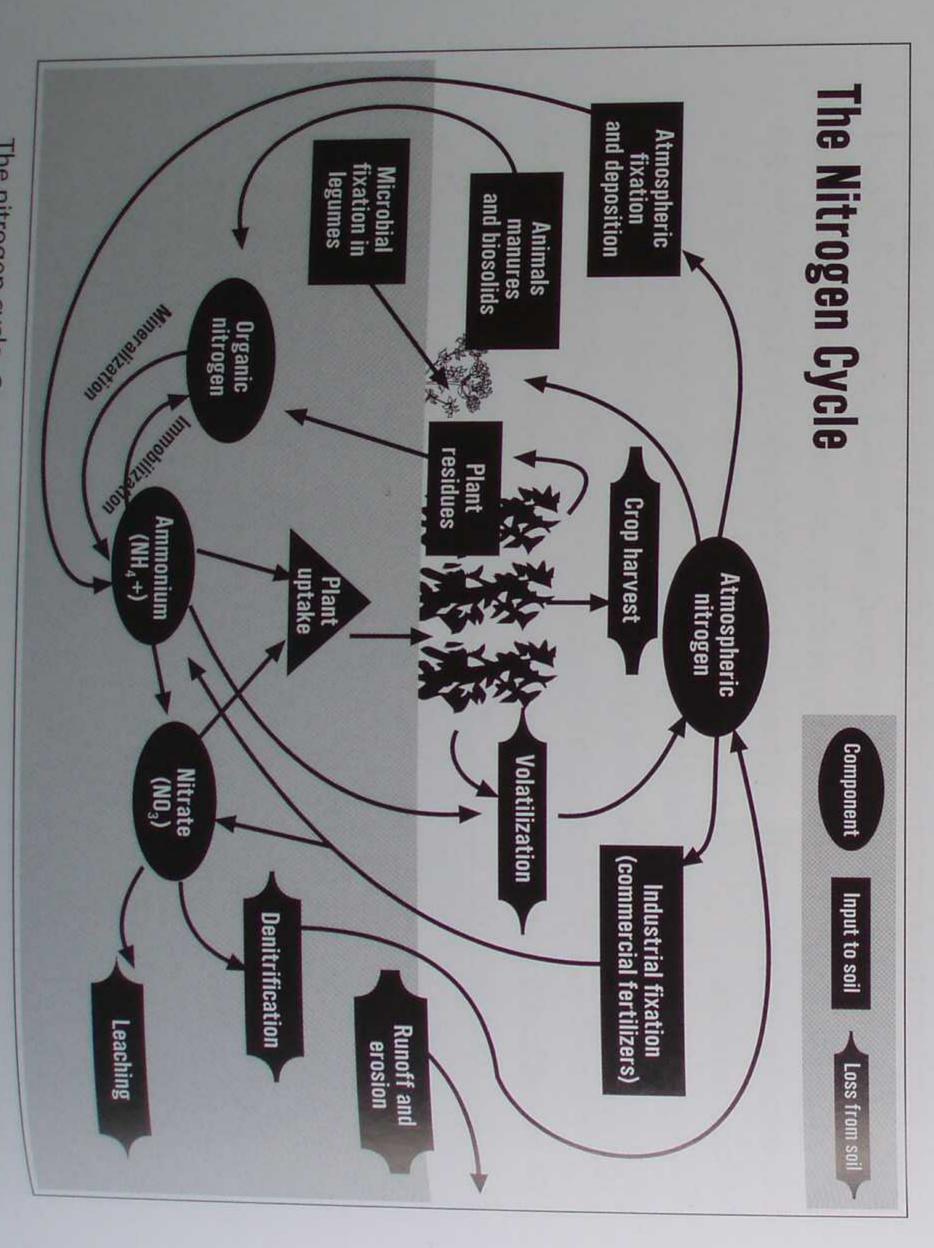
make plant-available, water-soluble sulfates. Liberated from organic materials by anaerobic bacteria, sulfur-containing compounds are produced by chemo-Similarly, sulfur is recycled. Sulfur-oxidizing bacteria use the element to

autotrophs, bacteria that get energy from the oxidation of sulfur. most important systems in the maintenance of terrestrial life: living organisms The nitrogen cycle, propelled in part by specialized bacteria, is one or f the

nitrogen fixation. and useless for plant needs. For plants to be able to use nitrogen, it has to be gen molecules together make this nitrogen inert for all (NH4+) nucleic acidsproduce the vital organic compounds, the building blocks of li ), nitrate (NO<sub>3</sub><sup>-</sup>), or nitrite (NO<sub>2</sub><sup>-</sup>) ions. This important process is called combined with either oxygen or hydrogen--using nitrogen. The strong bonds holding atmospheric nitro--producing ammonium practicable purposes -amino and

plants, particularly legumes, where they form visible nodules. live free in the soil; Rhizobium species actually live in the root ti name for a comic book superhero). Azotobacter, Azospirillum, and Clostridium Azospirillum, Clostridium, and Rhizobium (any one of which would be a great Certain bacteria convert nitrogen from the atmosphere into The genera that accomplish this nitrogen-fixing feat are Azotobacter, ssues of certain plant-available

recycling of carbon and sulfur requires the interventions of living organisms. These are always taught as chemical processes, but they are really biological. but we do want you to focus on the fact that nitrogen fixation as well as the We don't mean to suggest you need to memorize the species of soil bacte-



The nitrogen cycle. Courtesy Tom Hoffman Graphic Design.

case of the biology creating the chemistry to us. with specific plants or existing symbiotically within organisms. Sounds like a Bacteria carry out these processes in the soil, forming symbiotic relationship

into nitrates (NO<sub>3</sub><sup>-</sup>). ond type of bacteria, nitrate bacteria (Nitrobacter spp.), convert the nitrites somonas spp.) convert the ammonium compounds into nitrites (NO2). A secnematodes after eating bacteria and fungi. Next, special nitrite bacteria (Nitronium usually figures as part of the waste product produced by protozoa and involves the decomposition of proteins into ammonium (NH4+). This ammo-Another part of the nitrogen cycle, the place at which it "starts" in the soil,

lower, very little if any of the ammonium is converted. by organisms in the soil is not all converted to nitrate form. If the pH is 5 ity above 7, and nitrification can occur. If not, the ammonium first produced to bind soil particles together) happens to have a pH above 7. Thus, if there are when soil pH drops below 7. Bacterial slime (already mentioned for its ability bers (and hence the conversion of nitrogen into nitrates) therefore diminish enough bacteria in an area, the slime they produce keeps the pH in their vicin-Nitrifying bacteria do not generally like acidic environments; their num-

soil, but they are essential in that they keep the nitrogen cycle moving. the atmosphere. Obviously, denitrifying bacteria do not help the fertility Denitrifying bacteria convert nitrogen salts back to N2, which escapes into

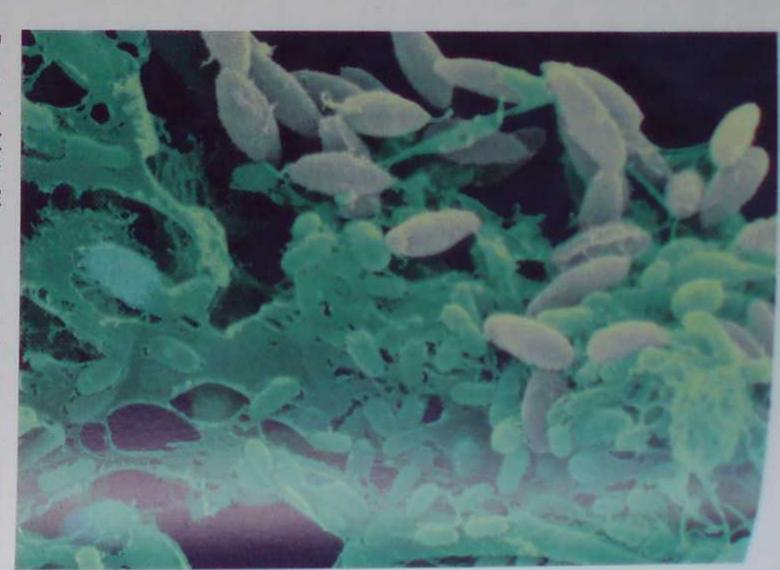
### Biofilms

so the pH remains relatively constant. where it counts most, in the rhizosphere, but also buffers the soil in the area, that bacterial slime in the soil is slightly alkaline not only influences the pH Bacterial slime, or biofilm, is a matrix of sugars, proteins, and DNA. The fact

ing this substance as a means of propulsion. (Most bacteria, however, travel inside sticky globs of biofilms, complete with an infrastructure of channels more whip structures, or flagella, that resemble and operate like propellers.) Biofilms save bacteria from desiccation as the soil dries; soil bacteria often live defense against antibiotics produced by other organisms, including fellow bacfilled with water for transport of nutrients and wastes. Biofilms can also be individual bacteria to antibiotics and microbicides. Some bacteria use their film as a means of transportation, literally squi Bacteria colonies protected by slime are 1000 times more resistant than an astonishing bit of natural nanotechnology--with the aid of one or



Scanning electron micrograph (SEM) of a biofilm surface. Insect parts and plant fibers are embedded in the slime, along with numerous crystals. Photograph by Ralph Robinson, www.microbelibrary.org.



Bacterial biofilm on stainless steel, 1600x. Image copyright Dennis Kunkel Microscopy, Inc.

## Nutrient retention

Since the bacteria are themselves attached to soil particles, the nutrients decomposing organic matter and retaining them in their cellular structures. otherwise disappear as a result of leaching. They do so by ingesting them while Bacteria play a major role in plant nutrition. They lock up nutrients that might fertilizers. remain in the soil instead of being washed away, as is the case with chemical

isms, such as protozoa, play major roles consuming bacteria, very far, and there is ample source of bacterial food in the root zone, the nutritil the bacteria are eaten and reduced to wastes. Since soil bacteria don't travel nitrogen as ammonium (NH<sub>4</sub><sup>+</sup>) in their wastes, which are ents ingested by the bacteria are kept in the vicinity of the roots. Other organrhizosphere, right where the roots can absorb nutrients. Indeed, these nutrients will be tied up, immobilized inside the bacteria undeposited in the releasing excess

# Other benefits of soil bacteria

other bacteria. These anaerobic bacteria can be avoided when Some anaerobic bacteria produce alcohols that are toxic to plant life and to gardening by

sands of bacterial pathogens are in soil, and billions of dollars are spent every Pseudomonas species cause leaf curl and black spot on tomatoes. holderia cepecia is a bacterium that infects and rots the roots of onions. Some tumefaciens causes galls or tumors to grow on the stems of certain plants. Burkmelons, and cucumbers, and fire-blight of pathogens that cause disease in higher plants. The list of pathogenic bacte controlling the conditions that allow them to multiply: poor soil texture one, including bacteria that cause protect crops from damage by the space, standing water, and compacted soil. Other bacteria citrus canker, diseases of potatoes, pears, apples, and the like. Thouculprit bacteria. Agrobacterium , lack ria is are

bacteria that can eat oil spilled on a beach in Alaska; there are similar bacteria often responsible for breaking down pollutants and toxins. These processes are usually aerobic, requiring oxygen to occur. You undoubtedly have heard of healthy soil bacteria population than not. For example, bacterial activity is also Despite the presence of pathogenic bacteria, there are more benefits to a gasoline spilled on your lawn, for example.

compete not only with other bacteria for nutrients but also with fungi and have come to depend. One can only speculate that since these bacteria have to soil bacteria keep pathogenic bacteria in check, a big benefit of a healthy soil ducing phenazines, very strong, broad-spectrum antibiotics. Obviously, many monas bacteria can correct take-all, a disastrous fungal wheat disease, by Soil bacteria produce many of the medicinal antibiotics upon which we organisms, they evolved protective capabilities. For example, Pseudopro-

nite amount of food the soil offers and thus keep each other's larger number of nonpathogenic bacteria outcompeting pathogenic bacteria balance. Soils with a high diversity of bacterial types are more likely to have a appreciate that bacteria are at the front line of defense. ral defenses is the best way to keep the bad All bacteria compete with each other and with other organisms for the fiand nutrients. We are convinced that using the soil food web's natuguys in check. Gardeners need to populations in

### Fungi

spore-producing mushrooms, soil fungi are as invisible as bacteria, requiring a of decaying. microscope of several hundred power to be seen. Even more on this, later in the chapter). But except for the white threads and the white toadstools, bracket and coral fungi, and puffballs that appear in the lawn tions of mycelia are usually hidden in the organic matter they are in the process or on the bark of trees (or they know soil fungi from the diseases they cause\_ VER 100,000 different kinds of fungi are known, word, however, and most gardeners immediately think of the familiar suggest a million more are out there waiting to be discovered. Say the the visible congregaand some authorities

in the soil food web and are an important tool for those who garden using soil are now placed in their own kingdom in the domain Eukarya. dom; but because fungi are unable to photosynthesize, and build their cell without chlorophyll and included for classification purposes in the plant kingwalls from chitin instead of cellulose, among other unique characteristics, they food web principles. It wasn't too long ago that they were considered plants Fungi, too, are underappreciated by gardeners, and yet they play a key role

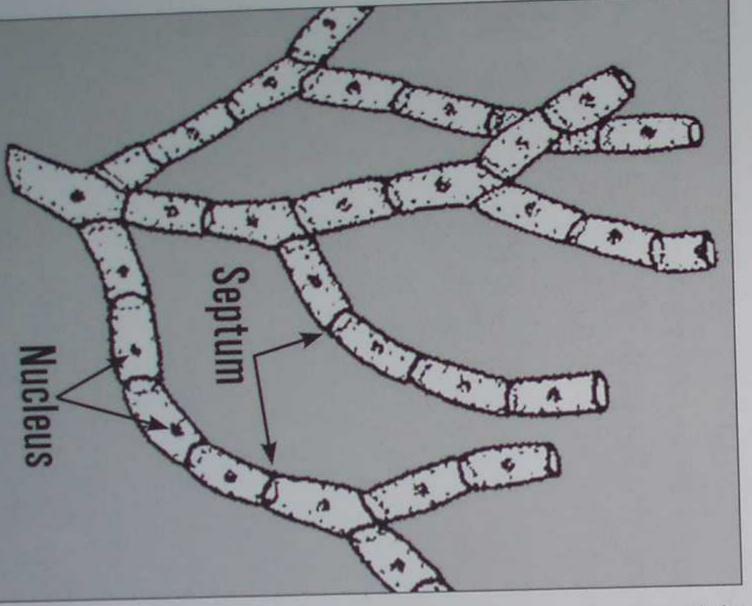
sealed off from other cells in the strand, thus allowing liquids to flow between cells with distinct, enclosed nuclei. Each cell can have more than one nucleus. ible threads, or mycelia (singular, mycelium), which you may have seen in deible throad. gular, hypha). A single hyphal strand is divided into cells by walls, or septa Fungi usually grow from spores into thread-like structures called hyphae (sinspores, but never by seeds, as the most advanced plants commonly do. spores hart named in the spores have not been spores as the spores have not spore and the spores have not spore and the spore in the spo (singular, septum). The walls connecting hyphae cells are seldom completely Fungi, like higher plants and animals, are eukaryotes: organisms that have

a network +h:-1. The form a manneter of 0.2 to 5.5 interours form being 2 to 15 micrometers with a diameter of 0.2 to 3.5 micrometers a network thick enough for the human eye to see. A teaspoon of good garden A fungal hypha is considerably larger than a bacterium, the average length -still so

bolete or an intricate Amanita muscaria in all their fruiting glory. These and lions upon millions merge together to produce something as obvious as a king soil may contain several yards of fungal hyphae, invisible to the naked eye; mil-



Amanita muscaria, the beautiful but poisonous fly agaric. Photograph by Judith Hoersting.



A diagram of a hypha. Courtesy Tom Hoffman Graphic Design.

other mushrooms are simply the fruiting bodies of fungi. Consider the energy

and nutrients required to produce them. One major advantage fungi have over bacteria, and perhaps the reason they

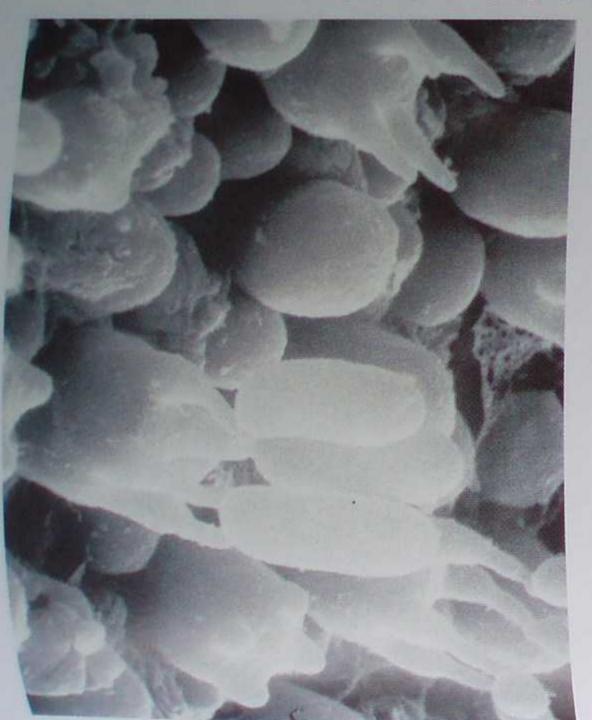
nutrients from one location to another, relatively far away from its origin. short distances, which allows them to locate new food sources and transport in length. Unlike bacterial cells, whose world is a very finite one, fungal hyphae to spread through the soil. Fungal hyphae are thus able to bridge gaps and go are truly epic. And unlike bacteria, fungi do not need a film of water in order can travel over space measured in feet or meters, distances that were misclassified for so long as plants, is the ability of fungal hyphae to grow for a bacterium

and bacteria. Fungal hyphae contain cytoplasm, a liquid circulated throughout nutrients are immobilized and will not be lost from the soil. thus transferred from the tip of the fungal hypha to a wholly n toplasm and from there through the main body of the fungus. Nutrients are drains its hapless victim of its nutrients and distributes them in the hyphal cythe septa in their cells. When a hyphal tip invades a nematode, for example, it can be several yards away (think conveyor belt). Once inside The ability to transport nutrients is another key difference between fungi ew location that the fungus, the

sure survival, fungal spores can develop tough membranes that allow them to including attractive scents, triggers, springs, and jet propulsion systems. To engo dormant for years if the conditions are not right for immediate germination. ments, they have devised some elaborate methods to achieve or truffles below-Fungi produce special structures—for example, mushrooms above ground -to disperse spores. Since fungi grow in all sorts of environspore dispersal,

As with bacteria, fungi occur universally; some species even exist in the

American Phytopathological Society, St. Paul, Minnesota.



conditions for growth are not right. continents away from their source, but they may not be functional because the tralia. While dormant spores can be found around the world, they itors from, say, Alaska, will recognize species of fungi growing in far-off Ausfrozen region of Antarctica. Airborne dispersal of spores helps explain why visconditions to germinate and grow. Thus, fungal spores may be found need the

# Fungal growth and decay

ars). Fungi, however, win in the competition for more complex foods: they the foods that feed bacteria, most go for tougher-to-digest foods (mainly that is, growth at their hyphal tip. Apical or tip growth is an incredibly comtheir ability to penetrate hard surfaces. Fungi have perfected apical growthcompound that binds and protects cellulose. Another characteristic of fungi is produce phenol oxidase, a strong enzyme that dissolves even lignin, the woody cause bacteria are better and faster at grabbing and taking up the simple sug-While some fungi prefer the "softer," plex process, an engineering job akin to building a tunnel under a river and reing hyphae; when hyphal growth stopped, the Spitzenkörper disappeared. It scientists identified a dark spot, the Spitzenkörper, in the tip of actively growseems this mysterious region has something to do with controlling or perhaps directing apical growth. great coordination of events. Even before electron microscopes, easier-to-digest sugars characteristic of be-

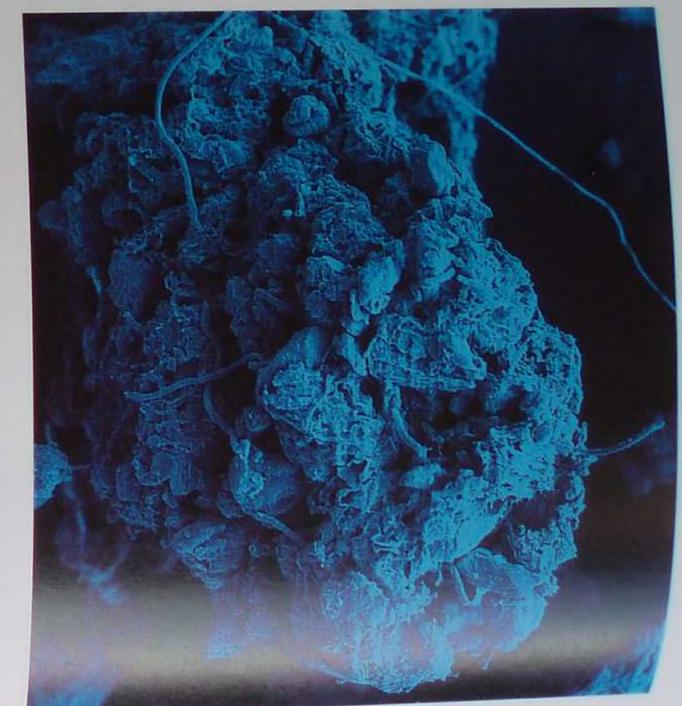
and along the sidewalls, elongating the hyphal tube. Materials for the growth of fungal hyphae are supplied to the advancing tip by the cytoplasm, which pha as well as out while this growth is happening. All the while, powerful encourse, it is important to keep extraneous material from flowing into the hytransports vesicles loaded with all necessary "construction" zymes capable of dissolving all but the most recalcitrant carbon compounds ter into simple sugars and amino acids, yet they do not decay the chitin cell During apical growth, new cells are constantly being pushed into the tip powerful enough to convert lignin, cellulose, and other tough organic released as the new cells are put into place. Think about it: these enzymes supplies. Of

distance covered to the movement of a typical soil bacterium, which may speed, which is incredibly fast for such tiny organisms, and compare the grow up to 40 micrometers a minute. Discount for the moment

only 6 micrometers in its entire life.

As with the death of any organism in the soil, the death of fungi means the

Dead fungal strands attached to a soil particle. Image copyright Ann West.



scopic tunnels, up to 10 micrometers in diameter, through which air and water soil food web. But when fungi die, their hyphae leave a subway system of micronutrients contained within them become available to other members elude protozoa: protozoa are considerably bigger than the tunnels. can flow. These "tubes" are also important safety zones for bacteria trying to of the

and fingernails. Bacteria can hold their own, but they require simpler-to-digest release allow fungi to penetrate not only the lignin and cellulose in plants toods, often the by-products of fungal decay, and often only after such food has are in the Minor Leagues of decaying ability. (dead or alive) but also the hard, chitin shells of insects, the bones of animals, been broken or opened up by fungi and others. Compared to Fungi are the primary decay agents in the soil food web. The -as many gardeners have learned--even the protein of strong fungi, bacteria enzymes they toenails

### Fungal feeding

The acidic digestive substances produced by fungi and leaked out of their hymouthparts; instead, fungal decay breaks up organic materials ach as a vessel in which to digest food, however. Like bacteria, phal tips are similar to those utilized by humans; fungi don't require a stomsis) and active transport. Nutrients taken in by fungi are usually pounds the fungus can then ingest through its cell walls via diffusion (osmojust as they are when ingested by bacteria, and later released. then, fungi should be viewed as living containers of fertilizer. Like bacteria, immobilized fungi lack into com-

teria, the other primary nutrient recycler in the soil food web. bring the nutrients back down into the root zone—a huge advantage over bactend up into the leaf litter on the surface of the soil, decay leaves, and then this, too, as the nematode-trapping fungus proves). Fungi can, for example, exsources instead of waiting for its food to come close (though it can clearly do growth gives a fungus the ability to move relatively long distances to food making nutrients available to plants and others in the soil community. Hyphal the fungus has moved on, opening up organic material for bacterial decay to grow and as a consequence, the digestion of organics continues even though Excess acids, enzymes, and wastes are left behind as the fungus continues and

of fungi to gather and transport it over distances is truly remarkable. This minabsorbing several crucial nutrientsexudates. Thus the same fungus can extend hyphae downward and outward, fungal hyphae that often ends at the root of a plant, where some fungi trade for is inside the cellular membrane, it is transported back through the network of compounds from different sources simultaneously. Once the nutrient material eral is almost always chemically locked up in soils; even when it is applied as do fungi seek out this necessary plant nutrient, but they have the ability to free it from its chemical and physical bonds. Then they transport their quarry fertilizer, phosphorus becomes unavailable to plants within seconds. Not only to plant roots, where the phosphorus is absorbed and utilized. Soil fungi are usually branched and quite capable of gathering organic -as well as water. In the case of phosphorus, for example, the propensity -phosphorus, copper, zinc, iron, n back itro-

good, but the plant is in control. plant root tip, it was attracted to that plant by the plant's exudates. Fungi are Don't forget that in those instances where a fungus brings food back to a

# Fungi and plant-available nitrogen

as waste after they are consumed by fungi or when the fungi die and are de-Some fungi trade nutrients for exudates, but most often nutrients are released soil food web is that plants can take up nitrogen in two forms, either as ammocayed. Much of what is released is nitrogen. A key tenet of gardening with the nium ions (NH $_4^+$ ) or as nitrate ions (NO $_3^-$ ). The nitrogen released by fungi is in ammonium form (NH<sub>4</sub><sup>+</sup>). If nitrifying bacteria are present, this in two steps to nitrate (NO<sub>3</sub><sup>-</sup>). is converted

member that bacterial slime raises soil pH; nitrogen-fixing bacteria generally The enzymes produced by fungi are decidedly acidic and lower the pH. RepH above 7. As soils become dominated by fungi, the populations of

you prefer to have your ammonium converted to nitrates (who wants what is is great if you are a plant that prefers ammonium to nitrate, but not so good if web: fungally dominated soils tend to have nitrogen in ammonium form. This nitrates. This has an important implication to gardening with the soil food therefore remains as plant-available ammonium instead of being converted to ish because the pH is lowered by the acids the fungi produce. More ammonium nitrogen-fixing bacteria required to convert ammonium into explained in chapter 12). nitrates dimin-

## Fungal adaptations

nematode-strangling fungus proves it. The fungus that developed this very art-Fungi have developed all sorts of clever strategies to make it through lifeall blind, but it attracts them to its trap in the first instance. process. Not only does the fungus figure out a way to kill nematodes, which are trapping mechanism developed from an inverted branch using only three cells. pecting victim is killed in a tenth of a second. Pretty amazingnal to let water in; the cells then swell to three times their size and the unsusbranches each consist of only three cells, which, when touched, produce a signematode is actually just a hyphal branch, twisted back ful and useful adaptation is Arthrobotrys dactyloides. The ring fungus releases a chemical that attracts the worm. Once again, nanotechnology can only hope to duplicate such a complicated on itself. These that trapped the In this case, the a sophisticated JH0-

hypha enters the nematode's body, secretes its powerful enzymes, and starts absorbing nutrients. As this is exactly what the nematode has been doinging—the worm is usually a real treasure trove of nutrients for the fungus. gus is eaten by one of its predators or it trades them for exudates. Then the These nutrients, of course, are then locked up inside the fungus until the funnutrients are mineralized and again are available to plants. Within a matter of only a few minutes after trapping, the tip of a fungal

drops from the tips of its hyphae; an unsuspecting nematode (our perennial at the supermarket, uses another clever technique to trap food. It emits toxic and within minutes is immobilized. A few hours later, and the fungus is inside fungal fall guy), out and about, looking for food, touches a drop with its mouth the nematode, already digesting it. The fungus Pleurotus ostreatus, the common oyster mushroom you can buy

or stun it and then consume it. Other mechanisms have evolved as well. Some fungi use adhesives to stick to nematodes. Other soil fungi trap protozoa and This is not a bad way to ensure a meal: attract your food and either trap it

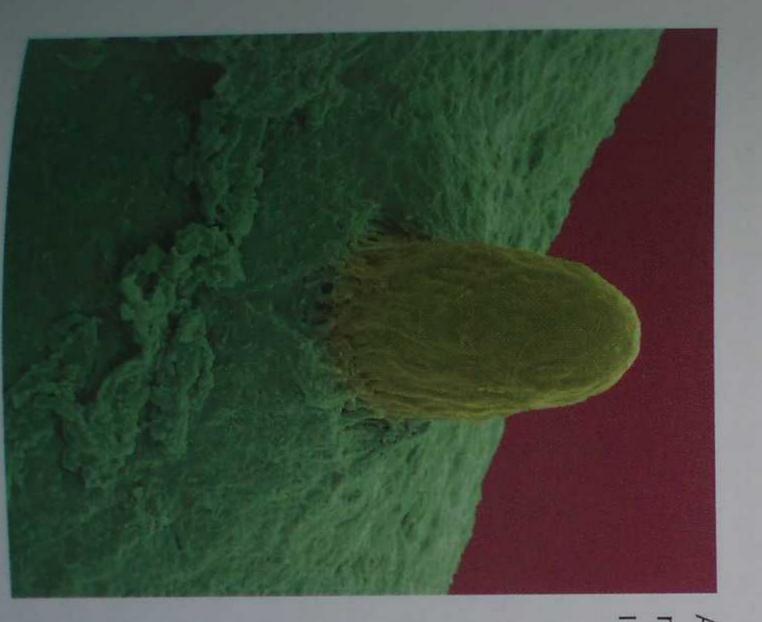
immobilize plant nutrients. the naked eye. Once attached, the fungi digest their prey and again lock up or even springtails, much larger microarthropods that are big enough to see with

be in the vicinity of specific prey. source. Others demonstrate the ability to track specific chemicals they know to them to orient in a certain direction so they can invade their prey or other food Some fungi clearly possess tactile- or contact-sensing capabilities that allow looking for nutrients. If you have ever seen a well-trained bird dog look for a downed bird, you get the idea. The dog circles until its nose finds the bird open question. It is known that some send out filaments as if they were scouts What drives soil fungi in the direction of particular nutrients is still an

other and transporting nutrients back to the base of the fungus. All the while, other strands "scout" for more food to attack. Nutrients are held inside cell walls, preventing them from leaching away. gesting the material, often combining one nutrient source material with ana source is found, fungal strands head over to the area and literally settle in, di-For the gardener it is sufficient to know that fungi can find nutrients. When

### Fungi and symbiosis

sults in the formation of lichens. In this symbiotic relationship, the fungus gets Soil fungi also form two extremely important mutual relationships with plants. The first is the association of certain fungi with green algae, which re-



A small branch protruding from the main thallus of a tree lichen, 140×.

Image copyright Dennis Kunkel Microscopy, Inv

the lichens grow. This creates minerals and nutrients for soil, soil strands make up the thallus, or body, of the lichen, in which the food from the alga, which utilizes its photosynthetic powers while Chemicals secreted by the fungus break down the rock and wood up the fungal pon which pair lives. microbes

associations between plant roots and fungi. In return for exudates turn, cannot live without the plant's exudates. It is a wonderful world, indeed. back to the plant. The plant becomes dependent on the fungi, and the fungi, in roots, mycorrhizal fungi seek out water and nutrients and then bring them The second are mycorrhizae (from the Greek for "fungus-root"), symbiotic Mycorrhizae have been known since 1885, when German scientist Albert from plant

grew faster and much larger than those in the sterilized soil. Yet it was only in ilized soil inoculated with forest fungi. The seedlings in the inoculated soil into the agricultural industry's lexicon, much less the home gardener's. plural, mycorrhizae) and mycorrhizal (its associated adjective) star the 1990s that the terms mycorrhiza (the symbiotic root-fungus relationship; Bernhard Frank compared pines grown in sterilized soil to those grown in sterted to creep

once mentioned them out of sheer ignorance, a state shared with most gardenworse, we learned that these relationships began some 450 million years ago, ers. We now know the extent of our ignorance: at least 90% of all with terrestrial plant evolution: plants started growing on the earth's surface mycorrhizae, and the percentage is probably 95% and even higher. What is orrhizal fungi, plants do not obtain the quantities and kinds of nutrients only after fungi entered into relationships with aquatic plants. Without mycneeded to perform at their best; we must alter our gardening practi to kill these crucial beneficial fungi. had written a popular garden column every week for 30 years and never We're the first to admit that we were blindsided by the subjectces so as not plants form -and one of

fragile. Too much compaction of soil, and fungal tubes are crushed and the physical alteration of the soil (rototilling, double digging) destroy fungal hyfungi killed. Clearly fungicides but also pesticides, inorganic fertilizer, and phae. Chemicals do so by sucking the cytoplasm out of the fungal even decrease when fungi are exposed to air pollution, particularly that contilling simply breaks up the hyphae. The fruiting bodies of mycorrhizal fungi taining nitrogenous substances. Perhaps gardeners lack appreciation for fungi because all soil fungi are very body. Roto-

close to the surface of roots and can form webs around them. Ectomycorrhizal fungi associate with hardwoods and conifers. The second are endomycorrhizal Mycorrhizal fungi are of two kinds. The first, ectomycorrhizal fungi, grow



Ectomycorrhizal fungi forming a dense white net around roots. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.



Endomycorrhizal fungi penetrating roots.
Courtesy L. H. Rhodes. Reprinted, with permission, from http://www.apsnet.org/, American Phytopathological Society, St. Paul, Minnesota.

grasses, shrubs, perennials, and softwood trees. into the soil. Endomycorrhizal fungi are preferred by most vegetables, annuals, fungi. These actually penetrate and grow inside roots as well as extend outward

area of plant roots; the effective surface area of a tree's roots, for example, can be increased a fantastic 700 to 1000 times by the association. Mycorrhizal fungi places the plant roots alone could not access. These fungi are not lone miners, ergy to extend out into the soil, pumping moisture and mining nutrients from get the carbohydrates they need from the host plant's exudates and use that enthe roots of different plants, not only the one from which they started. It is either. They form intricate webs and sometimes carry water and nutrients to strange to think of a mycorrhizal fungus in association with one plant helping Both types of mycorrhizal fungi can extend the reach as well as the surface

others at the same time, but this occurs.

seems to be a major function of many mycorrhizal fungi; the acids produced phosphorus back to the host plant. Mycorrhizal fungi also free up copper, calby mycorrhizal fungi can unlock, retrieve, and transport chemically locked-up cium, magnesium, zinc, and iron for plant use. As always, any nutrient compounds not delivered to the plant roots are locked up in the fungi and are re-Finding and bringing back the phosphorus that is so critical to plants

leased when the fungi die and are decayed.

## Pathogenic and parasitic fungi

spp.), and white rusts (Albugo spp.). downy mildew (Plasmopara spp., Sclerophthora spp.), root rots eases on wheat, oats, rye, fruits, and pines. More common garden problems are fungi, for example, impact the flowers of cereal grains. Rust fungi cause dislong; the topic fills many books and is beyond the scope of this The list of fungal pathogens impacting agricultural and horticultural crops is some of their pathogenic and parasitic fungal cousins from invading the plant. leaves produce exudates that attract bacteria and fungi as well); this prevents ten in conjunction with bacteria, around roots (and even on leaf surfaces, as Beneficial fungi compete for nutrients and form protective webs and nets, of-(Phytophthora one. Smut

stems, and flowers? Most powdery mildew fungi produce airborne spores that a catch-all name for a group of fungi that infects different plants with the same results, an unsightly gray or white powdery fungal growth that covers leaves, Be there a gardener who has not encountered botrytis or powdery mildew,

Gray mold fungus (Botrytis cinerea) attacking a strawberry plant. Photograph by Scott Bauer, USDA-ARS.



survive for a decade or more in dormant stages. It enters the plant through hosts in your yard. How about fusarium wilt on tomatoes, the first thing to sus-80F (15 and 27C) and high humidity, these spores germinate and infect their do not require free water to germinate. Given temperatures between 60 and roots and invades its water distribution network. Further testament to the pect when a tomato's leaves start to yellow from the bottom of the plant up? It death—a tiny fungus taking down towering oaks. The fungal activity decays a power of fungi is Armillaria mellea (oak root fungus), which causes sudden oak tree's lignin and cellulose to such an extent that the tree dies. caused by Fusarium oxysporum f. sp. lycopersici, a soil-borne fungus that can

plants, including stomata (the openings on leaf surfaces that allow tough-to-digest lignin, it shouldn't surprise any gardener that some fungi can dissolve the cuticle and cell walls of the plant it is attacking. If you think this is some fungi can penetrate granite in search of food. difficult, think about the fungi that penetrate bathroom tile, and know that Pathogenic and parasitic fungi make use of various entry points into and wounds. And, of course, with all this talk of enzymes decaying plants to

trition at the expense of living plants. This is not our purposerealize that soil is loaded with fungi, a concept most gardeners readily grasp because of direct experience. This entire book could be filled with descriptions of fungi that get their nu--only that you

## Functional overlap with bacteria

It should be obvious by now that in a healthy soil food web, fungi and bacteria shoulder much the same work and share many of the same functions. Like bacteria, some fungi produce vitamins and antibiotics that kill pathogens in the soil as well as in the human body. Remember penicillin, the most famous fungus-turned-antibiotic of all? In 1928, when English bacteriologist Alexander inated a petri dish full of Staphylococcus bacteria. It ruined his experiment, but bacteria were found growing near the fungus, and the world of medicine returned to his lab after his vacation, he found a fungus had contam-

as well as causing diseases. As well, their ability to impact soil pH makes them never been the Fungi, like bacteria, play crucial roles in the soil food web as decomposers, cyclers, soil structure builders, and beneficial symbionts, preventing

an important tool for gardening with the soil food web.

### Chapter 5

# Algae and Slime Molds

quences on how the play unfolds. when one or another character is removed, it may have significant consepoint that the soil food web is a community of organisms playing LGAE AND SLIME MOLDS are not related; we merely group them together because, while they have roles in soil food webs, they don't affect gardeners. That said, we hope we have already made the out a drama; generally

#### Algae

quire a film of water to survive. in soil, on or near the surface (where sunlight is available), not that grow in hot deserts and at the frozen poles—though even these still re-While most algae require very moist conditions, it is surprising t three kinds of algae: marine, freshwater, and terrestrial, the latter often living river, or lake, at the beach, or, if not there, on the glass of a fish tank? There are isms, including seaweeds and even giant kelp. Who hasn't seen algae in a pond, Algae are broadly defined as single-celled or thread-like photosynthetic organo find some near roots.

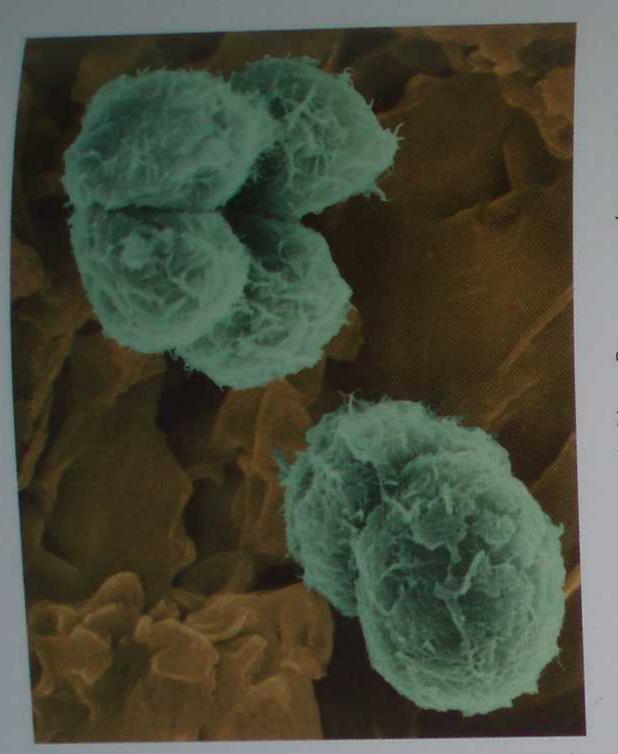
that decays and disappears after the organism dies, leaving behind, in huge The cell walls of diatoms are composed of silica covered with an organic skin atoms, a form of algae, do contain cellulose, and in this way they are and, unlike plants, they have no true roots, leaves, or stems and d like plants, are primary producers, not dependent on the soil's organic matter ing they take energy from the sun and produce their own food. Indeed algae, numbers, the silica skeletons that make up diatomaceous earth, a product favascular (water- and food-conducting) system. The cell walls of all fungi. Moreover, algae lack the specialization that characterizes higher plants, or other members of the soil food web for their food needs as are bacteria and miliar to many gardeners. thought of as primitive plants because they are photoautotrophic, mean-Although algae are closely related to bacteria on the tree of life, lon't have a they are ofbut the di-

Most gardeners associate algae with bodies of water, not the raised bed or

of life by providing necessary organic matter when there was no other. ter to form early soils. In this important way, algae helped start the succession surfaces and, when they died, combining with weathered rock, and air, and waphyta). At one time algae served as pioneer organisms, growing on moist rock soil may contain anywhere from 10,000 to 100,000 cells of green algae (phylum gae require not only light but a film of water in order to survive. A teaspoon of Chlorophyta), yellow-green algae (Xanthophyta), and diatoms (Bacillariolawn, yet there you will find them if there is enough moisture--terrestrial al-



Diatom skeletons, 445x. Image copyright Dennis Kunkel Microscopy, Inc.



Green algae growing on the bark of a tree, 40×. Image copyright Dennis Kunkel Microscopy, Inc.

of rock surfaces caused by lichens—the symbiotic relationship between certain the dead algae combine, producing soil eventually. This is not unlike the decay bolic functions. This causes rock to weatheralgae and fungi. The fungus provides a humid and somewhat protected enviweathering brought about by biological activity. Resultant bits of minerals and their fungal partners, and the process of weathering is sped up food from the alga. In this relationship, the decay abilities of algae are aided by ronment in which the alga can live and, in return, receives photosynthesized can get nitrogen from the water in which they grow. nonsymbiotically, similar to nitrogen-fixing bacteria. This is how rice plants the enzyme nitrogenase to fix nitrogen, either in a symbiotic relationship or Lichens contribute nitrogen to the soil, and blue-green algae (Cyanophyta) use Algae help to create soil by forming carbonic acids as part of their meta--a great example of chemical considerably.

sunlight, which can only penetrate a short distance into the soil. However, presence can also help to form air passageways in otherwise compacted soil. slimes—all sticky stuff—which help bind and aggregate soil particles. Their where they do exist in the soil, algae can excrete polysaccharides, And algae fit into some soil food webs as primary producers that are eaten by certain nematodes. In truth, the role of algae in gardening is minor because of their need for mucilage, and

#### Slime molds

damp, rotting wood, leaves, manure, lawn thatch, rotting mushrooms, and The slime molds are unusual-looking, amoeba-like organisms that inhabit other organic material. They spend most of their lives pursuing bacteria and yeast in the soil. The few hundred different kinds of slime molds are in many slime molds engulf food and digest it internally. "digest" their food externally and then bring the nutrients inside the organism, ways like fungi but largely differentiated by the way they eat. Whereas fungi

and Myxomycota (plasmodial slime molds)—have similar life cycles: they start out as spores and germinate into myxamoebae, amoeboid organisms that live in the soil and ingest bacteria, fungi spores, and small protozoa, mouths mandibles designed to scoop up the soft mold and cram it into their that have the server in the se nutrients they contain and preventing them from leaching out. They them selves are for I for the them The two groups of slime molds—Dictyosteliomycota (cellular slime molds) locking up the

At some point, for no apparent reason, individual myxamoebae swarm

way. The species of one common plasmodial slime mold genus, *Physarum*, are usually about 1 inch (2.5 centimeter) thick and can grow to 1 foot (30 centimeshades of tan, yellow, pink, or red, and are actually quite attractive in their own a dollop of jelly, or, in some cases, vomit. These masses are of various sizes, in ters) or more wide. together; up to 125,000 or so form a mass that looks something like a big slug,



from http://www.apsnet.org/, American Phytopathological Society, St. Paul, Minnesota. Myxamoebae stage of slime mold on grass. Courtesy B. Clarke. Reprinted, with permission,



Slime mold swarms can look like dog vomit. Photograph by Tom Volk, University of Wisconsin La Crosse, www.TomVolkFungi.net.

does so at an average speed of 1 millimeter per hour, engulfing food as it goes. ium (or multinucleated mass of cytoplasm) emerges from the Even more amazingly, if you cut a plasmodium in half or even If a source of organic dead matter is put near a plasmodium, moves over leaves, grass, driveways, logs, mulch and anything else in its way. It The individual cells in the mass lose their walls, and the resulting plasmod-, it will go to it. soil and slowly in quarters, the

parts will come together again. All sorts of theories have been put forward to explain why these organisms

gether. There is, after all, something to be said for strength in numbers. What into a growing mass. mix, the attraction increases until literal swarms of myxamoebae congregate and more organisms gather on the path, each adding its chemical slime to the it travels, and take the same trail, adding their exudates to the path. As more molds come in contact with this "slime sheet," not unlike that left by a slug as in its wake as it travels, presumably on a path toward nutrients. Other slime is known is that each individual myxamoeba leaves a bit of chemical attractant swarm. It may be that when food becomes scarce, there is a need to work to-

structure, or sporangium. This unusual-looking body is of a distinctive shape you can grow in your gardens. and white and form a beautiful net of colors that really is as pretty as anything top of which spores are formed. Sporangia come in yellow, blue, red, brown, for each slime mold species. Some sporangia are like tiny raised towers, in the Eventually the plasmodium finds an appropriate spot and forms a fruiting

the slime each individual myxamoeba creates helps bind soil Although these organisms don't play a major role in the garden, when a garconditions become unfavorable, plasmodia dry up and turn to powdery dust. dener comes across a slime mold, he or she remembers it. From the soil food web perspective, slime molds help cyc le nutrients, and particles. When

### Chapter 6 Protozoo

ber that protozoa are single-celled organisms with a nucleus, which makes a group of non-algal, non-fungal, animal-like unicellular organisms, across karya. Protozoa (which term we use descriptively in this book, as shorthand for them eukaryotic and therefore, along with fungi, members of the domain Euseveral kingdoms-but don't get us started!) are almost always heterotrophs, meaning they cannot make their own food. Instead, they obtain their nutrients extent, other protozoa. by ingesting bacteria, primarily, but also the occasional fungus and, to a lesser OST GARDENERS first poked and prodded protozoa as part of a biology lab assignment, which invariably involved identifying sketching cell parts of a paramecium; they may therefore rememand

protozoa are considerably larger than bacteria, 5 to 500 micrometers versus 1 organisms, 500 micrometers is pretty largeto 4 micrometers. This may still seem small to you, but in the scheme of microconditions a paramecium, at least in water, is visible to the human eye. You still have to look very carefully and certainly will not be able to differentiate any of those internal or external features you were told to label in school, but without a microscope you can see them flitting around. Through an electron microscope, unseen detail is observable. Paramecia are still the favorite microbe. That's because these and other soil -so large that under ideal lighting

terium. By way of comparison, if a single bacterium was the size of a pea, a paramecium would be as large as a watermelon. This is why bacteria can hide into. Another way to make the comparison is to go back to that same teaspoon of good soil, with its billion-count bacteria—and "only" several thousand from most protozoa in soil pores that are too small for the protozoa to Protozoa are something to stay away from if you are as small as a bac-

youthful hope you may have that they only live in pond water, a majority of them live in the soil; however, all do require moisture to lead an active life. Over 60,000 kinds of protozoa are known and, contrary to any residual

paramecium as seen through an electron microscope, 130x. Image copyright Dennis Kunkel Microscopy, Inc.



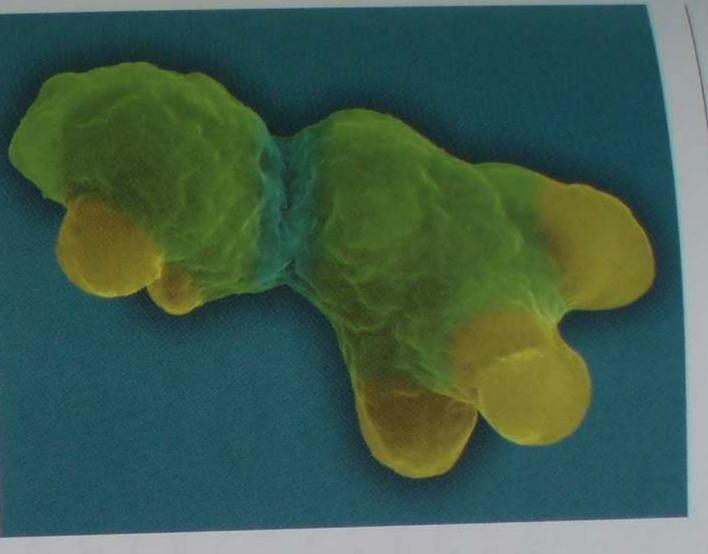
and then some—is in order. Given the crucial role protozoa play, a quick review of some school biology

## Amoebae, ciliates, and flagellates

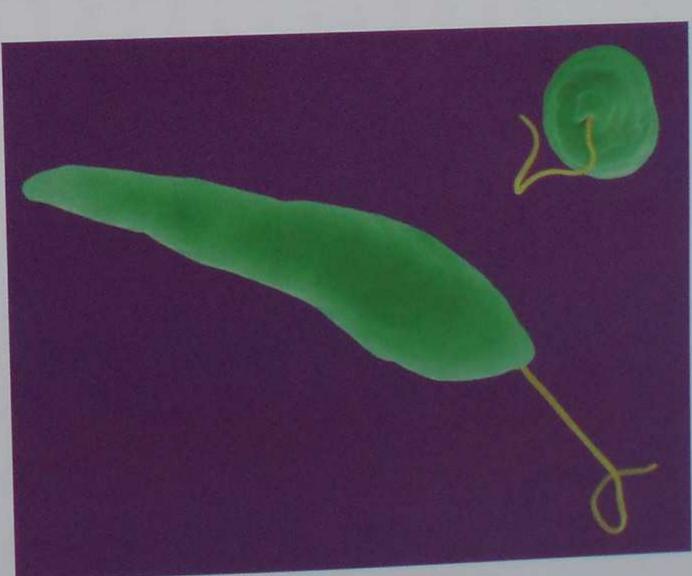
sequently expelled. digestive enzymes. The entire vesicle is then absorbed, and waste products subof two types. The first has a shell-like exoskeleton and five rounding them and engulfing them in gas bubbles, into which are transmitted they weren't so transparent. Amoebae lack a mouth and ingest bacteria by surrelatively large microorganisms, and many would be as visible as paramecia if The other class lacks any shell or predefined pseudopodia; these amoebae are (think of a bowling or golf glove), through which the pseudopodia can appear. false appendages called pseudopodia ("false feet"). Pseudopods themselves are by pouring their cytoplasm—the soup with all its life partsconstantly on the move, a feat (if you will pardon the poor pun) accomplished animals with amorphous forms most will remember as amoebae. These are Protozoa come in three basic "models." First are the pseudopods, single-celled predefined holes into one or more

are covered with rows of hairs that beat like the slaves' oars on a Roman galley, they can be ingested. The familiar paramecium is a ciliate protozoan. their amoeboid cousins but still much larger than their bacterial prey. Ciliates propelling the organism to food—or away from enemies. In addition, these Next in size are the ciliates. These protozoa are considerably smaller than create currents that bring bacteria into the ciliate's mouth region, so

long, whip-like hairs, or flagella, allow them to move about in The third and smallest type of protozoa are the flagellates. Their one or two search of food.



An electron microscope photograph of an amoeba, 700×. Image copyright Dennis Kunkel Microscopy, Inc.



Euglena, 440x. Image copyright Dennis Kunkel Microscopy, Inc.

A few flagellates, like euglena (the "classic" freshwater flagellates of pond most, however, are heterotrophic, obtaining nutrients from eating and digestwater), produce their own food via photosynthesis and are thus autotrophs; ing other organisms in the soil.

## More symbiotic relationships

tionships, particularly with bacteria, to such an extent that such associations appear to be the norm rather than the exception. A classic example is that of the flagellates residing in the guts of termites, which digest the wood fibers the termite eats. We now know that the relationship is actually a three-way one. Electron microscopy reveals working bacteria in the gut of the termite as well; these fix nitrogen from the atmosphere for the flagellates. Not often do you find a triple symbiotic relationship, though surely more will be discovered as As so many of the soil food web organisms do, protozoa form symbiotic relaexploration courtesy of the electron microscope continues.

Lots of ciliates, too, enter into symbiotic relationships with bacteria. Some ciliates live in sand and "farm" bacteria colonies; and it is the methane-generation bacteria. ating bacteria inside ciliates that are responsible, in part, for the methane g that develops in some ciliates as anaerobic respiration takes place.

## Population-control police

Protozoa are attracted to and enter into an area where there is a good supply of bacteria in a pretty consistent progression (on average, a protozoan can eat crobes; these can move into small spaces in the soil, places where the large pro-10,000 bacteria a day). First come the flagellates, the smallest of these mirive on the scene, the still-large population of bacteria provides plenty of tozoa cannot and where bacteria are plentiful. Even after the larger ciliates arsustenance for both the original flagellates and the newer ciliates. Finally, amoebae move through in search of bacterial prey (and also smaller protozoa). The combined pressure on the bacterial population becomes so bers start to diminish. As readily available bacteria become harder to find, the larger ciliates and amoebae start to eat more of the smaller ciliates and flagellates. This reduces the population of ciliates and flagellates which, in turn, allows the populations of bacteria to stabilize and return to a level that maintains the soil food web balance. great, num-

and it lacks the oxygen that they require. Another reason is that the bacteria are tozoa are restricted by bacterial slime; this film is hard for them smaller and able to hide in tiny soil pores. Why aren't all the bacteria consumed by protozoa? One reason is that proto penetrate,

results in increases in the bacterial populations upon which they surviving bacteria. Not having to compete all the time for food means they can curs because fewer bacteria means less competition for nutrients among the divide well fed. Likewise their progeny will have something to eat so they all the bacteria and fungi they need to eat. can multiply as well. If protozoa can keep their own numbers in check, they have It seems counterintuitive that increasing protozoa populations most often prey. This oc-

search for sustenance, some protozoa attack nematodes. Others tode populations by competing for the same, limited food resour protozoa and fungi. This also helps keep bad-guy nematode populations from It is not just populations of bacteria that protozoa keep in balance. In their reduce nemaces, i.e., other

in a cyst Hamiltonian and dividing and go dormant, encasing themselves in a cyst. How long protozoa can survive in this state varies from species to species; some can withstand an extended dry spell of several years. Protozoa need moisture to live, travel, and reproduce, and hydroscopic provides it, under normal soil conditions. If things dry that thin film of water left on the surfaces of soil particles and aggreup, however, This tech-

pique ensures the survival of both the protozoa and the plants that benefit from the nitrogen and other nutrients released by their activity.

#### Mineralizers

Of critical importance to the workings of the soil food web are the waste products produced when protozoa ingest bacteria or fungi. These wastes contain carbon and other nutritional compounds that had been immobilized but are now once again mineralized and made available to plants. pounds, including ammonium (NH<sub>4</sub><sup>+</sup>), are among them. If nitrogen-fixing have good populations), free ammonium is converted into nitrates. If not, the bacteria are present (remember, these usually require a pH of 7 or above to Nitrogen com-

nitrogen remains in ammonium form. system. Our premise is that by interfering with or destroying the soil food web. much as 80% of the nitrogen a plant needs comes from the wastes produced by stead of an enjoyable hobby. If you are not convinced, then consider that as bacteria- and fungi-eating protozoa. Since bacteria and fungi are attracted by plant exudates to the rhizosphere, and that is where protozoa consume them a huge source of plant food is delivered, right around the roots. Mineralization of nutrients is crucial to the survival of plants in a natural gardener has to step in and do extra work, making gardening a chore in-

## Other soil food web functions

ingesting small particles of organic matter. These are then broken up into All protozoa participate to some degree in the decay process by inadvertently smaller pieces if not totally digested and become available to bacteria and fungi in the waste stream. And other soil food web members rely on protozoa as one of their food sources—another reminder that it is a soil food web, not chain, with which we are dealing. Certain nematodes, for example, are dependent on better ingest them. Worms too rely on healthy populations of protozoa. Wit out protozoa in the area, gardens are devoid of worms. Similarly, many n their food source and have developed specialized mouthparts

croarthropods require a healthy dose of protozoa to thrive. healthy food web these are kept in check by other, cannibalistic protozoa. So a certain degree protozoa serve as a food source for themselveseven the worst of them, crucial characters in a healthy soil food web. Finally, not all protozoa are beneficial. Several kinds eat roots, but in

### Chapter 7 Nematodes

showstopping 30 feet (9 meters). Fortunately, this nematode lives in the plaare difficult to see without a microscope. When you can see them with the centa of sperm whales, not in soil. cause the largest known nematode, Placentonema gigantissima, can grow to a naked eye, they usually look like moving human hairs. We say "usually" beters (versus 0.5 millimeter for a decent-sized protozoan). Still, most nematodes protozoa, with lengths averaging 2 millimeters and diameters of 50 micromedescriptor for these microorganisms. Nematodes are considerably larger than protozoa, mineralize nutrients contained in bacteria and fungi. Their name is derived from the Greek nema, which means "thread," an apt EMATODES are nonsegmented, blind roundworms that, along with

about them save the parasitic ones that damage roots. million species in total. They are everywhere, yet most gardeners know little form of animal life next to the arthropods. Over 20,000 species of nematodes have been identified thus far, and scientists suggest there may be as many as l These fascinating roundworms are actually the second most dominant

eating nematodes, making the total number between 40 to 50 nematodes. The bacteria-eating nematodes, 20 fungal feeders, and a few predatory and plantavailability of the food sources they require. number of fungi- versus bacteria-eating nematodes is directly related to the Our teaspoon of good soil teeming with microbial life averages about 20

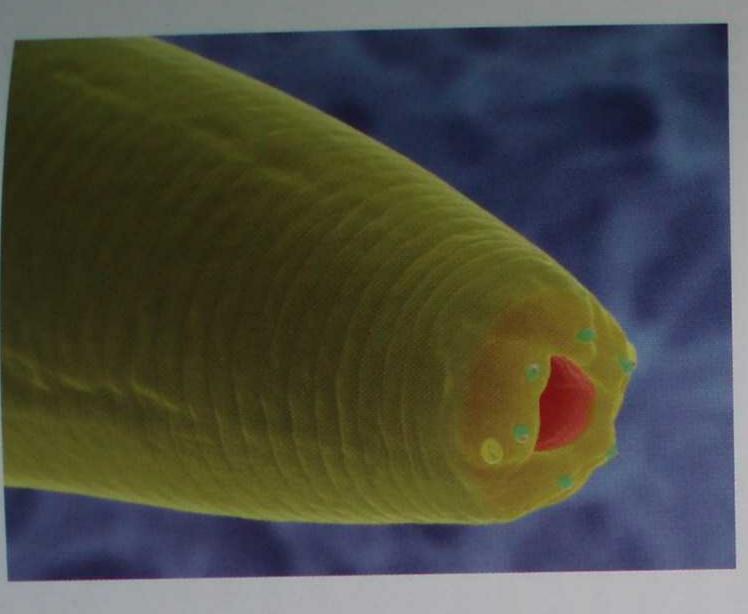
#### Picky eaters

that runs from the mouth to the anus, which is located in their tail end. Nema-Nematodes are major consumers in the soil. All have a long alimentary tract chemical attack and provides lightweight structural support. For the gardener, tode skin is actually a cuticle; it protects the animal from both physical and developed specialized mouthparts to allow them to attack and get at their own the best way to classify them is by their eating habits: various nematodes have particular brand of prey.

Obviously, nematodes that eat roots do not help the crop in question. into the root to feed. Herbivore (plant-eating) nematodes can create lesions in the root as well as cysts and large bulges that gardeners refer to as root knots. (that is, they feed on the root surface), while others are endoparasitic, entering cell walls with ease. Some of these root-eating nematodes are ectoparasitic parasites usually have needle-like stylets that enable them to puncture Let's start with the nematodes that eat living plant material. These plant

smaller microbes' bodies, making them once again plant-available. tozoa, both these types of nematodes mineralize the nutrients contained in the the chitin cell walls of fungal hyphae. Like their fellow fertilizer-spreaders, progivores: they eat fungi. This type of nematode also has stylets, for puncturing can consume multitudes of tiny bacteria in an hour. Other nematodes are funmouthpart is usually a hollow tube. A bacteria-eating nematode so equipped Next are bacterivores, nematodes that eat bacteria. Here the specialized

thus preventing overgrazing of bacteria and fungi and keeping populations of use was to control slugs). Predatory nematodes eat other nematodes as well, invertebrates such as slugs (the first beneficial nematodes sold for gardening other small members of the soil food web-Predator nematodes feed on protozoa, algae (including diatoms), and -grubs, weevils, wasps, even small



An SEM image of the stylet end of a fungieating nematode. Image copyright Dennis Kunkel Microscopy, Inc.



A typical predatory nematode. Photograph by Bruce Jaffee, UC Davis.

some of the decay that occurs in and on the soil. creased decay of organic litter. Thus nematodes are indirectly responsible for such an extent that fungal populations are increased, to a point, resulting in ining on bacteria, fungal grazing by nematodes frees up fungal food resources to destructive nematodes, primarily the herbivores, down. As with protozoa graz-

sponsible for the decomposition of organic matter. merest fungus spore. Some even ingest organic matter and so are directly re-Other nematodes are omnivores, eating any and all of the above, to the

## Mineralization and other tricks

predominately in ammonium form (that is, it is not converted to nitrate). nium form. Again, if the populations of nitrogen-fixing bacteria in the area are low (as they will be when the pH is below 7), the mineralized nitrogen remains more of the previously immobilized nitrogen into the rhizosphere, in ammothan protozoa do; those that eat fungi and bacteria, therefore, release even bacterivores and fungivores) do for gardeners. Nematodes need less nitrogen Arguably, mineralization is the most important thing nematodes (at least the

the flow of nitrogen available to plants is greatly diminished. nutrients. Unable to search for food, they either die off or move elsewhere, and compacted. Either of these conditions will block nematodes from searching for their numbers will be reduced if the soil is of the wrong texture or if it is too fungi, and protozoa, they require more porous soils in which But here's something new. Because nematodes are bigger than bacteria, to travel, and

porting bacteria to areas far from their origin. This is because bacteria attach its way through the soil in search of food. Since bacteria themselves have extremely low mobility in the soil, this is a great advantage to them: they can to the skin of nematodes and are spread to other areas as the nematode makes tion in a new area. Fungi, too, can hitch a ride on a nematode. Often this is bethe long run occasionally eats the progeny of its fare and increases mineralizaness while it is being eaten alive. cause the hapless nematode is prey to a fungus attack and goes about its busi-"taxi" to new food sources. It also may be said to help the nematode, who in Not just these escapees but all nematodes inadvertently play a role in trans-

They may have specialized mouthparts, but they do not have eyes. How does a blind nematode survive in the soil or anywhere else for that matter? matodes can sense extremely minute variations in soil temperatures. They Nematodes have developed some interesting ways to locate food in the soil. what temperatures particular food sources live in; they will move Some ne-



A fungal spore and tube has entered the side of this nematode and is heading toward its retracted stylet. Photograph by Bruce Jaffee, UC Davis.

travel along it until they bump into their preferred food. through soil until they find the right temperature gradient and continue to

in its rings, attracts nematodes with a chemical. Clearly, there are disadvantheir prey and attacking. Our favorite fungus, the one that captures nematodes Once they are on the scent, they act like heat-seeking missiles, locking in on tages to this method of finding food. Others find food by sensing particular chemicals associated with them.

like each and every other organism in the soil food web, deserve (and have) their own books. In the end, nematodes are incredibly diverse and interesting animals that,

### Chapter 8 Arthropods

and even protozoa is greater. size, the arthropods do not lead in terms of biomass: the biomass of nematodes living organisms are arthropods. Still, for all their numbers and their larger tion: arthropods rule the world. Somewhere around three-fourths of all VEN IF YOU DIDN'T KNOW what they were called, you've seen and know lots of arthropods: flies, beetles, and spiders, for example. No exaggera-

mented limbs and segmented bodies, but you get the idea). iar examples of marine arthropods; their shells are chitin. As with the cuticleskeleton made from chitin, the same material that makes up the walls of funjointed legs and segmented bodies, all arthropods have in common an exogus cells. You are familiar with the shells of lobsters, shrimps, and crabs, familstructural frame (an internal skeleton is considerably more complicated and skin of nematodes, this exoskeleton provides protection an heavier). As arthropods grow, they shed their exoskeleton and grow a new, Arthropod is Greek for "segmented feet" (actually, arthropods d a lightweight In addition to possess seg-

starting with a head, or cephalum; then a chest, or thorax; and different form for their adult lives. A caterpillar, to use one famous example, is the early part of their lives in a larval form; and then metamorphose into a very men. Most arthropods live life in three stages. They start as eggs; hatch and live again. Many arthropods live all three stages in or on the soil, but many reside the larval stage of a butterfly, the adult who will lay eggs to start the cycle over there during just one or two. Of course, any gardener who has worms fully appreciates that it takes only one stage to damage Arthropods usually have three (but may have only two) a plant. body segments, finally an abdofended off cut-

scope to see. Those that can be seen only under magnification measure a couple of yards across to tiny mites that require a powerful micromicroarthropods; those that can be seen easily without the aid or microscope are known as macroarthropods. Arthropods range in size from the humongous Alaskan king crabs that are classified as of a hand lens

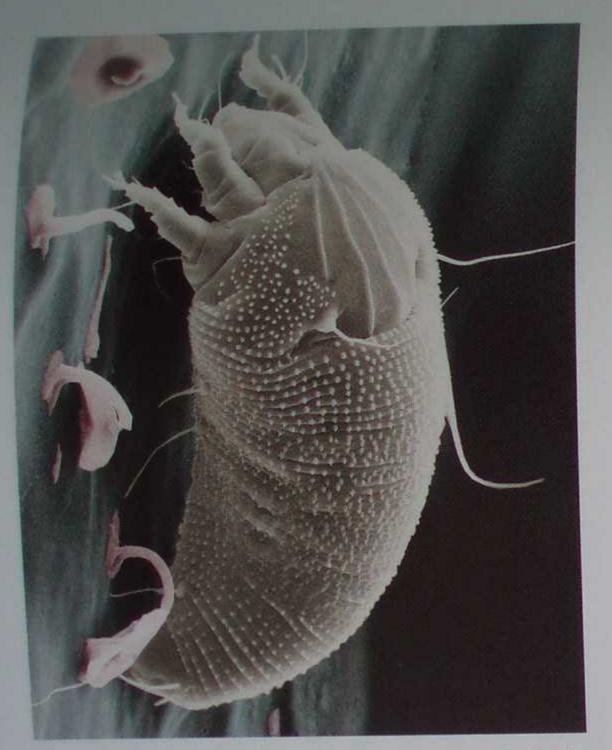
about the health of soils and the plants growing in them. presence or absence of certain of these key players can tell a gardener much are important to the community as shredders, predators, and soil aerators. The Besides being food for other members of the soil food web, soil arthropods

### Classifying arthropods

with information? There are just too many kinds of soil-dwelling arthropods to show you the readers how to use the soil food web without overwhelming you arthropods: the phylum Arthropoda is by far the largest in the animal kingscientific nomenclature as well. Bear with us for the little we do use. describe them all, or even come close to doing so, and frankly, there is too much for the most part, not many more. Part of the problem is that there are too many know a few of the popular and unpopular ones that inhabit local gardens, but arthropods together as simply "insects" or "bugs." Any given gardener may Without more than a passing interest in them, most gardeners lump all the -so large that it presents a real challenge for us: how can we the authors

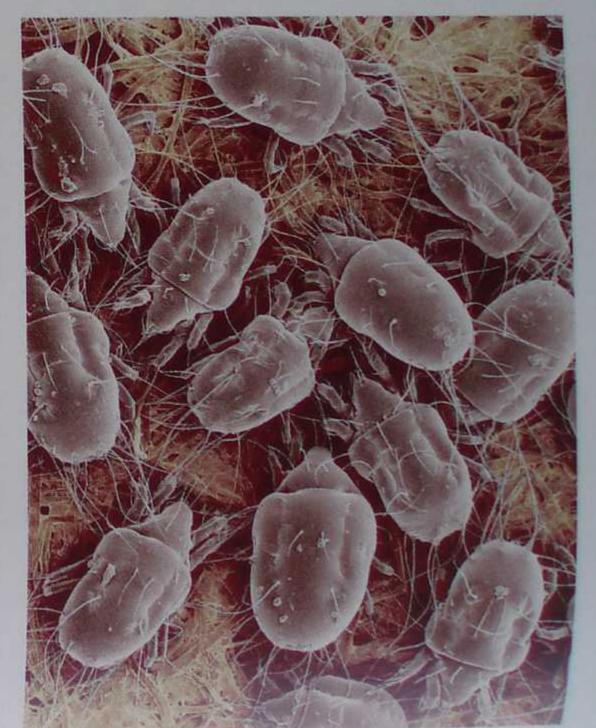
of the phylum Arthropoda, whose members have the greatest impact on the have not learned the alphabet soup of words scientists use to classify members soil food web. Here, we list the classes, as a start: Latin or Greek, is truly the only way to accurately identify a plant; but most Gardeners are agreed that using scientific names, usually derived from

Class Arachnida: spiders, scorpions, mites, ticks, and daddy longlegs



A rust mite (Aceria anthocoptes), 700×. Photograph by Eric Erbe, digital color by Christopher Pooley, USDA-ARS

Dust mites (Tyrophagus putrescentiae), 100×.
Photograph by Eric Erbe, digital color by Christopher Pooley, USDA-ARS.





Millipede foraging on soil. Photograph by Frank Peairs, Gillette Entomology Club.



Female Mormon cricket. Photograph by Michael Thompson, USDA-ARS.

Class Chilopoda: centipedes Class Diplopoda: millipedes

Class Insecta: springtails, silverfish, termites, mayflies, dragonflies, damselhoppers, katydids, crickets, rock crawlers, web spinners, zorapterans, flies, stoneflies, earwigs, mantids, cockroaches, walking sticks, grasspsocids, book lice, bark lice, chewing lice, sucking lice, scorpion flies, beetles, sawflies, bees, wasps, and ants fleas, thrips, lacewings, ant lions, true bugs, moths, butterflies, flies,

Class Malacostraca: sow bugs and pill bugs

sands of different kinds of insects live in and on the soil and plants, as few garof this one class, the order Coleoptera (beetles), as you go about deners need to be reminded. Surely you have seen representatives of one order You are already familiar with many members of the class Insecta. Tens of thouyour garden-



Formosan subterranean termites feeding on spruce and birch wood. Photograph by Peggy Greb, USDA-ARS.



The predatory beetle *Thanasimus* formicarius feeds on the pine shoot beetle, a serious pest of pines. Photograph by Scott Bauer, USDA-ARS.

ing chores: with approximately 290,000 species described, it would be hard to miss them.

### Soil food web functions

ating smaller pieces. As a result, fungal and bacterial activity is increased beshredders. They chew up organic matter in their constant quest for food, cre-Most soil arthropods, particularly those that reside on the soil surface, are an easier avenue of attack. cause shredding exposes surfaces on organic litter that give bacteria and fungi

to their bodies or in the debris they push or carry about. Since most arthropods are food for still larger animals, the total distances microbes can be moved be truly great. Microbial activity is increased if the taxi takes its fare to a good arthropods, mites and springtails, are alone responsible for recycling up to 30% (consider a bacteria colony eaten by a grub that is then ingested by a robin) can food source. Still, it is the shredding that is most important. Two common of the leaves and woody debris deposited on a temperate zone forest floor. As they shred and move about, arthropods also taxi microbial life attached

ing sources of organic nutrients. And even if the supply of available organic matter is abundant enough to satisfy any reasonable arthropod, some (mole crickets, root maggots, cicadas) subsist on roots anyhow. Fungus gnat larvae, for example, hatch and immediately start eating root hairs, eventually eating their way into the roots and stem to the great detriment of the invaded plant. In the face of insufficient dead organic matter, arthropods often attack liv-

Dark-winged fungus gnat larvae.

Photograph by Whitney Cranshaw,
Gillette Entomology Club.



survive; by removing their fellows, these predator arthropods ma other arthropods to fill the emptied niche, helping to create complete digestion of soil matter. Finally, in much the same way protozoa and nematodes do, some arthropods eat fungi, others bacteria, but this time releasing nutrients on a larger scale, befitting their greater numbers and size. Still other arthropods eat other members of the soil food web in order to ke room for

soil. A surprising number, however, live at least part-time below their waste products also add organic matter. face. As these arthropods go about their business, they mix and aerate soil; Many arthropods carry out their daily routines only on the s urface of the the soil sur-

#### Mites

are mites, of which there are two basic kinds in the soil. The first, oribatid Several soil arthropods play dominant roles in the soil food web. Among them mites, actually have the highest populations of any soil arthropod, with up to several hundred thousand per square yard; a primary reason for this is that the female oribatid mite doesn't need a mate to lay fertilized eggs. These important mites are 0.2 to 1 millimeter long. Oribatid mites inhabit soil surfaces, particularly litter debris but also live plants, including mosses, and lichens. Some oribatid mites feed on live nematodes, others on dead springtails. Most, however, eat fungi and algae and decaying plant matter and, because of the are vulnerable when they are born and in the later nymph stage, as adults their bers, are major recyclers and decomposers in the soil food web. Although they by ants, beetles, and larger animals, like salamanders. exoskeletons make these mites impervious to most forms of predation except ir large num-

soil. Their populations (and there can be several hundred gamasid mites in a Their name of soil mites, gamasid mites, are major predators in the

square yard of soil) are dependent on the availability of their food source, the presence and numbers of gamasid mites are considered useful tools in dewhich happens to be most any other arthropod that grazes in the soil. As such, and that usually means a healthy soil food web. Soft-bodied for an arthropod, termining soil health: if there are lots of them, their fellows must be plentiful, themselves prey to all sorts of other arthropods. they fare less well than oribatid mites against predators, however, and are

they are often confused—all mites, like spiders, have eight legs): they inject uid the mites then suck. Gamasids subsist on collembolans, insect larvae, and their victims with enzymes that dissolve their innards and turn them into a liqmatodes and fungi. insect eggs. Those that live in the soil, as opposed to on its surface, also eat ne-Most gamasid mites act in a manner reminiscent of spiders (with whom

#### Springtails

among the more active insects in the soil. You can expect to find up to 100 of The springtails (Collembola spp.), another important group of arthropods, are ing from 0.2 to 2 millimeters long, they are often seen as little critters that jump these "soil fleas" into the air when the top layer of soil debris is disturbed. per square inch in soils with enough organic material. Rang-

folds beneath them but is capable of being straightened in an instant (fluid pours into its base), propelling the animal up to a yard backward (hence their common name), out of harm's way. Springtails lack wings. Instead, they possess a forked tail, or furcula, that

several different kinds of environments. Those dwelling on the surface, for As with many members of the soil community, springtails have adapted to



Springtail showing the well-developed furcula that enables these animals to "jump" up to a meter away from predators. Photograph by Michael W. Davidson, Florida State University.

example, have well-developed furculas, eyes, long legs, and antennae, while those that dwell in deeper parts of the soil are blind or near blind and don't ing tails," are especially adapted to live among grasses. about in search of food. Some springtails, with even more developed "springneed a large furcula or long legs, as these would be hindrances in traveling

A springtail's diet consists of bacteria, fungi, and decaying organic matter.

Springtails are also sometimes consumers of nematodes and dead animal matter, and are themselves the favorite food of mites.

### Iermites and ants

ants, are not really related even though they look similar. Ants are related to Two other abundantly represented members of the soil food web, termites and legs, and a hard exoskeleton. Termites, by contrast, are blind bees and wasps; they usually have eyes, opaque bodies, a narrow waist, long helps decompose organic matter on the soil surface. translucent bodies and short legs. The shredding activity of both these insects and have soft,

it. Some of this organic matter is brought down into tunnels and burrows, they open up organic matter, making it easier for fungi and bacteria to get at where it becomes available to different populations of microbes. Indeed, it is the construction of tunnels and mounds that distinguish bot ants from other microarthropods. In constructing their homes, ants and termites mix surface and subsurface soil. In the case of ants, up to six tons of soil may be mixed a year. In tropical areas, the contribution ant and termite activity makes to the mixing of soil is greater than that of worms. Ant and termite tunnels obviously provide a way for air and water to get into the soil and for other animals to move about. Sometimes these tunnels make it to penetrate the soil; often, roots will follow tunnels. Termites eat mostly materials containing cellulose. As do other arthropods, h termites and easier for roots

material, and as these mounds are weathered and break apart, they alter the surface soil mix. Finally, termite hindguts contain anaerobic bacteria that produce methane, so much so that termites are a major contributor of this greenhouse gas to the atmosphere. lermite and ant mounds formed on the surface of soil contain subsurface

their presence ball. In sum, because of their huge numbers and the varied jobs is not only working but healthy and thriving. they perform,

### Chapter 9 Earthworms

7000 or so species of earthworms common to good garden soils. Technically earthworms are segmented worms, or oligochaetes, and grow anywhere from Eisenia, or Lumbricus, unfamiliar generic names for the most familiar of the not be familiar with pot worms unless they have tropical fish, for which live pot miliar pot worm (Enchytraeus doerjesi) found in forest soils (gardeners may garden earthworm, only a few millimeters to a few centimeters in length; they succeed and replace earthworms in acid forest soils, which earthworms shun. worms are a favorite food). Pot worms are much smaller than the traditional As unbelievable as it sounds, an acre of good garden soil contains 2 to 3 mildo a bulldozer's amount of work and indeed, this crew is capable of moving an astonishing 18 tons of soil a year in search of food. In an acre of forest soil, one might find about 50,000 of their cousinsparison. Obviously, earthworms do not play as large a role in the soil food web few inches to as much as a yard in length. They include the smaller, less fa-• ARTHWORMS are the most recognizable of all animals in the soil food earthworms (anywhere from 10 to 50 per square foot); this is enough to web and, as it turns out, one of the most important to gardening. Most probably the ones you will run into will be a species of Aporrectodea, -a large number, but small in com-

ern coast of North America. The worms rode along in potted plants and ship ballast and, one would imagine, arrived as valuable luggage cherished by farmers, who knew the high worth worms would have in the new world. Once here, they moved across the continent in soils that held fruit trees and other nursery stock. They thrived. The only place in North America European worms have not done well is in the warm desert of the Southwest. The common night crawler (Lumbricus terrestris), for example, which is dominant in garden soils from sea to shining sea, arrived with the Europeans. Nor is the red wiggler the warm fetida), a common compost worm, a native (though it is often called of forests as they do in that of gardens. (Eisenia fetida), a common compost worm, a nauve (unous) with those that the Wisconsin red wiggler); still, it is a favorite (and rightly so) with those the maintain vermicompost (worm composting) bins. All earthworms have th Early European settlers transported many earthworm varieties to the east-

ability to spread into new areas, survive, and multiply to tremendous popula-

placed in a small cocoon. Each cocoon contains 15 or more baby worms, who of sexual organs. Each has a slime tube in which to incubate eggs that are all the while, their large populations in soil are understandable. themselves, once hatched, are usually mature enough to breed four months. When one considers that some worms live for 15 years, breeding It takes two worms to produce offspring, although worms carry both sets in only three or

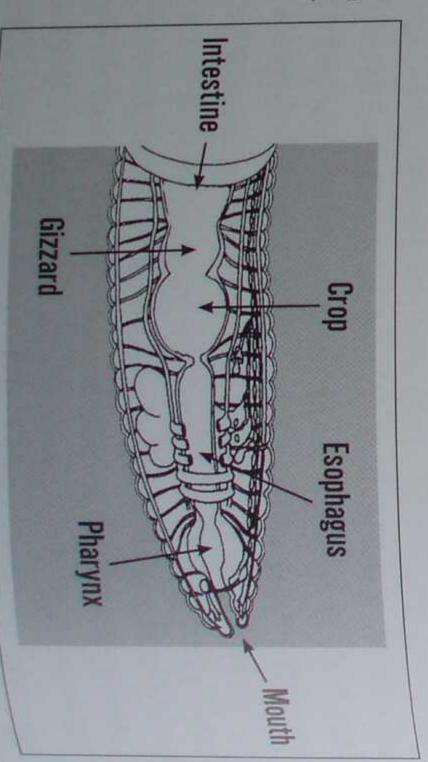
at length (and even wrote a book about them, The Formation of Vegetable that every particle of soil has been through a worm at least once. Whether he Mould Through the Action of Worms with Observations on Their Habits), argued was right or wrong, their role in the soil food web is key. They are intimately tion of soil particles, and the movement of organic matter and microorganinvolved in the shredding of organic matter, the aeration of soil, the aggregaisms throughout the soil. They also increase microbial populations and aid plant root growth. Worms are a powerful force in the soil. Charles Darwin, who studied them

### Eating machines

Although earthworms have no eyes, sensory cells in their skin are very sensitive to light. Their mouth, or prostomium, is a fleshy pad that looks somewhat like an extended lip; it, along with the worm's pharynx, is extremely muscular, but there are no teeth.

no surprise that soils with large populations of worms are usually bacterially dominated. Other foods are fungi, nematodes, and protozoa, as well as the organic matter on or in which these microorganisms live. How What does a worm eat? Bacteria, primarily, which is why it should come as does a worm eat?

The business end of an



start to break it down into particles. Saliva is mixed in, moistening things up. It starts by pushing its pharynx out of its mouth and uses it and its prostomium grab food and bring it inside its body. In the food goes, and strong muscles

is partially filled with sand and small rock particles. As the gizzard contracts and storage compartment it travels to the gizzard, an extremely strong muscle that intestine. Just before, however, it is mixed with a liquid calcium carbonate. extends, the food is ground up by the sand, which serves as the "teeth" toothless worm. When the food is sufficiently ground up, it travels to the worm's Next, the food travels down the worm's esophagus into a crop. From this

stead on bacteria. All the grinding in the gizzard assures that what food does the least that earthworms lack the necessary enzymes to digest it, relying insorbed into the worm's bloodstream, and any organic matter that is not fully ing there to quickly digest it. Nutrients produced by the bacteria are finally abarrive in their intestines is sufficiently small and opened up for the bacteria livit is a fantastic soil amendment. digested is eliminated. This may be useless waste to a worm, but to a gardener Given their reputation for recycling organic matter, it is surprising to say

### Vermicastings

ter than soil that has not moved through worms. This is an astonishing increase and radically changes the composition of the soil, increasing CEC Vermicastings (the name given to worm poop) are 50% higher in organic matbecause of the greater amount of charge-holding organic surfaces. Other nutrients, therefore, have the ability to attach to the organic matter that has

passed through a worm. those produced by bacteria in the worm's intestines) unlock many of the chemical bonds that otherwise tie up nutrients and prevent their being plantavailable. Thus, vermicastings are as much as seven times richer in phosphate than soil that has not been through an earthworm. They have ten times the available potash; five times the nitrogen; three times the usable magnesium; bonate added during digestion). All these nutrients bind onto organic matter and they are one and a half times higher in calcium (thanks to the calcium car-The benefits don't stop there. The worm's digestive enzymes (or, properly,

surface annually. This almost unbelievable number is clearly significant to gardeners: the ability to increase the availability of nutrients without carting in and adding tons of fertilizer is about as close to alchemy as one can get. Worms can deposit a staggering 10 to 15 tons of castings per acre on the

### Master shredders

nity by competing with fungi and bacteria for nutrients, indeed sition of plant material, directly and indirectly. They open up leaves and other the leaf litter in the garden and on the lawn, greatly speeding up the decompotheir very populations. The magnitude of the impact of earthworms is shown by the same time, they may also change the composition of the food web commuorganic matter, giving bacteria and fungi better access to the cellulose (and other three months with it. In some parts of the United States and Canada, forests have require one and perhaps two years to decay without worm shredding, but only this simple fact: leaves on the forest floor or in a garden or lawn would normally worms, then, obviously facilitate the recycling of nutrients back to the plants. At carbohydrates) and lignin (a noncarbohydrate) in the organic matter. Earth-Earthworms are classified as shredders. As they search for food, they break down far faster than is healthy for the trees and the rest of the soil food web. the floor habitat, and entire forests are affected as the litter layer been invaded by earthworms left by fishermen. These have completely altered is being decayed even eating into

organic litter that microorganisms can eat. Microbial popula during their formation and elimination, creating protected enclaves of fungi are also enhanced because some microbes are mixed into worm fecal pellets and bacteria. The end results of worm shredding and digestion are minute particles of tions in the soil



#### Burrows

they do. While making their way through the soil to feed, worms can rocks that are six times their weight. Being in the soil provides them with moisture, temperature control, and protection from birds and other aboveground Earthworms are incredibly strong, a necessity given the amount of burrowing

they become filled with castings and litter; roots grow into these pathways, able nent and others temporary. The temporary burrows are often abandoned after composed. In making tunnels, soil from deeper in the ground is deposited on litter on the surface and pull some of it into their burrows, where it is later deworms move up and down in the soil, sometimes as deep as 12 feet. They shred to nutrients and the microorganisms that freed them. Certain kinds of earthinches (15 centimeters) of soil, but even these redistribute organic matter sevthe surface. Other earthworms travel horizontally, rarely leaving the top 6 eral feet (a meter or so) away, though in the same horizon. Either way, this movement is akin to delivering food to another area of town and impacts the entire population of a soil food web. Earthworms also move microorganisms, starting communities where once there were none. whether attached to their own bodies or to the litter they pull underground, penetrate deeper than they could by themselves, all the while having access Different kinds of worms make different kinds of burrows, some perma-

a couple of million worms burrowing about in that acre of good garden soil. mixing organics, they also increase its water-holding capacity. Again, think of soil, these pathways can bring water to all sorts of underground locations, And since some worms move vertically and some horizontally through the Their burrows become significant pathways for water drainage and air passage. whether put to immediate use by plants or stored, for later absorption. Earthworms not only increase a soil's porosity, but by breaking down and

## Everyone loves earthworms

Other than birds, a few parasites and parasitic flies, and the occasional mammal (a mole, a fishermanmies. The birds they attract to the lawn eat them, but from a soil food web microorganisms, but bird feet carry protozoa, and these are spread about when perspective, all is not lost. Not only does bird guano contain nutrients and the bird hops from spot to spot. And, occasionally, a bird will drop a worm into a new location (but not the early bird, who always gets the worm). -a tropical-fish fancier), earthworms have few

of the earthworm? Rototilling and other mechanical methods all these benefits, isn't it strange to count the gardener as one of the predators paths, and help bind soil particles together; they cycle nutrients and microbes ity, fertility, and organic matter of soils. They break up hard soils, these chemicals are salts that irritate worms and chase them out of garden soils. gardener who uses chemical fertilizers is literally throwing salt on the wound: cutting them up into pieces that don't ever regenerate whole worms. And the destroy worm burrows and reduce or even destroy earthworm populations by to new locations as they work their way through soils in search can more readily digest them. They increase the porosity, water-holding capac-Look at the benefits of earthworms. They shred debris so ot of turning soil her organisms of food. With create root

munity. It means organic matter, bacteria, fungi, protozoa, and nematodesbase, chances are the other parts of the soil food web are in ord all necessary to support a worm population-A noticeable worm population is a clear sign of a healthy food web com--are in place. With these at the er as well.

#### Chapter 10 Gastropods

idea—it is an apt description of what these organisms seem to be: one big foot Worder Mollusca? Or perhaps you know them as shows and in lusks, but whoever bestowed the common name with Greek roots had the righ lusks are usually associated with salt- and freshwater creatures, clams and oysters in particular, not the garden. With some 40,000 species, gastropods are the species grow to 18 inches, fulfilling every gardener's nightmare. Besides, molthat does a lot of eating. Most garden slugs are the size of a fingernail, but some largest group in the order Mollusca. These gastropods (Greek for "stomach-foot") are often called mol-

350 million years ago complete with the shells developed to protect them from their water-dwelling enemies and chemicals in salt water. As one would expect and snails have a similar physiology. The main difference between the two from their appearance and the damage either can inflict to a garden, both slugs the snail's shell, which is made of calcium. Garden slugs evolved from the snails over the years and, depending on the species, either entirely or most Land snails, from which slugs further evolved, emerged from the sea some

snail has an advantage over the slug. The slug must find cover in a moist are to survive dry times. A snail can pull into its shell; seal off the opening by s and remain up to four years inside its sealed-off shell. When the snail is read creting slime material that hardens into a thick, leathery layer, or operculur to emerge, it simply eats its way through the operculum and is good to go. Slugs and snails are extremely susceptible to dehydration. Here is where the

Not having a shell has its own distinct advantages. Clearly a slug has great mobility and shape control; it can squeeze into spaces a hard shell would n night). In addition, maintenance of a shell requires access to calcium, limiting the areas in which any particular shelled gastropod can live. Slugs, who ne Why would snails evolve to slugs, losing such a wonderful device as a she vastly increasing its scavenging range (reported to be up to a mile

less calcium, are under no such stricture; their freedom to roam and ability to

get to new sources of food is unimpeded. Garden slugs and snails are nocturnal, probably because this is the time of

slime of sugars and proteins. soil or under debris. When nightfall arrives, they move about by gliding on a highest moisture or the least amount of drying heat. It may also be that this is single, muscular "foot" through which they secrete glycoproteinswhen they are less susceptible to predators. They spend the day hiding in the -a sticky

predators, just in case the gastropod is being followed. recognizable by other snails or slugs (and gardeners) or by the same slug restretch and slide forward over the slime. Slugs and snails are able to stretch up foot and is exuded from the foot's center. The outer edges of the foot then turning from foraging. Amazingly, the slime contains chemicals obnoxious to to 20 times the length of their bodies. The lubricant later hardens to form paths This slime is manufactured in cells located in the snail's or slug's muscular

moisture, are just right. They hatch in as little as two weeks, however, if condithe soil surface, where they can remain for years until conditions, primarily fertilization; most cross-fertilize, however, allowing both mates to lay 100 to after birth. They return to their "nest" each morning for the first several are tiny, but they are ready to eat like adults and search for food a day or two tions are right—which they usually are in the garden. Slug and snail juveniles 200 translucent oval eggs up to six times a year. These are deposited just under Slugs and snails are hermaphrodites, meaning they are capable of self-



grown after about two years. months; they become sexually mature after about six months and are fully

rasp, which allows these garden gastropods to grind their food down to very snails and slugs possess a radula, a series of chitinous teeth not unlike a wood you see above ground, three or four are underground, foraging in the soil. Both that slugs spend a mere 5 to 10% of their time above ground. For every slug Believe it or not, they don't graze only on surface plants. It has been reported snails and slugs also graze on fungi, algae, lichens, and rotting organic matter. You might think they are eating only your lettuce and kale crops, but both particles. Many slugs and snails are capable of digesting cellulose.

and bacteria can get at it. Their underground travels create pathways for air, tion and decay by shredding their food before they consume it. Like earthwater, and roots; the slime they produce helps bind soil. They themselves are a worms and some of the arthropods, they open up organic matter so that fungi spiders, garden snakes, salamanders, lizards, and birds. Some nematodes that food source for ground and rove beetles (particularly in their larval stages), in on a hapless slug, parts of which become a meal for the successful nematode subsist on slugs are now available commercially; these blind worms "heat-sink" while the remainder is left to bacterial and fungal colonization and decay. Snails and slugs have a place in the soil food web. They speed decomposi-

trolled; they do not become the serious pests they can be in a garden where the use of chemicals and other damaging practices has thrown the system out of gastropods are part of a healthy food web, their numbers are con-

#### Chapter 11

# Reptiles, Mammals, and Biro

rows. And did we mention browsing moose and deer?). fear (reptiles) or hatred (groundhogs, rabbits, moles—you name it, if it burmost gardeners would just as soon never see one in their gardens either out of ganic matter and providing pathways and reservoirs for water and air. Still, gardeners are plagued by them, but squirrels, mice, groundhogs, -all burrow and travel in the soil, mixing, moving, and depositing orrabbits, chipmunks, voles, moles, prairie dogs, gophers, snakes, E WON'T SPEND too much time on these larger animals. Many

from the role they play in other parts of the yard. But wherever they roam, their food web community, which recycles it into nutrients. They also carry mitiles, mammals, and birds serves as a food source for other ganisms, which far outnumber them in any soil food web. The dung of all reprole is important and entirely underpinned by microarthropods and microordeath their carcasses are decayed by soil life. crobes on and in their bodies and feet from one location to The role these larger animals play in a vegetable garden members of the is very different another, and at

known than those of other food web members; but like all forms of life, their The activities of larger animals are more easily observed and thus better

Chipmunks are always busy, and their activities affect the soil food web.

Photograph by Paul Bolstad,
University of Minnesota,
www.forestryimages.org.



numbers depend on the habitat and foods they require. The presence of birds moles burrowing about the lawn in search of Japanese beetle larvae. You ma comfort: a food web is in place and at work. Of course, the same can be said of seeing birds hopping across your lawn or even in your garden should give some in particular, indicates that larger arthropods, worms, and larvae are about, so soil food web works, you at least know there is a food source somewhere that not want to have moles tunneling in your lawn, but since you know how th about the moles without resorting to chemicals and poisons. is supporting the mole population. This should inspire you to do somethin

it, and very often not a positive one. Most gardeners have never heard of so the role of microbes and arthropods play in them. And, of course, the garden food web systems, even though they exist everywhere, and have no inkling balance a soil food web maintains. hardly ever knows when enough is enough and almost always tips the delica Where do we humans fit into the soil food web? We have a huge impact o

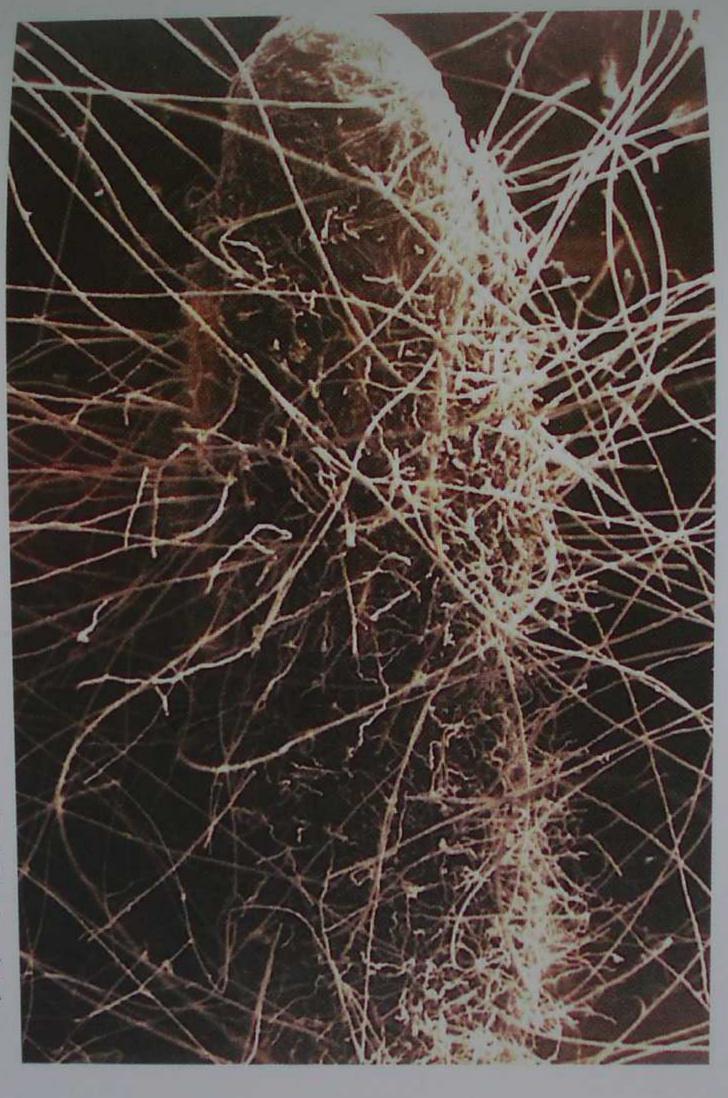
compacting soil; removing organic material from lawns and under treesa niche is destroyed, the soil food web starts to work imperfectly. Once a mer these human practices affect the soil food webs in your yard and gardens. On ber of a niche is gone, the same thing happens. In both instances, the garden must step in to fill the gap, or the system completely fails. Rather than worki see, does not require a lot of hard laboragainst nature, the gardener had better cooperate with it; and this, as we sh teams up with the soil food web, letting its members do the work. Rototilling; spraying with herbicides, pesticides, fungicides, and miticides; -not if the gardener understands a



Robins are great microbial "taxicabs." Photograph by Terry Spivey, USDA Forest Service, www.forestryimages.org.

#### Part 2

### plying Soil Food Web Science to Yard and Garden Care



nutrients and water. Courtesy Mycorrhizal Applications, www.mycorrhizae.com. Mycorrhizal fungi, extending from a root—and increasing the plant's ability to obtain

#### Chapter 12

#### How the Soil Food Web Applies to Gardening

zoa, nematodes, arthropods, and other members of the soil food web to wo type—things will only improve when you put all those fungi, bacteria, protoand you a better gardener. for you, 24 hours a day, 7 days a week, to make yours a better yard and gard for row crops in Georgia, but no matter your climate, whatever your soil tioning soil food web provides you as a gardener. Of course, what's good for cut flower field trials in California will be different from what's ideal OU NOW HAVE an appreciation of the many benefits a healthy, func-

soils. The bodies of all its members hold (immobilize) materials that will evenis consumed and digested by a protozoan or nematode, nutrients are left betually be broken down into plant nutrients. Every time a fungus or bacteriu their rhizospheres, the nutrients they provide are in the right location to hind in plant-available form. And since plants attract fungi and bacteria First, a fully active soil food web will have better nutrient retention in

soil particles into larger aggregates. Fungal hyphae, worms, insects and their with the efforts of bacteria that produce slime that binds the tiny individual small. This results in soils that have the right porosity, resulting in water retenlarvae, and even small mammals travel through soil creating tunnels, big a tion and drainage as well as aeration, all necessary for healthy plant growth. Next, a healthy soil food web results in improved soil structure, starti

tion growth and habits could throw the web out of kilter. Some members of t soil food web act like police, hunting down and capturing bad guys. Others act like doctors, dispensing vitamins and hormones. Fungi and bacteria serve barriers around plants, blocking the entry of herbivores intent on getting the plant roots, stems, or leaves; they also compete for the nutrients, space, an even the oxygen the bad guys need to survive. Soil food webs provide defenses against disease and those whose popul

the rhizosphere, which determines what kind of nitrogen is prevalent, nitra or ammonium. A plant that attracts and receives its preferred form of nitrogen Finally, soil food web organisms influence soil pH where it counts, right

including lots of the stuff man deposits there, purposely or inadvertently. there is something in the soil that eats almost anything you can tants in the air and in some instances, the water. In a healthy soil food web, which is what lawn and garden chemicals really are, not to mention the polluwill perform optimally. Soil microbiology can even take care of pollutants, find in the soil,

#### New rules

the soil food web (see the appendix for a recap of the whole list We have developed nineteen very simple rules to guide the gardener in using and survival. This is why inorganic, soluble nitrogen fertilizers do a great job ria. Plants need nitrogen to produce amino acids; it is crucial plants prefer soils dominated by fungi; others prefer soils dominated by bactelution, these nitrates (NO<sub>3</sub><sup>-</sup>) are readily available to plant roots, which pretty growing plants even while they are detrimental to the food webs. In water soing themselves to humus or clays as positively charged cations would. much act like sponges. As anions, they go into water solution instead of attach-). Rule #1: some to plant growth

there is a choice—some plants prefer their nitrogen as nitrates while others food web, nitrates and ammonium (NH4); and—as in most things in life when prefer ammonium. Two forms of nitrogen are available to plants when there is a healthy soil

dized or converted to nitrates by nitrogen-fixing bacteria when they are presleased in ammonium form in the waste stream. Ammonium is quickly oxient in sufficient numbers in the soil. This is almost always the case when the soils are dominated by bacteria as compared to fungi because the slime probacteria. In bacterially dominated soils, nitrifying bacteria generally thrive. duced by soil bacteria has a pH above 7, the right environment for nitrifying When nematodes and protozoa consume fungi and bacteria, nitrogen is re-

cay organic matter for nutrients. If there are enough fungal acids to offset the and therefore more and more unsuitable for most nitrifying bacteria. More bacterial slimes, the soil's pH drops below 7, making the environment acidic ammonium remains ammonium. Fungi foster lower pH numbers because they produce organic acids to de-

life out of the soluble nitrogen fertilizers you use not only suck the life out of the microbes in the soil food web, but they may not lizing even the land plants you seek to grow. Usually, plants can survive utiform of nitrogen over the other. lizing even the less preferred form; however, most plants do As a gardener you must appreciate that the plants in your better with one backyard are not even be the best

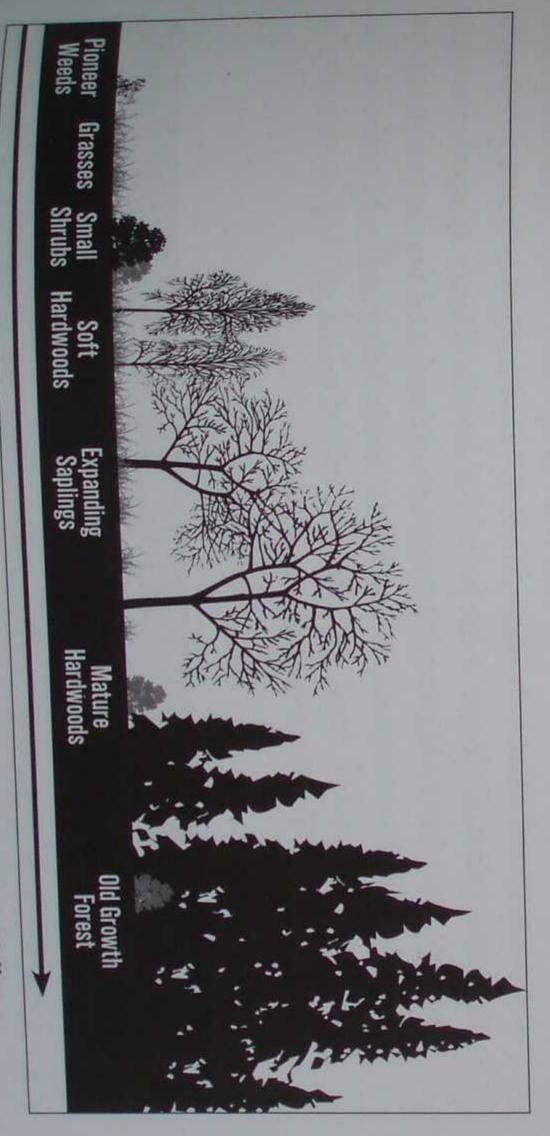
#### Who wants what?

in ammonium form and do best in fungally dominated soils. prefer their nitrogen in nitrate form and do best in bacterially dominated soils. web gardening rules. Rule #2 holds that most vegetables, annuals, and grasses The answer to what any given plant prefers is found in the next two soil food Rule #3 points out that most trees, shrubs, and perennials prefer their nitrogen

what is behind them, you will appreciate them even more. The rules make it easy to figure out what likes what, but once you understand one of the most difficult things about starting to garden with the soil food web. These two general rules take the guesswork out of what could have

and the plant life they support, fungal spores finally have enough nutrients at more organic litter accumulates in the waste products from these organisms themselves, the resulting fungi thrive. hand to germinate. With a place to take hold and the resources to support Early succession communities are bacterially dominated. As more and

more short-lived plants like annuals give way to more permanent, perennial life and the soil food web become more varied, fungal numbers increase and creasing fungal populations. Shrubs move in, followed by soft hardwoods, exgrassland plants. More organic matter is produced, providing food for ever-interia, which cannot possibly compete because they are limited to digesting in old growth forests. All the while, fungal biomass grows in proportion to bacpanding saplings, mature hardwoods, and finally the kinds of conifers you find Many other factors are involved, but to stick to what concerns us: as plant



Plant succession, from the weeds on bare soil to old growth forest. Courtesy Tom Hoffman Graphic Design.

ever-increasing mass of more complicated plants full of lignin and cellulose. simple sugars and other carbohydrates--which are in limited supply given the

rhizal relationships with plant roots when the plant dies after only a short peis explained by the tentative nature of early plant life. It is hard to form mycorriod of time. You might as well live on your own as there is no advantage to a fungal dominance increases in the soil each step of the way. Part of this increase Moving from the beach, so to speak, to grasslands to old growth conifers,

your lawn grass, incidentally. in the prairie plants, which like a balance between the two. This is analogous to growth-forest side, do best in fungally dominated soils. The inated garden or yard soils and those that grow toward the other end, the oldin dominance of fungi over bacteria generally has everything normally grow near the "beach side" of the continuum prefer bacterially domcrease in fungal biomass, not a decrease in bacterial biomass. It appears there is almost the same number of bacteriain a teaspoon of garden soil, prairie soil, or forest soil. The difference Plants that would to do with the in--100 million to 1 transition occurs

numbers stay pretty much the same in all growing environments: it is the innitrate. Anything in the ground for a year or more is usually going to prefer as are vegetables and annuals, then you know the preferred form of nitrogen is to consider how long it lives. If it is only going to be in the ground for a season, not be longer, but rather may have more branches.) And finally, the litter from that root is alive, the longer the mycorrhizal fungi will be, so to speak. (It might fungi are, then they have to have a live root with which to associate. The longer isms and take time to grow. If they are mycorrhizal fungi, which many soil crease in fungal biomass that changes the ratio. Fungi are very fragile organgreater amounts of ammonium. This makes sense as well. Remember, bacteria that are good fungal food sources. It is full of cellulose almost exclusively, plants that live a season or so generally doesn't have the lignin and cellulose which bacteria like. Bacteria reign. Another way to figure out what kind of nitrogen a given plant will prefer is

| Microbial position | 704                         |      | BACTERIA | CADDEN |
|--------------------|-----------------------------|------|----------|--------|
| 1000s              | 10s to 100s yards           | same | PRAIRIE  |        |
| 100,000s           | 1 to 40 miles (in conifers) | same | FOREST   |        |

teaspoon of various soils. Courtesy Tom Hoffman Graphic Design. of various soils counts of bacteria and protozoa; lengths of fungal hyphae) in a

### Fungal to bacterial biomass

appendix for a summary of specifics on ways to accomplish this). providing bacterial foods; subsequent chapters will explain just how (or see the gal to bacterial biomass (F:B ratio) has been observed and measured. To match For some of the specific garden plants you might encounter, the preferred funcan increase fungi by providing fungal foods or foster bacteria by

slightly more bacteria than fungi. More specifically, carrots, lettuce, broccoli, and cole crops prefer an F:B of 0.3:1 to 0.8:1; tomatoes, corn, wheat go for an ing labs will test your soil and provide you with an F:B ratio. F:B of 0.8:1 to 1:1. Lawns prefer an F:B ratio of 0.5:1 to 1:1. Agricultural test-If you are a vegetable gardener, you need to aim for a biomass that has

trees and shrubs originated, have a biomass of fungi over 100 times the biomass of bacteria. Conifers require the most fungally dominated soils with an F:B of 100:1. Orchard specimens do best in soils with an F:B of 10:1 to 50:1; and some trees (alder, beech, aspen, cottonwood, and others that originate from riparian ecosystems) actually do best in bacterially dominated soils when they are young and fungally dominated soils (an F:B of 5:1 to 100:1) when mature. 50:1 to 1000:1. Maples, oaks, and poplars require fewer fungi, an F:B of 10:1 to and fungally dominated soils (an F:B of 5:1 to 100:1) when mature. Trees require a higher F:B ratio. Forest soils, in which many of our landscape

nated soils. Again, the length of time a plant lives influences the rules. bacterially dominated soils, while most perennials prefer fungally domi Those of you who enjoy flowers will want to know that most annuals pre-

Shrubs generally prefer a higher fungal dominance than perennials (they are long-lived, so this follows our rule). Those native to conifer forests as opposed to deciduous forests require high F:B ratios; rhododendrons, for example, restrong fungal dominance, while a cotoneaster or lilac requires less. -but don't forget Rules 2 and 3, because th

management of nitrogen is fundamental to success in the yard and garden. There are more rules to come-

#### Chapter 13

## What Do Your Soil Food Webs Look Like?

for whatever you happen to be growing. what needs to be done in order to end up with the best possible soil food web F YOU ARE GOING TO USE the science to which you have just been exposed, webs in your yard. Once you have a base established, you can figure out the very first thing you need to know is the current state of the soil food

bacteria and fungi. These in turn attract varying predator organisms. So, as you a big surprise. Different plants produce different exudates that attract different Did we say soil food webs, plural? At this point in the book, etables, which is different from the soil life that supports your lawn and possiis going to be completely different from what surrounds the roots of your vegbly even the same trees on the other side of your property. would expect, the soil life around the roots of trees on one side of your house this should not be

less soil life than areas kept in a natural state. Parts of your yard that have been soil and take a census of what is there. planting of conifers. It is important to figure out what life makes up the varithan the areas you've left alone. You may have an orchard or a foundation heavily compacted or frequently rototilled will have fewer ous soil food webs in your yard. In order to do this, you must Areas that have been exposed in the past to commercial fertilizer will have fungi and worms go hunting in the

soil that, upon closer examination, will scare the daylights out of you. (In general we advise against putting anything under an electron microscope. At that soil again. Sometimes ignorance really is bliss; however, in this instance a little microarthropods present in soil, you may never want to put your hands in the level, all life has teeth!) The point is, when you get a good look at some of the dener. Just remember, you put your hands in the soil before you knew what was knowledge is not going to hurt you and will actually help you be a better garthere and never got hurt. The images in this book have forewarned you: you may find things in your

to astonish us. have done this dozens of times in our own yards, and what we find never fails You will want to repeat the following procedures with soils from each of gardens and lawn areas, and even around specific trees and shrubs. We

### Find the bigger animals first

Start by digging a hole in the soil at issue, about 12 inches (30 centimeters square. Use a spade or trowelsift through it, looking for the bigger animals you might find in the soil to be exact. Put all the soil you dig up onto a tarp or in a box so you can then worms, beetles, insect larvaeeye and pick up without having to resort to tweezers. Keep track of what you -it doesn't matter, and measurements don't hav -any living organism you can see with the naked

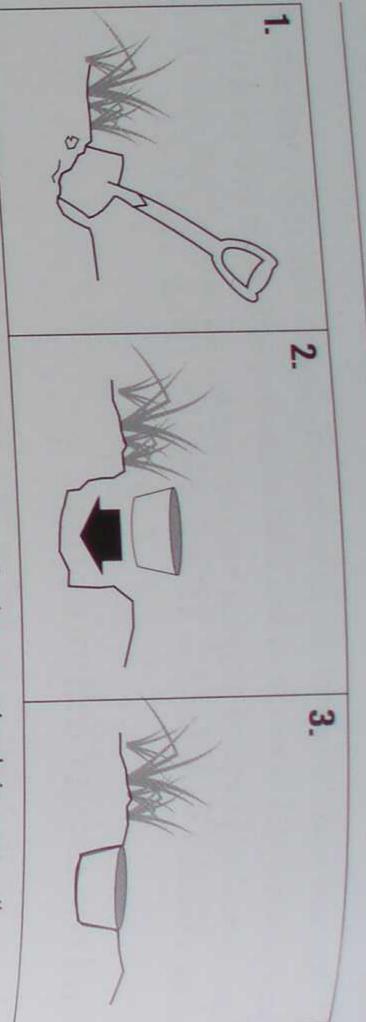
frankly the variety of them is so great as to be beyond the scope of this boo Do your best in making identifications. Seek help from others. In time you will become sufficiently proficient for the purpose. This is new stuff, and just being exposed to it will make the learning experience easier. It didn't take us very long, and it won't take you long to become familiar with soil food web organisms. None of us are trained at identifying all the organisms in our soils, and

occasional nematode. If worms are in your sampling, most probably a whole serve as foods for small mammals and eat bacteria, fungi, protozoa, and t set of soil food web organisms are busy at work in that soil—and it's probably good, rich, organic, nicely textured soil, at that. Similarly, the presence of millipedes and centipedes, beetles, spiders, springtailsyou find worms or their castings, it is a good sign. Remember that worms -indicates a healthy soil food web. If you find these, you have a go You are already teaming with microbes, not to mention mac -even a few slugs and

arthropods and worms. need to set soil traps. Many soil food web organisms roam at or above the s face of the soil for all or part of the day. To count as many of these as possil Io make sure you are really capturing what is in your soils, however, y

| EARTHWODING E 20 | ARTHROPODS |               |        |
|------------------|------------|---------------|--------|
| E 20             | <100       | GARDEN        |        |
| 10-50            | 500-2000   | PRAIRIE       | PAIDIE |
|                  | 10-50      | 10,000-25,000 | FOREST |

Number of visible organisms in a square foot of various soils. Courtesy Tom Hoffman



Tom Hoffman Graphic Design. A simple trap will allow you to take a census of the larger animals in your soil. Courtesy

ground level. If you are in rain country, prop up some kind of you will need to bury a quart-sized container in the soil so that its lip is at inch of animal-safe automotive antifreeze or toss in a mothball or two, and leave umbrella will do) to keep water from getting into the trap. Next, pour in half an it alone for several days to a week. Make as many traps as areas you are testing. cover (an open

traps to be counted later. Give traps a visual check every now and then to see what has been captured. If you have kids or pets, skip the antifreeze and use don't eat each other and mess up the census); they are not attractants, so they mothballs at your discretion. Both are used to kill entrants to the trap (so they are not absolutely necessary. By the end of the week, you should find a few of the larger arthropods such as beetles, millipedes, and centipedes. You might also find some slugs and even a worm or two. Unsuspecting gastropods and macroarthropods will fall in these simple

a lot of work to restore the soil food webs in your yard. If few of the larger participants in soil food webs are present, some link or links before them on the food chains that make up the web are missing. Take inventory of all your traps. Traps empty? This means you need to do

### Count the smaller organisms

Surveying the microarthropods requires a different kind of trap nel, named after Giovanni Berlese (1863–1927), the scientist who invented it. -a Berlese fun-

liter-sized plastic bottle, the kind soda or juice comes in. Turn window screening down (this is the funnel). Next, place a 2-inch-square of meters) inside the bottle so it settles in the neck. Nothing larger than the openwindow screening with openings approximately 1/16 to 1/8 inch (1.5 to 3 millimeters) incide the ings of the screen will settle through. You can easily make your own Berlese funnel. First cut the bottom off a the bottle so the

tainer has two purposes. The first is to act as a repository to collect the organsoda bottle and doesn't balance very well. We use large, recycled yogurt or cotsecond is to hold the funnel and give it stability. It is, after all, an upside-down isms that fall into it through the screen and down the neck of the funnel. The and are really easy to come by. tage cheese containers because they are just the right size to hold such a bottle Next, set the mouth of the bottle into a quart-sized container. The con-

on the top few inches of many soils. Start with a particular garden or your The next step is to fill the funnel with soil and duff, the organic debris that

lawn and sample down to about 8 inches (20 centimeters).

ethyl alcohol into the holding container so it just covers the bottom. Either of these will kill all the organisms that fall in so they don't eat each other before leaving the container; the plastic is too slippery. A few organisms will be lost to you get to observe your catch. You can skip this step with no fear of the critters tainer; this can be a morbidly fascinating show. cannibalism, as the feeding frenzy that goes on in the soil continues in the conyou want to do things a bit more scientifically, pour a bit of antifreeze o

(where it is perfectly comfortable) down into the container. Suspending a 40to 60-watt lightbulb over the open end of the funnel (or placing it under an exshould be about 6 inches (15 centimeters) from the source of the heat. Be careisting light source of similar wattage) accomplishes this. The top of the funnel by overheating the materials in your Berlese funnel, your spouse is not going ful: you can have the best soil food web going, but if you burn the house down Next, apply heat. This gets the life in your mixture to move from the soil

to be happy no matter how well the garden turns out.

days. Its light and heat will drive the soil organisms down through the screen into the wading pool in the container. Some folks put a few mothballs on the top of the soil instead of using the heat from a lightbulb with the same results: a mini-stampede of microarthropods and other organisms into your observatory. You can peek as often as you want, but don't stop the process for a minimum of three days (a week is best) if you expect to get all the life you can into Turn on the bulb and leave the Berlese funnel undisturbed for at least three he

contents with a magnifying glass or a MacroScope, a monocular that allows you sional gastropod as if they were only a couple of inches or so from your eyeball. Now it's time to count your catch. Your best bet is to look at the container's back at arm's length but view the trapped microarthropods and occa-

this book, remains just as amazing) the first time we did this were the number What astonished us (and frankly, despite all the research we have done

but as lifelong gardeners (who have lived a fairly long life and spent an awful beetles, springtails, and more. We simply had never seen most of these before. of living things we sawamazed and feel the same kind of astonishment. there. How wrong this proved to be. We are pretty sure you lot of time digging around in the soil), we thought we knew One might expect this to be true when the subject matter involves microbes, -mites, the larval stages of a half-dozen animals, tiny what was living will be equally

mally in your soil food web, you may need to contact your local cooperative sources are available on the Internet. extension or other governmental agricultural agent for information on what ent areas and since it is important to have at least a general idea of what is noryou have collected. You can also contact the nearest universit Since populations of micro- and macroarthropods are different in differy. And many re-

to be going by at the time the traps are set, but it is a snapshot of at least the Similarly, a lack of diversity and numbers should cause some concern; you'll on track and suggests good populations of microorganisms too are present. microarthropods in the catch basin of a Berlese funnel is a good sign things are mobile members of the soil food web. A diverse and numerous population of need to do some work to return them. Admittedly, these censuses are not perfect. You are catching what happens

### "Counting" microorganisms

How do you assess the population of microorganisms, which are, after all, the bers of nematodes, protozoa, bacteria, and fungi will help tell you what nutrimajor source of nutrient retention and cycling in the soil food web? The numents are available to your plants and the ability of your soils mit that you will not be able to determine precisely what is immobilize these nutrients. If you know what is in the soil, you know what is with a powerful microscope. You will be able, however, to identify nematodes, measuring is best left to the professionals. some protozoa, and algae, and at least see (but not identify) bacteria. Exact -but when it comes to the microorganisms, we will in your soil, even to mineralize and be the first to ad-

and protozoan populations and more, because these are what worms generally your samplings, there is every likelihood that your soils contain good bacterial of mushrooms. If you already care for your property without the use of pestimycelia (where there is decaying organic matter) or fruiting bodies in the form eat. And in some soils and mulches, you can see evidence of fungi, either But first, let's make some inferences. If you found lots of earthworms in

your soil food webs are at least fairly healthy. cides, fungicides, and salt-based fertilizers, and you know that organic matter perate zone), you have yet another strong indication that the base members of placed in your yard and gardens decays rapidly (within six months in a tem-

a certain degree. First, take a Berlese or kitchen funnel and put a hand's-length section of surgical tubing over its smaller end; clamp the tubing shut with a dechlorinated water, forming a thick but soupy mud. Fill the funnel half full large paper clamp. Next, collect a few handfuls of soil and mix them with some. The nematodes will sink into the funnel's neck. After 24 hours, quickly with the mud, and then pour more water in, so it covers the mud and then open and close the clamp, and examine the concentrate you've just released with the best magnification you have. A microscope and a few drops on a slide could produce a great show. You may not want to, but you can measure some nematode populations to

quires the training and the sophisticated lab equipment of a professional. Traditional soil tests determine elemental deficiencies in the soil (NPK tests) and poses, quantifying the amount of fungi and bacteria, especially, is critical measure the soil's pH and CEC. These are useful, but for soil food web pur-But again, to get a really accurate assessment of microbial populations re-

agricultural soil tests; and protozoa can be seen in relatively inexpensive microscopes. If you have good numbers of beneficial nematodes and low-tono bad guys, you know you have good nutrient-cycling capabilities. The same lab that tests your soil for biology, are biomass numbers. How much fungal is true if you have lots of protozoa. But what you also want to know, from any biomass is there in the soil? How much bacterial biomass is there? This is where the nutrients are stored—in the bodies of fungi and bacteria. This information will determine which type of organisms dominate in your soils and in what It is pretty easy to get soils tested for nematodes by almost any lab that does

ing soils for their microbiology. You should be able to find a lab to take care of your needs (an analysis of a compost sample, courtesy Soil Foodweb, Inc., www.soilfoodweb.com, concludes this chapter). Armed with the results of your own visual surveys and such microbiological lab tests, you will know what is active in your soil and, by implication, what isn't there. Next, you need to learn what you can do to maintain and support existing members of the community. But rest assured: whoever is missing can be activated by soil food web gardening techniques. More and more agricultural testing labs are recognizing the value of test-



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e-mail: info@soilfoodweb.com

| Organism<br>Sample | Biomass Data<br>Unique<br>ID | Dry Weight<br>of 1 gram   | Active<br>Bacterial | Total<br>Bacterial | Active<br>Fungal  | Total<br>Fungal   | Hyphal   |   | Protozoa   |   | Total<br>Nematode   |
|--------------------|------------------------------|---|---------------------|--------------------|-------------------|-------------------|--|---|--|---|---|
| π.                 |                              | Fresh<br>Material   | Biomass<br>(µg/g)   | Biomass<br>(µg/g)  | Biomass<br>(µg/g) | Biomass<br>(µg/g) | Diameter<br>(µm)   | Flagellates   | Numbers/g<br>Amoebae   | Ciliates  | Numbers<br>#/g  |
| 363<br>364         | NW Vermi<br>KIS-Thermal      | 0.31  | 188<br>468          | 4,002<br>2,193     | 46.0<br>32.7      | 4,928<br>5,959    | 2.75<br>3.00   | 1,136,894<br>469,291  | 146,682<br>19,478  | 1,831<br>1,557  | 48.1<br>67.2  |
| Bold<br>Means Low  |                              | Both Too wet: allow material to dry out a bit, to prevent anaerobic conditions. | Both Excellent.     | Both Excellent.    | Both Excellent.   | Both Excellent.   | Community of disease- suppressive fungi present in both. | This a good when they ence as indicate of flag. This indoor of mid- | ent protozoan naterial will produced inoculum of pen applied to the ciliate numbers tructure in the aggregates materials out of the aggregates and andicates a broad prosites, and the versity of bacters. | rovide protozoa e soil.  indicate compost. hay be nside, materials pregates, conditions, h numbers noebae. I diversity perefore | Good numbers and diversity.  Possible switchers present Need to maintain adequate fungito protect plants. |

|                    |    |     | 10000 + | 10000 + |     |    |
|--------------------|----|-----|---------|---------|-----|----|
| Range 0.85 25 3000 | 25 | 300 |         |         | 100 | 30 |

Immature compost can have activity ranging from 10 to 100%. Mature compost should have activity between 2 to 10%. Fungal activity and biomass depends greatly on the plant being grown. Desired range given here is for a 1:1 compost.

A - Hyphal diameter of 2.0 indicates mostly actinomycete hyphae, 2.5 indicates community is mainly ascomycete, typical soil fungi for grasslands, diameters of 3.0 or higher indicate community is deminated by higher trades.

diameters of 3.0 or higher indicate community is dominated by highly beneficial fungi, a Basidiomycete community.

Season, moisture, soil and organic matter must be considered in determining optimal foodweb structure.

If sample information, such as pesticide, fertilizer tillage, irrigation are not included on the submission form, sender's locale is used. One report is sent to the mailing address on the submission form.

All submissions receive free 15 minute consultation, call 1-541-752-5066

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00363: Mature compost from NA, Smell: Mild. For use in tea brewing. 00364, Mature compost, mild odor

| Sample | Assay      | Notes   |
|--------|------------|---|
| 363    | Activities | Actinos present   |
| 363    | T.F.       | Good diveristy and hyphae diameter ranging from 1.5 to 8.0                                |
| 364    | T.F.       | Great diversity with diameter ranging from 1.5 to 20 and mostly 3 and lots of long hyphae |

| Organism<br>Sample<br># | Unique<br>ID            | Total Fungal<br>To<br>Total Bacterial<br>Biomass | Active to<br>Total Fungal<br>Biomass | Active to<br>Total Bacterial<br>Biomass   | Active Fungal<br>to Active<br>Bacterial<br>Biomass | Plant Available N Supply from Predators (lbs/acre)                              | Root-Feeding<br>Nematode<br>Presence                 |
|-------------------------|-------------------------|--|--------------------------------------|---|--|---|--|
| 363<br>364              | NW Vermi<br>KIS-Thermal | 1.23<br>2.72                                     | 0.01<br>0.01                         | 0.05<br>0.21  | 0.24<br>0.07                                       | 300+, but N loss<br>300+, but N loss  | None detected<br>None detected                       |
|                         |                         | Fungal dominated compost, suitable for           | Fungal<br>component<br>is mature.    | NW vermi/<br>bacterial<br>component is  | Compost<br>will become<br>more bacterial           | Excellent nutrient cycling.   | Possible switcher present.  Need beneficial          |
|                         |                         | variety of plant applications.                   |                                      | Material Not mature. Wait to apply this material until activity drops below 10%. Material is currently suitable for making tea. | with time,   | N loss results from anaerobic conditions, as indicated by high ciliate numbers. | fungi and nematodes to combat these pest conditions. |
| Desired<br>Range        |                         | *(1)   | *(2)                                 | *(2)  | *(3)   | *(4)  | *(5)   |

(1) For the following plants, Grass: 0.5-1.5; Berries, Shrubs, grape: 2-5; Deciduous Trees: 5-10; Conifer: 10-100.

(2) Active organisms in mature compost should be below 0.10. Compost is not mature, i.e., not stable, if greater than 0.10.

(3) For annuals, ratio should be 1 or less, for perennials, ratio should be 2 or greater.
 (4) Based on release of N from protozoan and nematode consumption of bacteria and fungi. Often protozoa and nematodes compete for food resources. When one is high, the other may be low. Also, if predator numbers are high, the prey may have low numbers
 (5) Identification to conver.

(5) Identification to genus.

| Nematodes per Gram of Compost |      |       |
|-------------------------------|------|-------|
|                               | 363  | 364   |
| Bacterial Feeders             |      |       |
| Butlerius                     | 4.86 | 1.04  |
| Cuticularia                   | 7.42 | 14.62 |
| Eucephalobus                  |      | 0.35  |
| Mononchoides                  | 0.77 |       |
| Plectus                       |      | 1.04  |
| Rhabditidae                   | 1.53 | 1.04  |
| Rhabdolaimus                  |      | 0.35  |
| Fungal Feeders                |      |       |
| Aporcelaimus                  |      | 0.35  |
| Mesodorylaimus                |      | 0.35  |
| Fungal/Root Feeders           |      |       |
| Aphelenchus                   | 0.26 |       |
| Ditylenchus                   | 0.26 | 0.70  |

#### Chapter 14

#### Tools for Restoration an Maintenance

your plants what they need in the way of nutrients and protection. to take whatever action is necessary to ensure your soil food webs give ow that you have an idea of what populates your soils, it is time

## Compost, mulch, and compost tea

gardener. With most soils, your first aim will be to restore a diverse and whole This is when you begin teaming with microbes and become a soil food web in your soils but in your plants as well. Some areas (lawns and soil food web. As beneficial organisms return, you will see a difference not only take longer to establish or alter. Much of your yard's response will have to do for example) respond very quickly; other spots will have soil food webs that with previous practices. If in the past you saturated your yard with commermay have to completely reestablish soil food webs; this may take a year or more. cial pesticides, herbicides, fungicides, or salt-based chemical fertilizers, you lished food webs, employing some new practices and intensifying others. Gardeners who have been "organic" usually need only to tweak their estabbeds of annuals,

dener's tools, and it takes only three strategies to restore the soil food web using right kinds of organic matter; and applying actively aerated compost teas them: applying the proper kind of compost; mulching the right way, with the strategies, either alone or in combination. Employed proper ment tools will replace conventional fertilizing with chemicals. These tools (AACTs). Once established, soil food webs can be maintained with the same feed the microbes that feed the plants. If you keep the microbes happy, healthy, It's simple. Compost, mulch, and compost tea are the soil food web garly, these manage-

and diverse, you will have excellent results.

can inoculate an area with microbes to support a soil food web. Properly made anyone knew they existed. It is a proven, effective growing medium. Compost compost contains the entire complement of soil food web fungi and bacteria, protozoa and nematodes. It is also full of organic matter, Compost has been used to support soil food web organisms long before microorganisms;

pile it always has a rich, dark, coffee color. The only caveat is that in modern times, of anaerobic microbes doing their thing. It should smell earthy and fresh, and which provides living space and nutrients for the gang of microbes a compost we seek to avoid do not break down quickly enough in compost. contains. Finished compost never smells bad, which would be a sure has to know what was used to make the compost, as many of the chemi-

ganic we mean natural material, full of carbon and nitrogensoil community's organisms and plenty of organic foods for them to live on. grass clippings, and wood chips. These provide the proper environment for the riod of time. By providing different kinds of organic matter as mulch, you can After all, these are what make up the compost pile. Mulch is a form of cold comprovide more of the type of nitrogen preferred by the plants grown in the area. establish or supplement different members of the soil food web, ones that will Organic mulches, too, are an effective soil food web gardening tool. By it doesn't heat up like a compost pile, but it will decay, over a longer

properly made AACT contains the same set of microorganisms as the compost tinguish these modern compost teas from old-fashioned teas like the ones your from which it derives. The term "actively aerated compost tea" is used to disnure in water for a few weeks. AACTs are prepared by pumping air into a mixture of compost, dechlorinated water, and microbial nutrients. Unlike microorganisms are the beneficial ones. The energy from the air bubbling fashioned teas, which went anaerobic, AACTs remain aerobicthrough the mixture strips the microbes out of the compost and into the tea. that can be applied to soil. Here they grow and multiply, forming a stew of beneficial food web microbes Actively aerated compost tea is a liquid easily extracted from compost. A grandparents may have made by soaking a bag of compost or ma--and the aerobic

compost and have a higher concentration of microbes, so you don't need teas can also be sprayed on leaf surfaces, where compost will not stick. Here the nearly as much tea as you would regular compost to inoculate an area. These beneficial microbes in the tea outcompete pathogens for food and space. Aerated compost teas are easier to make and much easier to apply than

## More work now, much less later

amount of work it takes Using compost, mulch, and compost tea properly will greatly work involved in making the conversion from chemicals to microbes, but ultimately, once you gear up and make to maintain your yard and gardens. the necessary changes, there will be less to There is a bit of reduce the

do. The microbes will be working for you. You will need to water less because getting the kind of nitrogen they prefer. capacity. You won't need to fertilize because there will be proper microbial the food web animals will have improved your soil's watercycling of nutrients in the soil. And you will be able to ensure your plants are and air-holding

tools to make things better if things do go wrong. And if all You will have fewer plant health problems and some effective, easy-to-use this doesn't save

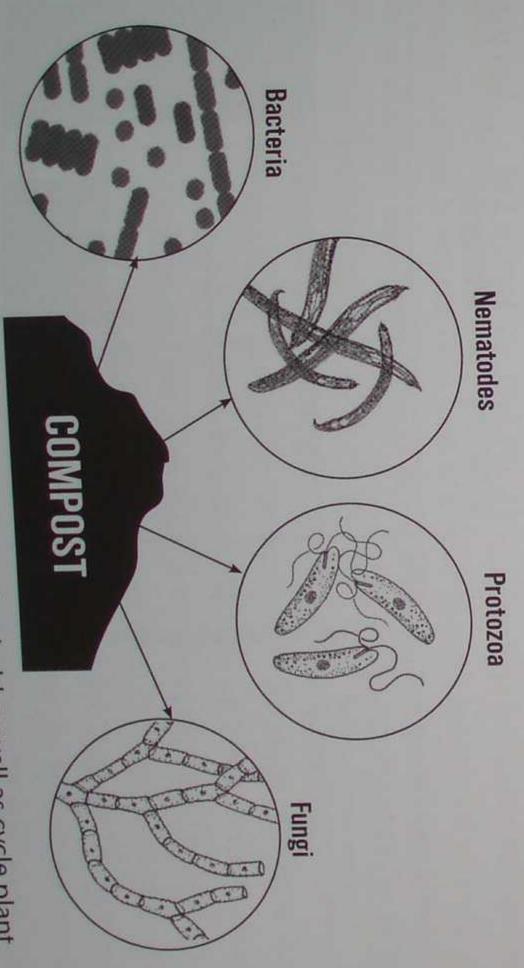
print to read—and no health problems for you, your family, or your pets. you time and effort, not having to rototill or turn your garden soilsleaches into the water table. When you team with microbes, surely will. Best of all, there are no dangerous chemicals; nothing there is no small

deserves and will get its own chapter. Once you start applying all the rules using these three tools, we are quite sure there will be no looking back. You have now heard, briefly, what the main soil food web tools are; each

#### Chapter 15 Compost

900 feet (150 to 300 meters) of fungal hyphae, 10,000 to 50,000 protozoa, and post contains all manner of microarthropods and sometimes worms. It teems 30 to 300 nematodes. In addition to extremely high microbial numbers, comtions, are simply too large to fully comprehend: up to a billion bacteria, 400 OMPOST is a whole universe of diverse soil food web organisms. Never organisms per teaspoon in compost, especially the microbial populamind the huge numbers in good, fertile garden soil: the numbers of to

soils around your yard and introduce, maintain, or alter the soil food web in a particular area) establishes the use of compost as a major soil food web tool. Rule #5 elaborates on this: adding compost and its soil food web to the surface spread life as far as they can. It is microbial manifest destiny. But you can best the compost you apply to your gardens, trees, shrubs, and perennials will of the soil will inoculate the soil with the same soil food web. The organisms in satisfy a plant's nutrient needs by adding compost with the right microbial domination. Rule #4 (compost can be used to inoculate beneficial microbes and life into



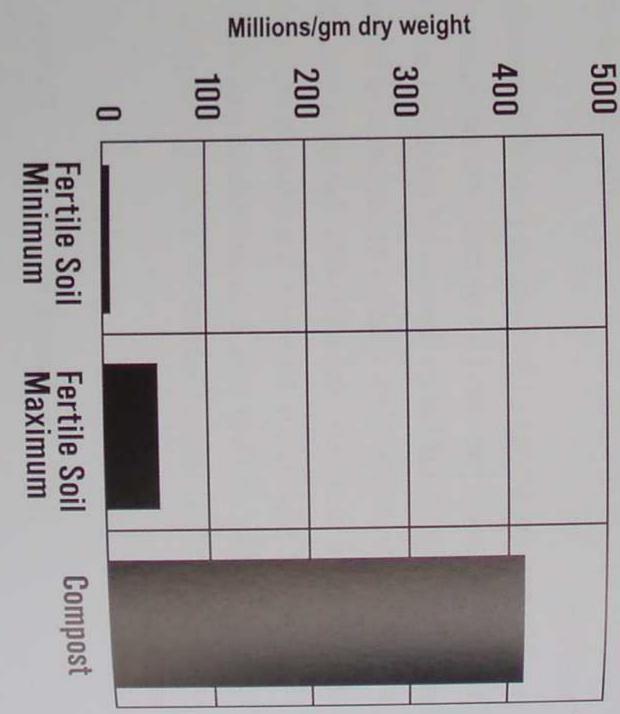
nutrients. Courtesy Tom Hoffman Graphic Design. Compost contains the key soil food web organisms that hold as well as cycle plant

### Not all composts are the same

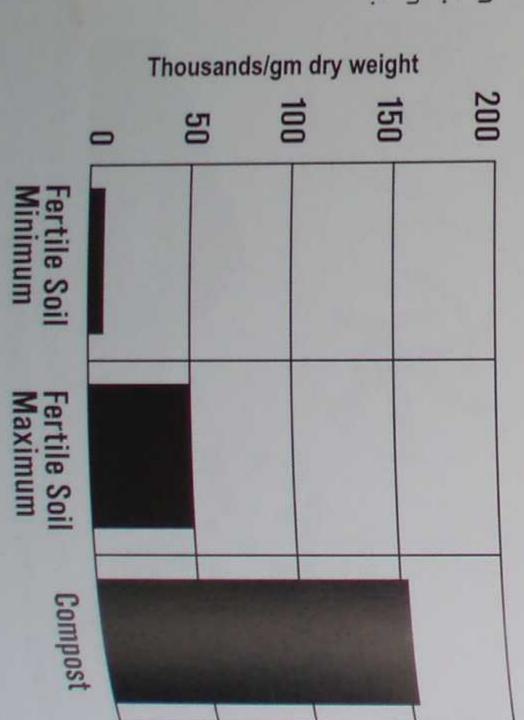
they apply it—it is all the same. There is more than one kind of compost, how-Most gardeners don't give compost much thought. They make or buy it, and and pH in the end. But surely, upon reflection—and especial ever, which is something that amazes many veteran compost that the end product is always the same doesn't make any sense. As with almost something about the soil food web organisms that make up compostthought that all compost, no matter what went into it, had comes out at the end. every other system, what goes into it does have something to do with what the same biology ly after you know makers. We, too, -the idea

can make either compost that is dominated by fungi or com The fact of the matter is that by using just a bit of soil food web science, you post that is domi-

Bacteria populations in fertile soil and compost.
Courtesy Tom Hoffman
Graphic Design.



Fungi populations in fertile soil and compost.
Courtesy Tom Hoffman
Graphic Design.



production of one of these forms of nitrogen over the other makes real sense. and some in nitrate form (see Rules 2 and 3), making compost that fosters the nated by bacteria. It all depends on what you put into the compost pile or bin to start. And because some plants prefer their nitrogen in ammonium form

### to make compost

on a farm or in a garden, you routinely used compost and manure to increase fertility. This all changed when internal combustion engines replaced the horse, and fewer and fewer homes, particularly in urban settings, featured chickens, cows, pigs, and other livestock. Agriculture and horticulture required seat to chemicals when it came to growing things; before that, if you worked Farmers have been using compost to improve their soils at least since the time of the early Romans. It was only in the last century that compost took a backchemicals because there was a dearth of manures and thus compost.

Making and using compost has made a strong comeback among home gardeners and has even become politically correct: composting conserves valuable landfill space by recycling at least some of our household wastes. Dozens of compost bins are commercially available, and a like number of books can tell you how to make compost, in myriad ways. At the heart of every composting system, however, are the soil microorganisms, the members of the compost's food web. They are the ones that make compost, no matter what method is employed. Their metabolic activity creates the heat and by-products that make the composting process work.

This is a chapter, not a book, on composting. What we will describe here is just a bit of the science behind composting and a few basic procedures for making compost at home. Once you have made a few batches, you can experiment and create a system that best fits your plants' needs and your climate, space availability, and even spousal demands. Besides the necessary soil mispace crobes, composting requires heat, water, air, and organic materials with the

crobes, composting requires heat, water, air, and organic materials right amounts of carbon and nitrogen. All are mixed in the proper ratio.

Organic materials are easy to come by: grass clippings, autumn leaves, wood chips, straw, sawdust, branches, and virtually all kitchen scraps (except meats and fats). Human and pet feces should not be composted because of the possibility that disease organisms might survive even the high heat of the compost process; for the same reason, we personally discourage the timeworn practice of using other manures in compost. Why take the risk when you don't know what kind of antibiotics and other drugs were used to feed the animals?

to be worried about E. coli?

are necessary to build structure and enzymes. process and the proteins (including their chief component, amino acids) that lism. The microbes also need nitrogen to make the enzymes used matter in the compost pile, just as they do in the soil. This fuels their metabo-Bacteria, fungi, and other microbes seek mostly carbon from the organic in the decay

have active bacteria, protozoa, or nematodes without the water necessary for crobes and to prevent them from dying or going into dormancy. You cannot Moisture is necessary to provide the optimum environment for the mi-

their transport and other life functions. and decay will occur under these conditions as well; however, so quire oxygen. It is true that anaerobic conditions can develop in a compost pile boniferous and nitrogenous materials are aerobic. They breathe duction of things detrimental to plants, such as alcohols, of whi one part per million will kill plant cells. Obviously, then, it is important to keep compost piles aerobic, which is why compost piles are turned and opened up, Air is needed because the beneficial soil organisms that break down carch as little as will the proair; they re-

bringing air into the system. rather from the soil life's metabolic activity, most of it from bacterial activity. the composting cycle. lations and causes them to change in character at the appropriate time during As you will see, this heat is what creates an environment that increases popu-Finally, the heat required for composting does not come from the sun but

rich, crumbly, dark, coffee-colored, sweet-smelling humus-soil sible to make good compost in as little as a few weeks. But no matter what pens to be full of life. Though it could take as long as a year or more, it is posmethod is employed, it is the microbes that do most of the work. Mix these ingredients in the right proportions, and you will that also hapend up with a

## Mesophilic and thermophilic stages

of these phases is the mesophilic. Mesophilic organisms thrive Composting material goes through three distinct temperature phases. The first temperatures, between 68 and 104F (20 and 40C). in moderate

while, brown rot fungi (basidiomycetes, "regular" mushrooms) and certain bacteria (Racill... are particularly adept at depolymerization, as this process is known. Meanchains of cellulose, which are broken into smaller chains of glucose; bacteria ficult-to Jims spp., Heliospirillum spp.) are active breaking down other difficult-to-digest material. These microbes produce endospores, spores that are Even in this first stage, work begins on the straight, difficult-to-digest

phase of composting, and they return when temperatures cool. resistant to chemicals and heat; this enables them to survive the next, hotter

those adapted to higher temperatures take over. it becomes too hot for the continued activity of the mesophilic organisms, and some of these animals results in further chemical breakdown. All this metabolic activity creates heat, raising the temperature to 104F (40C). At this point, matter in the pile as they search for food, and microbial activity in the guts of Larger soil organisms join the fungi and bacteria, breaking apart organic

The metabolic activity of these cool-loving bacteria increases the temperature "cool" bacteria—can continue to operate at temperatures as low as 32F (0C). thrive at temperatures just above freezing though some of thema frozen winter, it is simple: some bacteria are psychrophilic, meaning they of the pile just enough to wake up the higher-temperature, mesophilic organisms so they can take over. In case you are wondering how a compost pile heats up in the spring after -the really

phase, can withstand temperatures of 104 to 150F (40 to 65C) and over. Durcayed. Many more bacteria (Arthrobacter spp., Pseudomonas spp., Streptomyces teins are also decomposed. Hemicelluloses, more resistant structures, are ing this period the complex carbohydrates are fully broken down. Some proroles. Their metabolic heat causes the temperature in the compost pile to conand other actinomycetes) and fungi join in or begin to play more prominent tinue to rise; these high temperatures also kill off pathogens that might be in Organisms in the second stage of the composting cycle, the thermophilic de-

should heat up to 135F (57C) in 24 to 72 hours; typically, if you have the right day and 150F (65C) in three. If the pile is not heating up, then you need to turn mix of carbon to nitrogen, the center of a pile will heat up to 135F (57C) it (that is, switch the inside and bottom materials in the pile with the outside and top materials) to add oxygen. If that doesn't work, add fresh, green matethey need). Newspaper, fruit pulps, or commercial compost inoculums rial (as these are full of easy-to-digest sugars that will supply bacteria the food also be added to help a pile heat up. These first two stages take place very rapidly. A properly made compost pile in a can

temperature, pathogenic microbes in the compost are killed. At 150F (65C), 140F (60C) and 150F (65C) for at least a few days because at this thermophilic this will start to burn off carbon. To temporarily cool an overheated pile, turn it (yes, turning encourages both heating and cooling). Not only does this open You have to monitor compost piles. It is advisable to keep a pile between seeds are also destroyed. Never let a compost pile get over 155F (68C) as



Turning a home compost pile. Photograph by Judith Hoersting.

doesn't do the cooling trick, add water or more brown materials, changing the teria are the primary heat-generating organisms, this will slow things. the pile up to air, it ensures all the material in the pile gets treated. If turning ratio of green (easy-to-digest bacterial foods) to more fungal foods. Since bac-

pose or use an oven thermometer. is more precise, however; you can buy a soil thermometer design transmit heat and will feel warm when things are going right. A thermometer heat. Or you can stick a long, gutter nail or metal rebar pipe into the pile; these There is nothing wrong with sticking your hand into the pi le to gauge the ed for the pur-

#### Maturation stage

starts to decrease. The mesophilic organisms, whose specially protected spores minish, there is a reduction of metabolic activity and the temperature in the pile As the complex proteins and carbohydrates are broken down and begin to dithe thermophilic organisms. The compost enters the final, maturation stage. enabled them to survive the higher heat stage, reassert themselves and replace

together are extremely strong and structurally much more difficult to attack nent, lignin, is completed. The bonds holding the chains of alcohols in lignin During the maturation stage, the decay of the most resistant plant compo-

pants in this last stage, the basidiomycetes, are still at work. the earthy smell associated with good compost and soil, which comes from their decay of cellulose, lignin, chitin, and protein. The major fungal particidifficult-to-digest plant remnants; these are the same organisms that impart chain-like bacteria that resemble fungi, continue their attack on these really and break apart than almost anything else in the pile. The actinomycetes, the

ing particles with a mucus that binds them together into aggregates. Ants, snails, slugs, mites, spiders, rove beetles, and sow bugs can come into the pile have lots and lots of bacteria and fungi to eat; as a group, they do well. Worms, port the microbial team. Grazing by nematodes, springtails, centipedes, and crobial populations increase, so do their soil-binding activities. Lots of nemaothers cause the populations of fungi and bacteria to increase; and as these miand open up the organic matter as they forage, shredding it and making it eastoo, work the organic matter in the pile, exposing it to bacteria and then coatier for microbes to attack. The end result of all these organisms going about their day-to-day business is compost. Also during this maturation stage, physical decomposers continue to sup-

It is best to keep the compost pile between 104 and 131F (40 and 55C) after the initial thermophilic run-up to 150F (65C). Make sure that the outside of the pile gets turned into the center so all the material decays. If the pile drops benitrogen material. If it stays above 131F (55C), consider adding more brown, low 104F (40C) before it is mature, consider adding some more green, high-init down, and if you have the strength, repeated turning is the only control you carbon-containing material. Of course, aerating a pile will always initially cool need. Watering a pile down will also cool it, but this is a more drastic step.

but don't let it become so saturated that there is no air supply in the pile. You ing it. If all goes well, and it usually does, "compost happens." After two or three turns, your pile should be compost. It is finished, or mature, when you cannot may have to add water as you turn the pile, or cover it to keep rain from soak-The pile needs to remain moist throughout the process. Don't let it dry out

# ratio and fungal vs. bacterial dominance

The ratio of carbon to nitrogen has to be right in order to make compost; the ideal C:N ratio for this purpose is somewhere around 25:1 to 30:1. If you have too much carbon, nitrogen is quickly used up and the decay process slows. If you have too much nitrogen, organisms snatch it up and then carbon is vented

ideal ratio, things go fast, and decay is complete. to the atmosphere or mixed with water and washed out of the p ile. But at the

Often gardeners divide available composting materials into two categories,

autumn leaves, bark, wood chips, twigs, and branchesgreen organic materials support bacteria (Rule #6). Brown itemspile. Nitrogen provides soil food web organisms with building blocks for prosources. The fresher the green item, the more nitrogen it will contribute to the contain plenty of the easier-to-digest bacterial foods and are good nitrogen bon provides members of the soil food web with energy for metabolism. Green brown and green. Aged, brown organic materials support fungi, while fresh, necessary in the decay process. teins, which are used, among other things, to produce the digestive enzymes -such things as grass clippings, fresh-picked weeds, kitchen scraps--contain carbon; car--including

supply of are grass clippings (19:1) and tree leaves (40:1 to 80:1)ple, is 500:1, and paper is 170:1. The two organic wastes you should have a good gether, these will give you near the proper ratio. Not all organic wastes at hand have the ideal C:N ratio; sawdust, for exam--mixed to-

highly fungal or highly bacterial, or a balance of the two: simply increase alfalfa meal, 45 to 50% fresh grass clippings, and 40 to 50% brown leaves or crease bacterial counts). A good mix of materials for a fungal recipe is 5 to 10% brown materials (to increase the amount of fungi) or green materials (to insmall wood chips. A suitable bacterial recipe would include 25% alfalfa meal, 50% green grass clippings, and 25% brown leaves or bark. It is possible to manipulate compost materials so that the end product is

use sugars and lots of nitrogen and are great for supporting brown materials in compost piles consist of difficult-to-digest lignin, cellulose, have the enzymes to break it down. Only then can bacteria attack it. and tannin (and some nitrogen as well). Fungi prefer this kind of material and Again, the green materials that go into compost provide simple, easy-tobacteria. The

### Other important factors

post will tend to buffer the pH around 5.5 to 7, so you want some fungi in all The bacteria in compost will tend to buffer pH around 7 to 7.5. Fungi in commaterial in your compost, the lower the pH, to a point. your composts to prevent them from getting too alkaline. The more fungal

that on into that go into compost piles should be free of these chemicals. Chances are they food web many. Pesticides, herbicides, miticides, and fungicides kill off

why take risks with chemicals when you don't have to? In addition, since many will break down over time, but maybe not before the compost is spread; and of these chemicals are nonselective when it comes to microbes, they can interto the heat and decay. fere with the composting process itself by eliminating microbes that contribute

obic. If the material is too big, there will be so much air diffusing through it much fine, particulate matter, and the pile will compress and quickly go anaerthat the pile will heat up too much. If the material is too large, it won't decomthe understanding you need and, finally, the control you want. of materials put into a compost pile, and only experimentation will give you to establish sufficient populations. There is a fine balance when it comes to size pose properly or fast enough because the bacteria can't get into it quick enough The size of the material put into a compost pile is also important. Too

3.5 feet square or round (1 cubic meter), in order for it to heat properly. You entire pile has to be aerated or turned at least a few times to keep it from going can make your piles bigger, but the increase in size creates more work, as the anaerobic. In our experience, a six-foot pile, wide and tall, is about as big as you will want without a lot of mechanical help turning and aerating it. Next, a compost pile requires a minimum amount of mass, approximately

It is quite easy to make compost literally in a pile, dumping ingredients



A professional turns his compost to aerate it. Photograph by Ken Hammond, USDA-ARS

three feet in diameter and four or five feet high works great. Using a wooden material and to make turning easier. A single ring of fencing or right on the ground and mixing them. Some prefer a caged area pallet or screen supported on concrete blocks at the bottom of the pile will almaterials and to aerate all you do is spin the drum a few times. composters swear by revolving bins for making compost: in go the organic need to experiment to suit your tastes and needs. problem with enclosed systems), these can be very effective. A ure out how to keep the materials in the bin from getting too m low air to circulate into the pile, making it much less work to maintain. Some oist (a chronic to contain the sgain, you will chicken wire, Once you fig-

Place materials in layers of 4 to 6 inches (10 to 15 centimeters), alternating between green and brown, and make sure each is moist. Once metabolic activity sary. If you are composting in a dry climate, flatten out or make a concave imanaerobic activity), make sure to mix wet material with dry material if necescomposting process. Since you don't want the pile to be wet (this encourages has started, you will need to make sure that the pile stays moist for the entire pression in the top of your pile to collect what rain does fall. Similarly, if you ing compost in an enclosed bin. are composting where it rains a lot, cover the pile with a tarp or consider mak-Whatever your setup, you will need to keep an eye on the pile's moisture.

handful from your pile and squeeze just a few drops of water is hard work, so it is better to get it right in the beginning. more. If your pile does get too wet, then add dry materials or turn the pile. This If a pile is too moist, it won't heat properly. You should be able to take a from it, but no

is no reason to risk adding diseased material or really noxious terial to your pile until you get the hang of the process and can distinguish and weed seeds have been destroyed. compost from what we can tell is merely "almost compost." There is a big difference. You have to finish the composting process to ensure Hot composting will kill weed seeds and pathogens in most that pathogens weed plant macases, but there

the finished product. If it smells bad, like vomit or putrefying out to a biological testing lab, but an easier and cheaper home test is to smell not be used. If it smells like ammonia, then it is not finished. In either case, aergar, then it contains anaerobic organisms and their by-products and should another nose test. You know what fresh soil should smell like; ate it to change these conditions, and let it sit for a few days before you give it should smell "clean" as well. How do you know you have good compost? Test it. You can send compost good compost matter or vine-

You can also plant something in it. Good compost supports plant growth. If

they hold won't be cycled and you will be able to tell by the plant deficiencies. there are not enough predators eating the fungi and bacteria, then the nutrients

### Compost for the lazy

adding them to the compost pile, they won't mat or smell. This assumes moisture and air are adequate. We learned from experience that if you spread fresh grass clippings out and let them dry for a day or two before equal volumes of grass clippings and leaves and work from there. If this right to work decaying it. If you don't have access to alfalfa meal, start with leaves and a 50-pound bag of alfalfa meal from an animal feed store. This mix works even better if the leaves are shredded so the bacterial microbes A modern mix for "instant compost" requires three cubic yards of brown tree up too much, use less grass. If it doesn't heat up enough, use more grass.

layer of leaves, and another layer of meal, and so forth. Water each layer lightly circulation through and to the middle of the pile. and then add the next. Add sticks and branches as you go along to increase air followed by a layer of the alfalfa meal (or grass) of the same thickness, another Make your pile in layers starting with 4 inches (10 centimeters) of leaves

rial needed by your army of microbes and other soil food web organisms, they to monitor the temperature: it shouldn't get over 150F (65C) or cool down will go to work. Heat will be noticeable in 24 hours. Thereafter you will need much below 104F (40C). Turning the pile will increase the heat until the pile cert again. Again, water will cool down a pile. reaches the mature stage, after which it won't heat up when you turn it. Turn-Once you have accumulated at least the three cubic yards of organic matelowers temperatures temporarily until the microbes start working in con-

will eventually decay, only very slowly; cool composting can take a year or more versus a few weeks or months for hot composting. The end result is compost, however, and as long as it contains the proper set of organisms, it doesn't matter which system you use. Note that worms, beetles, millipedes, and other micro- and macroarthropods will be represented in higher populations in cool times, no matter how energetic you are; the diversity of soil organisms it adds means a better ability to eliminate pathogens or control them, either by direct attack or by competition for nutrients and space. If this sounds like too much work for you, try cool or cold composting: pile organic matter in a corner of the yard and leave it. This material help your garden. In the soil food web, higher member diversity It is, therefore, a good idea to keep a cool compost pile going at all

#### Vermicompost

supporting good bacterial populations. polysaccharide as well as carbohydrates and simple proteinsbin, vermicompost has a bacterial dominance; the castingsbin to keep them in; this can be a simple wooden or plastic box. Just out of the the worms (that is, the bacteria inside them) digest the materials and create worm digestion). Heat is not involved, as this would kill the worms. Instead, which is almost always bacterially dominated (few if any fungi are involved in castings. You can buy special earthworms for this job and buy or make a small Processing organic materials through earthworms makes vermicompost, -are perfect for -coated with a

als need to be shredded or otherwise broken up, so the worms meats), paper, cardboard, leaves, and green grass; or you can use the same mavents unwanted seedlings from growing in the worm bin. Any brown materiweeds, thermally compost them first before adding them to the bin; this preterials as you would to start a normal compost pile. If your material contains doors will encourage arthropod and insect activity in it. help physically break down the matter for the worms. Putting your bin outquicker. With luck, your materials will also include some microarthropods to Good starting materials for vermicompost include food wastes (no fats or can ingest it

### Inoculate your soils

It doesn't take much compost to impart life to the soils. To inoculate your soils, preciated in veggie and flower gardens and lawns (review Soil Food Web Gararound trees and shrubs and most perennials; bacterial compost bacterial, or balanced) around your plants. Fungal compost should be applied put ½ to 1 inch (0.5 to 2.5 centimeters) of the appropriate compost (fungal, as six months. After only that short period of time, new soil life will be evident dening Rules 1 through 4!). Compost can work its magic in the soil in as little new life comes all the benefits of the soil food web: decompaction, aeration, in the first 6 to 15 inches (15 to 38 centimeters) of the soil inoculated. With this inches (46 centimeters). nutrients. After a year, the soil life will be down as deep as approximately 18 better water retention and drainage, and increased retention and availability of is most ap-

amount of work. The benefits derived from compost, however, are almost incalculable when it comes to managing the soil food webs in your life. Compost an indispensable soil food web gardening tool. Gathering the materials and making a compost pile does take a certain

#### Chapter 16 Mulch

things that were once alive and can be recycled back into nutrients by soil food however, we are only interested in organic mulches, mulches that come from dles, grass clippings, aged bark and wood chips, straw, well-rotted manure (if web organisms. Organic mulches include leaves and leaf mold, aged pine neeyou must), seaweed, "almost compost," plant remnants, and paper. evaporation, prevent weed growth, and insulate plants. Using this ULCH IS anything that can be placed on top of the soil to reduce definition, plastic sheeting makes great mulch. For our purposes,

### New reasons to use mulches

Most gardeners are familiar with the standard reasons to use mulch in the garden. A thick enough layer will smother existing weeds by depriving them of needed sunlight or prevent them from germinating in the first place. Mulches also help give landscaped areas a neater appearance and keep soils cool when there are freeze-thaw cycles, mulch is great at preventing premature plant there is too much heat; where it gets cold, mulches insulate the soil, and where heavy rains. They greatly reduce evaporation from the soil. growth by keeping soil frozen. Mulches prevent the soil compaction caused by

works wonders in imparting soil food web benefits to the soil. For example, nutrients and a home for certain soil food web organisms, and a good mulch are nutrient-rich worm castings, more worms, worm tunnels and dens, better arthropods are able to live in mulches, speeding decay, adding to the soil's water retention, and improved aeration. All manner of micro- and macro-Absent from the usual list of reasons to use mulch is that mulch provides pull mulch material into underground dens for shredding; the results

ganic content, and attracting other members of the soil food web. adding microbes quickly to the soil food web. Mulch cannot match compost's diversity of soil food web organisms; the decay process has not been completed readily acknowledge that mulch is not as effective as compost for

numbers of compost's organisms. (and may not even have started), and thus organic mulches lack the variety and

nutrients can be cycled from them. roots are located, things are fine. When mulches are used properly, however, able to shallow-rooted weeds, while deeper down in the soil, where your plants trients on the soil's surface, where the mulch is put down. These are not availwell: the biology in mulches ties up nitrogen, sulfur, phosphate, and other nument of plants in the area. This is another reason mulches control weeds so upon the bacteria and fungi-can result in nutrients being tied fungi which—if not matched by a feeding frenzy of nematodes and protozoa We also admit that mulches can result in a feeding frenzy by bacteria and up to the detri-

use the right kind of mulch, you can establish dominance of fungi or bacteria The one benefit of using mulches that should be evident to you by now: if you

### Bacterial vs. fungal mulch

ally attract microarthropods, arthropods, worms, and other soil food web paring green mulch on soil will foster populations of bacteria. Either will eventulocations. You know the routine—a soil food web evolves. shredding and tunneling through it, taxiing other members of ticipants. These will work through the mulch, pulling bits of Mulching your garden with brown leaves will encourage a flush of fungi; placports fungi; a mulch of fresh, green organic materials supports bacteria. Rule #6 remains operative here. A mulch of aged, brown organic materials supit into the soil, the web to new

sary sugars to attract and feed bacteria. Avoid grass taken from lawns where grass clippings, the most readily available green mulch, contain all the necespings too thick, as they can start to compost and go anaerobic. yards where dogs are part of the soil food web). Be careful not to pile grass clipweed killers and pesticides have been applied (and don't accept clippings from trying to impact. an offensive odor or heat that can interfere with the very soil food web you are A number of good organic mulches are available free or at low cost. Fresh This will create

after they fall. These support fungal dominance unless ground up into very least grow fungi faster) than do wood chips. fine pieces (in which case they are open to bacteria, who beat fungi into the material). It is also our experience that leaf mulches grow more Our favorite brown mulches are made from the leaves we save each autumn fungi (or at

ile and should be mixed with other materials to introduce some microbiology. Peat moss is often used as brown mulch. Peat, however, is biologically ster-

if you mix in some form of organic nitrogen, such as green grass or even alfalfa sawdust are great brown mulches and work fine, especially if they are aged should be avoided, but most other wood chips, shredded or chipped bark, and toxic to many plants. Cedar chips also contain high levels of terpenes only after they are aged a bit: they contain terpenes, volatile chemicals that are microbes from the soil under the mulch. meal, to ensure the C:N ratio is adequate and nothing need be borrowed by the needles, another brown mulch available to some, make great mulch, and

or four years, as the lignin, cellulose, and waxes in the bark are difficult for mi-For example, a 2-inch (5-centimeter) layer of bark chips will last about three start, but bacteria increase once they are able to get inside the material. hand, can be completely decomposed in six months; fungi dominate crobes to decay. During this time, fungi will dominate. Leaves, on the other How long mulch will remain effective depends on the kind of mulch used



Leaves make great brown mulch. Photograph by Judith Hoersting.

soil tends to support bacteria) means it is possible to use one kind of say tree leaves, and get two different soil dominances. Bury most mulch, and (mulch laid on the surface tends to support fungi, while mulch worked decay activity for a while because it is easier for them to travel from the soil to bacteria will have an easier time. If it is on the surface, fungi will dominate the Where and how you place mulches also plays an important role. Rule #7 into the mulch,

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grind mulch thoroughly, it speeds up bacterial colonization (Rule #8 ground up, it has a lot more surface area; increased surface area means it is easria need moist environments, or they go dormant. And if the material is ier to get into, and bacterial populations increase. To keep fungi from getting to their food source, some of these bacteria produce antibiotics that fungal growth, making it easier for the bacteria to attain dominance once they ground up and soaked. If you only have brown mulch material and need to get established. If you want more bacteria, use green mulches that have been top few inches of soil. establish bacterial dominance, chop it into really fine bits and mix some in the That is not all. The condition of the mulch is also important. If you i). Bactesuppress wet and

ity (Rule #9). Mulches with less than 35% moisture are considered "dry more dependent on moisture. If you want fungal activity, use brown leaves or wood chips; don't pulverize them or wet them much; and place them on the On the other side of the coin, coarse, dryer mulches support fungal activ-Sure, fungi need some moisture to thrive and grow, but bacteria are

#### C:N ratio—again

biology; and once again, the ratio of carbon to nitrogen comes into play. If In order to decay, mulch requires air, water, carbon, nitrogen, and the right there is abundant carbon in mulch but not much nitrogen, or a ratio of 30:1 or greater, then the decaying microbes use up the nitrogen in the mulch and, once that is gone, will take nitrogen from the soils touching the mulch.

at the thin interface of the soil and the mulch. Although it has a real impact there, it usually doesn't affect the rhizosphere or the bacteria and fungi that reside there. Still, there is no reason to court problems. Experience has taught us that the chances nitrogen will be immobilized in soils under wood chip mulch can be reduced by making sure the chips are 3/8 inch or larger. This prevents much of the bacterial colonization you would see in smaller wood chips, and People make a big deal of this nitrogen "robbing," but it usually occurs only

gen in the surrounding soils. where mulches are concernedit is primarily the bacteria that tie up the nitro-

#### Applying mulches

Mulches are easy to acquire and relatively easy to handle and use in support of surface) around your plants (vegetables, annuals, and grasses, or trees, shrubs, or brown; wet or dry; coarse or fine) in the appropriate way (dug in or on the mycorrhizal fungi. Do not put mulch snug up against stems or trunks; this can centimeters) and you may end up blocking moisture and air and smothering your soil food webs. Simply apply the rules and the appropriate mulch (green cause microbial decay of the plant itself, so back off a bit. perennials). Be careful: add a layer any thicker than 2 to 3 inches (5 to 7.5

ine how much more work they will save when you use them to help feed plants summer, insulating soils in winter. They save a lot of work, don't they? Imagthey can accomplish: keeping weeds down, holding in moisture during the the kind of nitrogen they prefer. So correct any mulching mistakes you may plant type you have. have made and reapply the proper kind of mulch, in the proper way, to each you already use mulches on your property, you know what great things

post organisms will inoculate the mulch, and begin to decay it as well. compost down first and then cover with mulch. As they do the soil, the com-Mulches excel when they are used in conjunction with compost. Put the

you don't also have the proper nutrient cyclers, specifically protozoa and grow your own protozoa by soaking fresh grass clippings, alfalfa, hay, or straw nematodes, it is not going to have a big effect on your plants. You can actually in dechlorinated water for three or four days. It is a good idea to bubble the water with an aquarium air pump and air stone (available at garage sales everynutrient cycling power of the second soil food web gardening tool. guaranteed to). Pour this protozoa soup on mulches, and you will increase the be able to just make out protozoa dashing around (use a hand lens, and you're Finally, you can foster all the bacteria and fungi you want in mulch, but if keep the mix aerobic. If you look carefully at this soup, you should

### Compost Teas

mulches around and applying them can be hard work. You also tools, compost and mulches. Besides the effort of turning a compost pile, if you chief problems with these two tools? They take a while to reach the rhizoslots and lots of both if you are working on anything but a small have a decent-sized garden and lots of trees and shrubs, carting phere. And neither mulch nor compost sticks to leaves. Plants area immediately around leaf surfaces. As in the rhizosphere, these microbes dates from their leaves, attracting bacteria and fungi to the phyllosphere, the leaf surfaces from attack. You cannot immediately introduce this into the rhizosphere, or into the phyllosphere at all, with compost or mulch. compete with pathogens for space and food and in some cases can protect the IOMPOST TEA-the third tool in the soil food web gardener's shedputs the microbiology back into soils. This is a good t there are some practical problems associated with using generate exuhing because microbiology the other two compost and yard. But the have to have

web microbiology in your yard and gardens, handily overcoming the limita-They are a fast, inexpensive, and definitely fascinating way to manage soil food tions of compost and mulch. Actively aerated compost teas, on the other hand, are usually easy to ap--to both soil and leaf surfaces—and are put right where they are needed.

### What AACT is not

extracts, or manure teas, all of which have been employed by farmers and gar-Do not confuse actively aerated compost tea with compost leachates, compost

of color and may have some nutrient value, but leachates do little or when water runs through it and leaches out. Sure, these concoctions get a bit crobial life to your soils: the bacteria and fungi in compost are attached to organic matter and soil particles with biological glues; they don't simply wash off. Compost leachate is the liquid that oozes out of compost when it is pressed Compost extract is what you get when you soak compost i in water for a to impart mi-

it safe or advisable to use them. alone (not to mention the risk of its containing anaerobic pathogens and alcobit of aerobic activity on the surface. couple of weeks or more. The end result is an anaerobic soup with perhaps a hols) suggests that compost extracts are not worth the effort. We don't consider The loss of aerobic microbial diversity

especially under anaerobic conditions, virtually assures the presence of weeks, is also anaerobic. Using manure is asking for pathogenic problems and, have to keep things aerobic. We want the beneficial microbes to be working in our soils and to get these, you Manure tea, created by suspending a bag of manure in water for several

### Modern compost tea

ial population, for example, grows from 1 billion in a teaspoon of compost to properly made, it is a concentrate of beneficial, aerobic microbes. The bacter-Modern compost teas, on the other hand, are aerobic mixtures. If the tea is 4 billion in a teaspoon of an actively aerated compost tea. These teas are made tive aeration, that brings old-fashioned anaerobic compost teas into the modrinated water and aerating the mix for one or two days. It is this mixing, or acby adding compost (and some extra nutrients to feed its microbes) to dechloern era; it is also what keeps these compost teas aerobic, and thus safe. The air supply must be sufficient to keep the tea aerobic throughout the entire process.

slime: plaque on your teeth. Bacterial slime in soils is just as strong. Consider, energy you have to use daily (or should) to remove another form of bacterial as well, that fungal hyphae grow not only on the surface of the compost crumb It takes energy to separate microbes from compost. You know how much

| 2-10                 | 20-50    | 1,000   | 1,000       | 5-20 µg     | 2-10 µg      | 150-300 µg     | 10-150 µg       |  |
|----------------------|----------|---------|-------------|-------------|--------------|----------------|-----------------|--|
| Beneficial nematodes | Ciliates | Amoebas | Flagellates | Total fungi | Active fungi | Total bacteria | Active bacteria |  |

Minimum standards for organisms per milliliter of compost tea. Courtesy Tom Hoffman Graphic Design.

Actively aerated compost tea is teeming with bacteria, fungi, protozoa, and nematodes extracted from compost.

Photograph by Judith Hoersting.

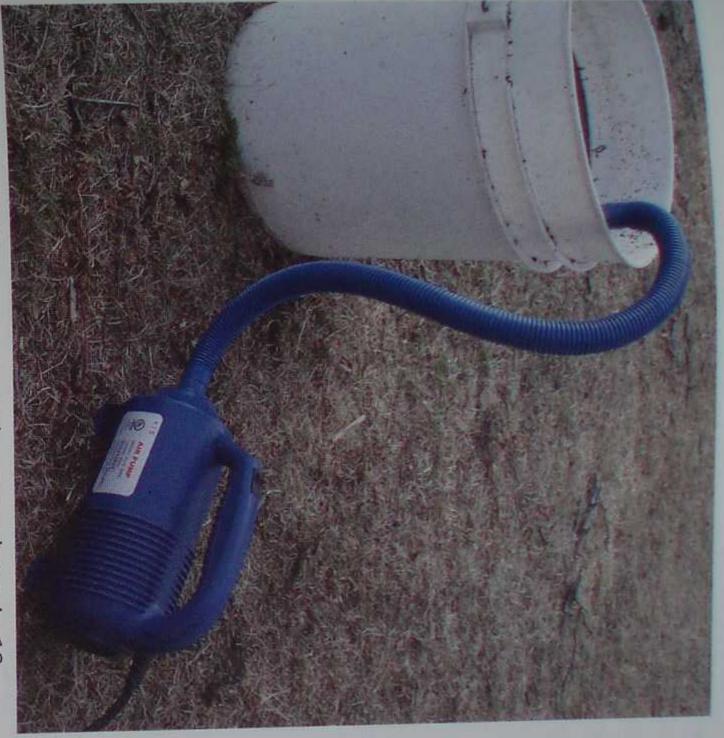


but inside its nooks and crannies; you have to use energy to pull these strands energetic action can kill these microbes. A brewer's action must be strong off and out in addition to getting the bacteria "unglued." Of course, too much once they are out of the compost and into the tea. enough to tease out the microbes but not so strong that the micr obes are killed

#### The brewer

More and more compost tea brewers are on the market. These range from small, 5- to 20-gallon systems that can easily make enough tea to take care of a look for compost tea brewers and compare them. Manufacturers should be to a thousand gallons or more of tea per brew. The Internet is a few acres (about 1.2 hectares) to commercial brewers capable of able to show tests demonstrating that their machines can extract viable popubers. Insist on seeing one, and if they don't have one, don't buy lations of fungi as well as bacteria. Only a biological test will tell the machine. you the numgood place to producing up

our suggestion for those just starting with teas. All you need is one of those ubiquitous five-gallon plastic buckets; add to this an aquarium air pump (the biggest outlet pump, use at least two single outlet pumps. Sufficient aera use with it. The better pumps have two air outlets; if you cannot get a doublesmells good, things are fine. If it starts to smell bad, the tea is going anaerobic. Once your system is operating, you will know if you have enough air. If the tea to air ratio and thus more air exchange with the water, but when bubbles get You can also make an actively aerated compost tea brewer. It is very easy and can afford) and air stone, and about 4 feet (1.2 meters) of plastic tubing to We learned in physics that the smaller the bubbles, the higher the surface tion is critical.



The KIS commercial brewer can make enough tea in 12 hours to treat a one-acre property. Photograph by Judith



The BobOLator, which uses a chamber to hold the compost, makes 50 gallons of tea in 24 hours. Photograph by Judith Hoersting.

attaches them to the pump) clean. Another system can be made replacing the work well as long as you remember to keep them (and the plastic tubing that too small, under 1 millimeter, they can cut up microbes. Aquarium air stones air stone with a two-foot link of 1/4-inch soaker hose designed for drip irrigagiving better bubble "coverage" than an air stone. tion systems. This hose can be coiled and taped onto the bottom of the bucket,

of the bucket, then connect the tubing and run it out of the bucket to the pump. If you want to have a really good-looking system, you can buy a small rubber grommet designed to be placed inside of the bucket wall so that you can thread the air tubing through it without having liquid leak out. If you put this low enough on the bucket wall, or even in the bottom of the bucket, it is easier to keep whatever you use to create bubbles down on the bottom of the bucket. Using a bit of duct tape, we tape the air stone or soaker hose to the bottom put it into the

tea brewer rather than allowing it to mix freely in the water. This eliminates the drench, straining is not a problem). A pair of large-sized pantyhose works well ing to use the tea in any garden sprayer (if you are only going to use tea as as such a "compost sock." Some people put their compost in a porous bag before they strain tea before you apply it, which you will have to do if you are go-We'll save the male readers some research time a soil

It is easy to make a simple actively aerated compost tea brewer using aquarium pumps and air stones.

Photograph by Judith Hoersting.



learned by standing around and reading the labels at the store display that the around the top of a five-gallon bucket, so that the legs fall into the bucket, and largest pantyhose are often size Q. You can stretch the waist of a size Q all "bag" this creates with compost. It will sit in the water. drop the compost right in the legs. Or you can tie the legs in a knot and fill the

# Siting and cleaning the brewer

bial activity slows. If temperatures get too high, then the microbes are literally Temperature is important when brewing compost teas. If it is too cold, microcooked or go dormant. Room temperature is ideal. Keep track temperature. This is one of the variables you can adjust later, if need be, and a cannot site your brewer in a warm place with steady temperatures, then a record of this information will be helpful to the lab testing your samples. If you small, inexpensive aquarium heater might be needed; these come with autosider "packing" your bucket with ice or occasionally adding ice matic thermostats. If it is too hot where you make tea, you may temperatures down. k of the water to it to keep have to con-

violet rays kill microbes. And, since the proteins (worm bodies, in a spot that can tolerate some spillage. compost have a tendency to foam in the tea, make sure you keep Compost tea should be made away from direct sunlight because its ultraprimarily) in your brewer



These black rings are bioslime that formed on the inside of a compost tea brewer basket. If allowed to remain, bioslime can detrimentally impact the quality of the tea produced. Photograph by Judith Hoersting.

right away when making actively aerated compost teas. Bacterial slime is strong stuff and can clog the air holes in bubblers and tubing. This bioslime will apand fittings to clean them thoroughly. So, even before you use your tea, clean late in the crevice at the bottom of the bucket. You may have to take apart hoses pear in the strangest places. It will stick to the sides of the bucket and accumu-"blow" it off with the force of water from a hose; at a minimum, flush it with water. Use a 3% hydrogen peroxide product or a solution of 5% baking soda your system. If you get to it while it is still wet, you can usually wipe it off or clean slime that has dried. It should be obvious but must be noted that it is important to clean up

#### Ingredients

protozoa because that's what's in compost. What makes these teas such a good Actively aerated compost teas contain lots of bacteria, fungi, nematodes, and tailor-make AACTs to feed plants according to their specific needs by adding soil food web tool (besides the high concentration of microbes) is that you can certain nutrients (see Rule #10). Use Rule #10, which applies equally to compost, mulches, and soil, when you make compost tea, and it evolves into Rule #11: by choosing the compost you begin with and what nutrients you add to it, you can make teas that are heavily fungal, bacterially dominated, or balanced. For many, the brewing process grows into a hobby in and of itself, not unlike making be

makes sense. After all, these chemicals are intended to kill or discourage microimportant that none of the ingredients you use contain any preservatives. This of carbon will filter four gallons of water a minute quantities of water. As a general rule, a carbon filter containing one cubic foot both chlorine and chloromines, and are particularly useful if you need large hour or two. The chlorine will evaporate, making the water safe fill your brewing container with water and run air bubbles through it for an bial life. If you are served by a water system that uses chlorine, you will need to chlorine and preservatives in the brewing water and ingredients. It is vitally rine-free water. Rule #12 is very important: compost teas are ver Carbon filters and reverse osmosis water systems also work well to remove All recipes, however, start with the basic ingredients, the first being chloy sensitive to for microbes.

and anaerobic. Don't bother with compost that was allowed to overheat, killing "almost compost," compost that hasn't finished the process or has isn't good compost. Obviously, the best way to know is to have it tested. Avoid remnants in it, and by all means give it the sniff test. If it doesn't compost is good, or it isn't compost). Again, make sure there are no chemical of microbes in your compost, you will have low diversity in your tea. beneficial microbes and reducing its soil food web. If you have Next, you need to use good compost (forgive this redundancy: to us, all a low diversity smell good, it gone stinky

side the worm, digesting food), especially when they are fresh. cial microbes and tend to be very bacterial (remember the role bacteria play invermicompost. You can use proportionately less compost the bigger the brew. five-gallon brew, you will need approximately four cups of either compost or Vermicastings are a good substitute for compost. These are For the initial full of benefi-

dered or liquid form, cane syrup, maple syrup, and fruit juices all feed bacteria teas are brewing. Molasses (nonsulfured, so as not to kill the microbes) in powsugars in four or five gallons of water will help bacteria multiply and establish in teas and increase their populations. Two tablespoons of any of these simple As for the extra ingredients, you can feed the microbial population while

| 500 gallons      | ou gallons      | Suoling cz      | DECHLORINATED WATER |
|------------------|-----------------|-----------------|---------------------|
| 15 lbs (60 cups) | 7 lbs (28 cups) | 5 lbs (20 cups) | WATER COMPOST       |
|                  |                 |                 |                     |

The amount of compost (or vermicompost) used to make tea varies nonlinearly, as this chart shows. Courtesy Tom Hoffman Graphic Design.

dominance. If you make a bigger brew, add more nutrients in the same proporterial food, though both will also support some fungal growth. size of your brew. More complex sugars and fish emulsion are also good baction: the amount of all added nutrients will vary linearly as you increase the

acids, and phosphate rock dusts, which not only provide the fungi with nutriden centers, and even animal feed stores, where it is often sold as powdered alent value but also give them surfaces to attach to while they grow. Ascophyllum grow in compost teas, as will aloe vera extract (without preservatives) and fish gae. The pulps of fruits like oranges, blueberries, and apples will also help fungi nodosum is a cold-water kelp that can be purchased over the Internet, at garappropriate enzymes) to a blend of fish to enzymatically digest the bones. own by adding papain (aka papaya peptidase) or kiwi (which also contains the bones and all). You can buy fish hydrolysate at some nurseries or make your hydrolysate (which is essentially enzymatically digested ground-up fish-Yucca and zeolites are also good fungal foods and do not support populations To encourage fungal growth in compost teas, add kelp, humic and fulvic

### Give fungi a head start

inated one. This is because bacteria not only grow but multiply rapidly in tea fungi in quantities sufficient to make a balanced tea, much less a fungally dom-Many new to tea brewing become frustrated because it can be difficult to grow for fungi to multiply in tea-they only grow bigger. The better way is to actigiven adequate nutrition; whereas the brew time is almost never long enough vate fungi in the compost prior to making tea, allowing populations to multiply before they are teased out of the compost and into the tea brew.

mix the compost with simple proteins that serve as a good fungal food—such things as soybean meal, powdered malt, oatmeal, oat bran, or, best of all, powtablespoons per cup of compost. Make sure there is sufficient moisture in the dered baby oatmeal. Thoroughly mix in one of these at the rate of three or four it. Put the mixture in a container, and place the container in a warm, dark compost, which is to say a drop of moisture can be squeezed out of a fistful of place. A seed-germinating mat, placed beneath the container, works great to This activation is easily accomplished: several days before brewing the tea,

sufficient numbers of them in the first instance, will have grown, and their invisible hyphal threads merged into a network of visible mycelia. The compost provide the proper heat. After about three days at 80F (27C), the fungi in your compost, if you had



Photograph by Judith Hoersting. Fungal mycelia are activated by adding fungal nutrients to compost before making tea.

should look like Santa Claus's beard, covered with long, white, fluffy strands. of compost will be glued together. In a few more days, there will be so many fungal threads, the entire container

#### leatime

peeling microbes off and out of it. Depending on the compost and the nutrients, you may experience a bit of foaming; this can signal that worm protein is Once you turn your machine on, the bubbles agitate the compost and start being released from the compost—a good thing. You can add will be destroyed—they are both very fragile; also, since mycorrhizal fungi live fungi at the very end of the brew cycle. If you put spores into the off of root exudates, they and the tea must reach plant roots quickly. being made, either they will be destroyed or the fungal hyphae they produce tea while it is mycorrhizal

coffee-brown and the course of the brewing, tea turns make tea in 12 L. commercial brewers, with their high-energy systems, teased out into the favorable sign: the humates in the compost are being teased out into the tea. The temperature of the brew may also increase a few It takes between 24 and 36 hours to develop a good tea using our simple

degrees, a result of increased metabolic activity. The best part is the smell. The healthy, sweet, earthy smell. smell of compost teas, especially when molasses is used as a nutrient, is a

a tea, it has probably gone anaerobic and should be discarded; do not toss it on important, they are using up all the oxygen. If you are offended by the odor of of manufacture, though it will last, diminishing in populations, for about three brew that they quickly deplete the nutrients and start eating each other; more to five days if kept refrigerated or if you continue to bubble air through it. your plants, for obvious reasons. It is best to use compost tea within four hours Compost tea has a very short shelf life. So many microbes now populate the

your machine in order to make better and better teas, meaning those that have higher numbers of microbes. For example, besides substituting the soaker hose used, 1/3 horsepower air pump, and now make seriously bubbling tea in a 30for the air stone, we also upped the size of our pump; eventually we found a gallon plastic garbage can (affectionately known as the "Lawrence Welk-oally experimenting, using specialized fish tank and Jacuzzi aerators, watering Lator"). The bubbles come from various pieces of equipment; we are continucan heads, and even a plastic water pipe pocked with holes made with 1/16- and 1/8-inch drill bits. After you have had some experience making teas, you may want to modify

#### Application

tea (our research shows no ill effects from unlimited applications). It doesn't Right at the outset we will tell you that you can never apply too much compost increase diversity of the microbial populations in your soils. Use tea on lawns, vegetables, trees, shrubs, annuals, and perennials. Unlike chemical sprays and nutrients available at the site. Repeatedly applying compost tea will only help burn plant roots or leaves, and the microbiology in the tea will adjust to the

soaks, compost tea is safe and easy to apply.

ing can (bacteria can impact the zinc in metal containers), or (if the tea has been strained) a hand pump sprayer. Since compost teas will "stick" to leaf surfaces, you can inoculate leaves with a foliar spray of beneficial microbes. To be effective as a foliar spray, the tea must cover 70% of the leaf surface. Cover both sides of the leaves. When applying compost teas to soils, drench your plants Once the tea is ready, apply it as a soil drench using a cup, a plastic water-

ern latitudes, you will want to apply before 10 a.m. or after 3 p.m., when UV And don't forget the sun: ultraviolet rays kill microbes. If you live in souththe area around them with the tea. You cannot overdo it.

about the timing of these since the microbes sink into the soil affect the microbiology in soil drenches, but you can be a bit lish themselves before the water even evaporates. UV layer almost immediately. millimeter; with that much water, bacteria can develop enough slime to estabposed to the sun's rays. Alternatively, spray with a drop diameter of at least 1 to a leaf (where they can get some protection)—far too long a period to be ex-It can take 15 to 30 minutes for bacteria or fungal hyphae to attach themselves rays are weakest, even on a cloudy day. There is no microbial sunblock lotion. rays can a more relaxed lso negatively and leaf duff

should be no forceful "splatting" of the tea onto the soil or lawn or plants, as up, so that the tea drops "parachute" on them, so test the tea from such a sprayer before using one. static sprayers, incidentally, may destroy microbes by putting the wrong charge this is what will sometimes kill the plant, not the pressure of the tank. Electrovelocity of the spray should be slow. Either stand back or turn the spray head gentle treatment. Sprayers must not exceed pressures of 70 pounds, and the carefully cultivated and nurtured in your tea are very much alive and require Remember, you are dealing with living organisms here. The down to the surfaces to be covered; there microbes you

should be at least 400 micrometers, which is big enough to let fungi and nematodes flow through but will keep out particulate matter that will clog convenmust take care not to strain the microbes out. The mesh of any "compost sock" tional sprayers. Alternatively, you can decant a tea solution by letting it sit for pieces; the bad news is that often the amount of fungi in the tea 15 minutes after the aeration is stopped. This gets rid of a lot of the bits and It is possible to use a hand pump sprayer if you strain your tea, but you is diminished.

fewer bends, larger orifices, and nozzles that support bigger prices and availability, check with your local builders supply store, concrete handling the particles of compost that would clog a normal garden sprayer. backpack mist sprayer is also appropriate, especially for a large yard. A great contractor, concrete supply store, or sand and gravel company. A gasoline ing tea into the water stream (see chapter 18 for more details). way to do a lawn is to use a traveling sprinkler with a fertilizer dispenser feed-Concrete sprayers look exactly like home garden pump sprayers, only with You will be better off if you invest in a concrete sprayer, which is capable of particles. For

create protective barriers around the roots and release nutrients leaves and compete with bad guys there as well. Whether sprayed or poured, the microbes in the tea will establish themcreate and improve soil structure. They grow, breed, attract predators, eat and be eaten, or go dormant. They make protective barriers on when they die.

able to ask for tests to see how the tea measures up and, of course, don't be afraid to give commercially made teas the smell test before buying or applying only make but will apply compost teas for you. In either case, it is still advisnot up to the job yourself, you can purchase AACTs from an ever-growing them. They may have started out fine but gone anaerobic before sale. number of commercial nurseries and garden centers; some companies not pathogens. There is little room or tolerance for a poorly made tea. If you are that the tea applied be a good one, full of beneficial organisms, not diseases or Compost teas go to work immediately, and for this reason it is important

should get a base reading on microbiology and arthropod counts before "takthe status of the soil food web organisms in the areas concerned. First-timers them (especially if you are paying for them) depends, as you can imagine, on need to apply tea less often. Thus, if your yard has had applications of chemistart applying tea once every month for a season and, finally, three times a year. cal fertilizers for years, you should put down compost tea every other week for three months to establish a healthy soil food web population. Then you can You can apply AACTs as often as you like, but how often you need to apply this very effective tool. As your soil food web becomes healthier, you'll

tive results (save for a few complaints from a spouse that felt too much time years one of us used about 60 gallons a week on a quarter-acre lot with posiwas being spent teaming with microbes). The general rule, however, is to apply five gallons of compost tea per acre as a soil drench, ten gallons if you are going to spray leaves as well. It is fine to dilute the tea; just make sure there were five gallons when you started. When you are more experienced, you can match the amount of tea you apply with soil tests and tea tests to achieve specific fungal or bacterial ratios. How much compost tea should you apply in any given session? For two

#### Timing

ample, it is a good idea to apply teas immediately after leaves fall in the au-There are certain times when it makes even more sense to apply a tea. For exapace all winter long. Even with snow cover, decay will occur at the interface of tumn. If the soil and leaf litter don't freeze in the winter, decay will proceed the snow and the soil surface, where it will warm up enough for microbial activity to continue. Come spring, just before plants start their new growth, put down tea again: ten gallons of soil drench per acre is our suggestion. Treat opening buds and young leaves to a foliar spray of five gallons per acre, as well. If your plants are thriving and are disease-free, you need apply tea only at these



Powdery mildew growing on leaves. Compost tea sprayed on leaves can outcompete this and other fungal diseases. Courtesy Clemson University, USDA Cooperative Extension Slide Series, www.forestryimages.org.



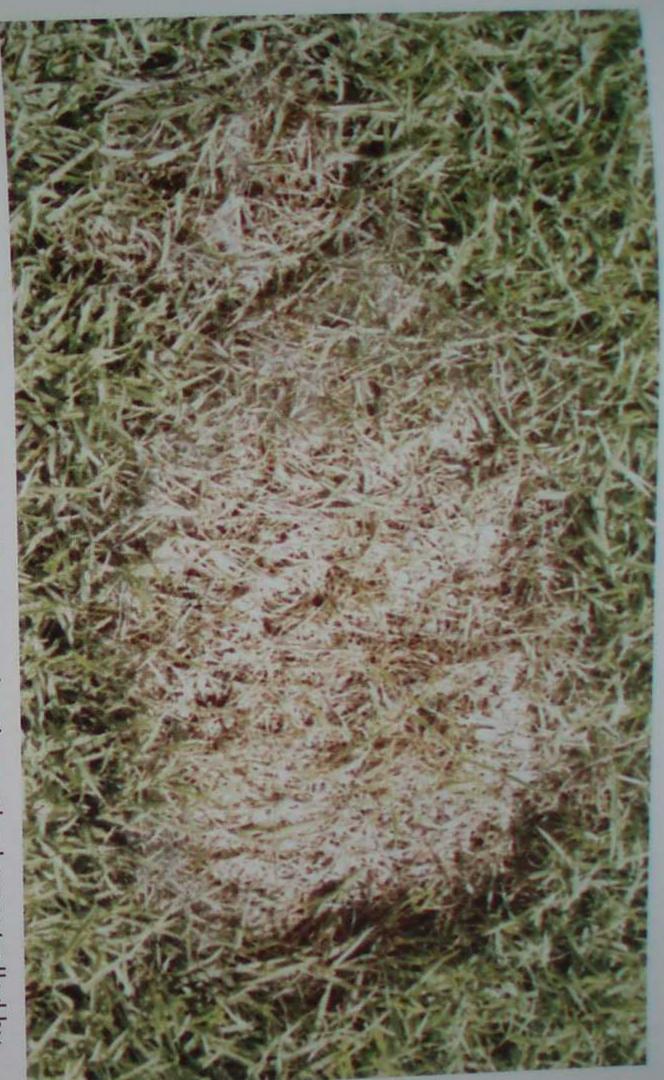
Powdery mildew up close. Image copyright Dennis Kunkel Microscopy, Inc.

two times; if you live in a tropical environment, you should apply tea four

sphere, fungally dominated teas have been used to prevent and suppress the growth of powdery mildew (Erysiphe graminis on turf, Phytophthora spp. on rhododendrons), downy mildew (Sclerophthora spp.), take-all (Gaeumannospp.), red thread (Laetisaria spp.), crown and root rots and damping off myces spp.), gray snow mold (Typhula spp.), pink snow mold porthe spp.), rusts (Puccinia spp.), and fairy rings (all sorts of (Pythium spp.), brown patch (Rhizoctonia solani), summer When it comes to outcompeting disease organisms in the soil or phyllofungi). patch (Magna-(Microdochium

mild cases of dollar spot (Sclerotinia spp.of fungal competitors), necrotic ring spot (Leptosphaeria spp.), yellow patch worms and the fire (Rhizoctonia cerealis), leaf spots (Bipolaris spp., Curvularia s) worms, and chafers; several reports attest to negative impacts o (Limonomyces spp.), and stripe smut (Ustilago spp.). Insects Bacterially dominated teas have been useful in outcompeting pathogens in -severe infestations also require lots too succumb to spp.), pink patch on whiteflies, fire

ply teas and repeat in five to seven days. Obviously, a prophylactic application At the first sign of disease or insect infestations on any of your plants, ap-



applications of actively aerated compost tea. Courtesy Clemson University, USDA Cooperative Extension Slide Series, www.forestryimages.org. Root rot and damping off (shown here on bent grass host) can also be controlled by

should be able to apply teas in advance of breakouts. is best: if you have a sense of your yard's phenology (seasonal cycles), you

have a tougher time of it when you add lots of protozoa and beneficial nematodes to the soil; this teas do and increase nitrogen cycling. Plantains, chickweeds, and nut sedges disappear if you reduce the nitrates in soils: use a fun-Finally, certain weeds are affected by compost teas. Clover and quack grass

gally dominated tea. Ivy also responds to highly fungal teas. Compost teas are a veritable liquid soil food web. Instead of lugging around

wheelbarrows of compost, consider compost teas, a concentration of the same microbiology. When you use them, you are really teaming with microbes.

### Chapter 18 The Lawn

nitrogen-based fertilizers and to do so cheaply. The rest is history: through when a company that sold grass seed came up with a way to lawn care has grown into a multibillion-dollar industry. aggressive advertising, and let's face it, fantastic results, the put down manure or top-dressed with compost. If you had weeds, you SED TO BE, if you were not happy with the way your lawn looked, you or your children eradicated them by hand. All that changed in 1928 chemical side of make synthetic,

### A vicious cycle

trates are so high, they are immediately effective: fertilizers are chemicals that Chemical lawn fertilizers work, and they work well. Their concentrations of niof synthetic fertilizers kill off most or all of the soil food web microbes (Rule feed the roots directly, bypassing the biology in the soils. However, applications #13). These fertilizers are salts, and when they come into contact with soil microbes, they cause osmotic shock—that is, water in the cells of these organisms flows to the higher concentration of salts without, literally cell walls and killing off the microbes that hold (bacteria and fungi) and cycle (nematodes and protozoa) nutrients. bursting through

strength, and the amount of fertilizer applied. A good rule of thumb, however, tilizers depends on the organisms in question, their concentration and is that 100 pounds of nitrogen lawn fertilizer per acre will wipe out a healthy soil food web. Lesser quantities kill fewer members of the soil food web, but do damage it nonetheless. What isn't killed outright by four 25-pound bags of lawn fertilizer is driven from the acre by its lack of food resources or by the odor of the chemical fertilizers themselves. When microbiology is missing, as you know, you have to apply (and reapply) the nutrients necessary to keep the How quickly a lawn's soil food web organisms are affected by chemical fer-

thrown out of whack; soil pH gets lower and lower as more nitrate salts are With the natural buffering action of bacteria and fungi lost, a soil's pH is

applied, eventually requiring readjustment. Matters are made even worse by the common practice of removing grass clippings while or immediately after mowing. The chemical gardener is usually one that "cleans up" after mowing, and even the organic gardener all too often has the knee-jerk urge to rake grass clippings. By removing clippings and autumn leaves, a gardener unwittingly compounds the destruction of life in the lawn's soil. Then again, if you don't have a soil food web to break down and decay leaves and clippings, you are compelled to remove them so they won't block the light the lawn needs.

izer you use, the more the soil food web is destroyed, and the more fertilizer end result is either a lawn in really terrible condition or a gardener who has to you'll need to fill the nutrient void you've created. It is a downward spiral. The do a lot of work. Removing the clippings from and applying salts to a lawn leaves the gardener, alone, to do all the work that was formerly carried out by the trillions upon trillions of microbes who used to be on the job. Earthworms leave the area when salts are applied; salts are irritants, and the gut microbes responsible for worm digestion die if fertilizers are ingested. The fungi that bind soil aggregates are gone. The bacteria that produce the slime that binds individual soil particles into aggregates are gone. The lawn's soils lose structure. Slowly, they lose the ability to hold air and water. It is soon Katy-bar-the-The use of chemical fertilizers sets off a vicious cycle, then: the more fertil-

door time, and more diseases and problems will arise. infested annually with mildew, black spot, rots, gray mold, and other disease-Without a well-populated soil food web, natural defenses are gone. Lawns



Dollar spot, one of the two most troublesome diseases of golf course greens, can caused by excessive nitrates in chemical fertilizers. Photograph by Kevin Mathias, USDA -ARS.

isms that would normally keep these things in check. By t causing opportunistic microbes clearly lack the diversity of crobes, you can have a healthy and attractive lawnyour part. -with a lot less work on eaming with mibeneficial organ-

#### Taking stock

of your lawn's soil food web. Biological soil tests by a competent lab are the As with any other area of the yard, it is important to first determine the status only accurate way to learn what needs to be corrected and exactly how much restoration work you have to do, but other things will give indication of its state. Earthworms, for instance, won't be present if there are no bacteria, fungi, and protozoa to eat; their presence, there indicator of a healthy food web. If you have a good population of worms, your nutrients to the grass roots, building water- and air-retention and drainage calawn already has lots of beneficial organisms building soil pacity, and fighting pathogens. So, if you see birds hunting for earthworms, lots of earthworms after a good rain, or worm castings deposited on the lawn's suradd microbiology to establish one. face at night, you probably have only to maintain the lawn's soil food web, not fore, is an excellent you a pretty good structure, cycling



A lawn maintained by the soil food web. Note the yellowish back area, which was not treated. Courtesy Soil Foodware treated, Courtesy Soil Foodweb Inc www.soil

or other soil food web participants that are missing. teria, protozoa, and nematodesthe soil. Use a Berlese funnel; if you discover that your soils are lacking these These help with nutrient cycling, open up the grass clippings, and hel little arthropods you need a hand lens, MacroScope, or light microscope to see. members, you can restore the microbiology by providing beneficial fungi, bac-Similarly, your lawn's soils should contain plenty of microarthropods--the base that will attract arthropods, p aerate worms. -the

# The care and feeding of microbes

ply of organic matter to feed the microbes in the soil. Microbe food? At the beginning or end of the growing season, spread an organic fertilizer (microbes, you feed them, and they feed the roots. big but necessary change in gardening terminology. When you team with microbe food, really) on your lawns. This will ensure that there is a sufficient sup-This is a

ing. Don't put anything on the lawn with NPK numbers greater than 10-10-10; potassium in the fertilizer, and this NPK trilogy appears on all fertilizer know these letters represent the percentages of nitrogen, phosphorus, and traditional organic fertilizers usually meet this criterium. Of particular note is that a high (anything over 10) concentration of phosphorus not only mycorrhizal fungi from growing but kills off the ones that are there. As stay away from additives that have high NPK numbers. Most gardeners Rule #14 warns that if you want to work with the soil food web, you need grass loses its ability to take up a resource easily, and no matter how much prevents a result, packag-



Mycorrhizal fungi (see bowl on the right!) help lawns grow. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.

phosphorus you put on the lawn, it is locked up quickly and unavailable to the

mycorrhizae-less grass plants. Our favorite microbe food for lawns is soybean meal with an NPK of 6-1-1.

This is applied at a rate of 3 or 4 lbs per 100 square feet. Other useful organic microbe foods include alfalfa meal, blood meal, cottonseed meal, feather meal taste) and fish bone meal (3 lbs per 100 square feetare not absorbed by plant roots—hence, microbe food, not fertilizer. will be a heavy fishy smell for a few days). These all feed the soil biology; they (all applied at the rate of 4 lbs per 100 square feet at first and then -but we warn you, there adjusted to

We know from Rule #2 that lawns prefer slightly bacterially dominated soils. season, as a bacteria-favoring mulch. The sugars in the grass will attract a For this reason alone it is a good idea to leave grass clippings on the lawn, all amounts of concentrated nitrates are not being sucked up into by plant roots. which ensure nutrient cycling. And you will have to mow less, now that high healthy population of bacteria. Clippings also foster populations It also helps to encourage a suitable environment for the lawn's microbes. of protozoa,

branches fall after a storm, do not rake them. Instead, mulch them up in place and make them available to the fungal components of a lawn, which are also by running your lawn mower over them once or twice. This will open them up important; fungi help provide structure and drainage and help with the This is why you should rejoice when you see mushrooms in your lawn. They harder-to-digest grass stems that can build up to a thatch layer in their absence. When leaves drop at the end of the season or when twigs usually a sign that things are healthy beneath the green grass. and small

killers) should be plug-aerated, a procedure wherein 2-inch-long plugs of soil attributable as much to poor drainage as to chemical fertilizers and weed Lawns that have not had the benefit of a healthy soil food web (which may

A handful of plugs pulled from a lawn during aeration.

Photograph by Judith Hoersting.



should be left on the lawn and allowed to decay. lawn, allowing water, air, and organic food to enter the root zone. The plugs are pulled from the lawn, creating holes throughout. These holes open up the

crobe food. This will fall into the plugholes and provide food down in the pacted, as it inevitably does. After this spring aeration, apply an organic mifragile, fungi are also the first soil organisms to go when a lawn becomes comticularly useful in keeping the lawn's fungal population healthy: or the back-and-forths of pets, children, and vehicles. The aeration is plug aeration in the early spring every three or four years will help the because it helps repair compaction caused by the weight of snow and as the

ily accomplished by applying a thin (up to a half-inch) layer of bacterially into the soil or to maintain what is already there. If the lawn is small, this is easapply a slightly bacterially dominated compost tea (see "Applying Compost Tea dominated compost to the lawn with a fertilizer spreader. If the lawn is large, Next, inoculate the lawn with beneficial microbes to put microbiology back later in this chapter).

affect microbes if you water using a sprinkler. The fine mist spray and the from the air to the ground helps clear most of the chlorine from this water. Of hose bib. One filter should last all season, but you should check the output occourse, you can buy an inexpensive chlorine filter and install it on the outside casionally to be sure. What about chlorine in the water you use to water your lawn? It shouldn't

# Weeding the soil food web way

appear in calcium-poor soil surfaces. Their long taproots seek out the calcium Lawn weeds can be influenced by the soil food web. Dandelions, for example, they lack, and the calcium is deposited in the soil when the dandelion dies. In lions sooner, boost fungal activity in the soils; fungi tie up calcium, much more so than do bacteria. You can also use a microbe food, corn gluten (a by-product of corn starch production), as an organic, preemergent agent. Put it on lawns with dandelions or other weeds just as they are coming to seed, and it will prevent the new seeds from developing secondary roots. In the meantime, its essence, dandelions can mine themselves out of existence. To get rid of dandethis calcium into the upper layer of soil, where it has been missing. In -unfortunately, sometimes quite a long time--the soil food web biology

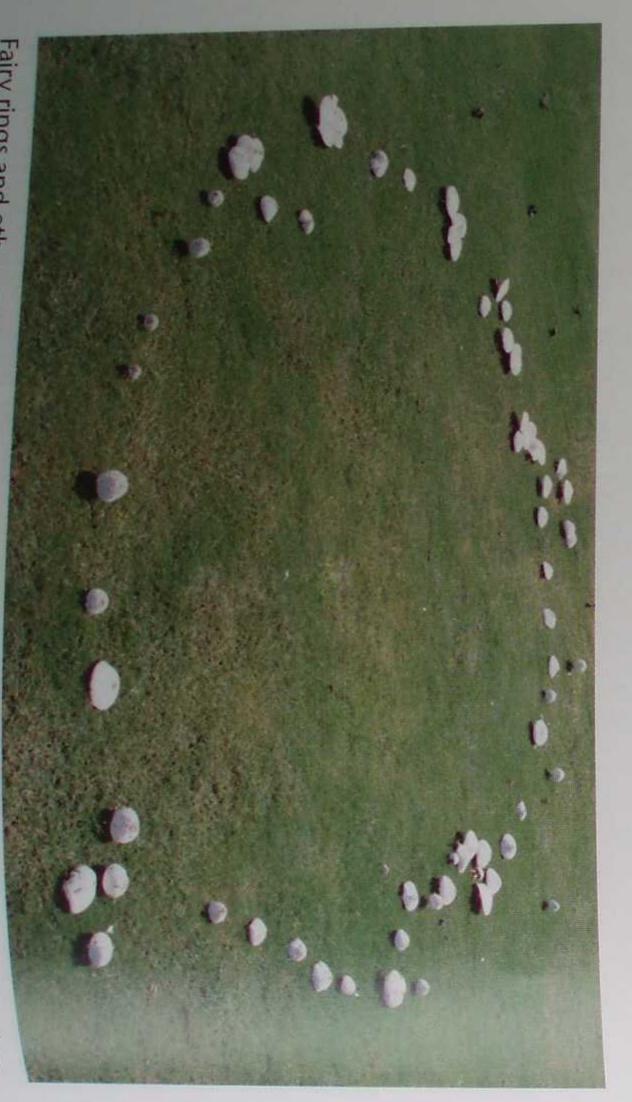
10-10-10 formula feeds the soil food web. Lots of clover or quack grasses in a lawn indicates that the soil food web is

you get when you put down a commercial lawn fertilizer. Stop applying chemcompost tea, or a protozoa soup can increase nitrogen cycling. Chickweed, a mass (and hence the available ammonium) in your lawn. ical fertilizers; instead, use the soil food web tools to increase the fungal biofrequent weed in lawns, thrives when there is too much nitrate, which is what not cycling enough nitrogen. Adding nematodes and protozoa via compost,

Moss, on the other hand, indicates that your lawn soil is already fungally

move the existing moss with a thatching rake and may have to apply iron to kill will lessen and eventually prevent the appearance of new moss. You should reually change to one "acceptable" to grass and not as "acceptable" to bacterially dominated compost to moss-infested lawns, and the pH will gradlike acidic conditions. Apply very bacterial teas and a thin topdressing of very dominated instead of being slightly bacterial, as lawn grasses prefer. Mosses moss. This

need to apply a bit more bacterial tea. If you are worried about fairy rings, for mushrooms in your lawn. Not too many, of course, which would mean you should then be outcompeted. In addition, recognize that microsure your teas and compost have a good diversity of fungi; the fairy ring fungi example, just increase the diversity of the fungi in your lawn soils keeping them in check. macroarthropods as well as mice and shrews eat these and many other fungi, As a "soil food webbie," you already know you should be happy to see by making and



Fairy rings and other monocultures of fungi in the lawn can be overcome by increasing diversity with compact diversity with compost or compost tea. Courtesy Clemson University, USDA Cooperative Extension Slide Series, www.forestryimages.org.

## Easy changes and good starts

it directly on the lawn, mix lime in when you are making compost. It will be get the same results by applying some soil food web science. Instead of putting sum, or sulfur to alter soil pH a few points in a decent-sized lawn; lime in parpH. Normally you would have to put down hundreds of pounds of lime, gypticular acts slowly, taking a season to effect even a point's change. However, you You can use the soil food web to your advantage when it comes to chang web cycling. You can put this compost directly on the lawn or you can make tied up by the microbes in the compost and released during the normal food can use considerably less (about one-quarter the amount) and take less time to ing

arbuscular mycorrhizae (VAM). A healthy lawn should have a good portion of type of endomycorrhizal fungal spores associated with grass plants, vesicularnity of chemical addiction. Before you broadcast grass seed, mix it with tablish a healthy soil food web from the very start, sparing your lawn the indigroots colonized by VAM for the lawn as a whole to get the benefits of the mycorrhizal relationship. VAM colonization helps grasses compete with weeds both water and nutrients back to the roots. Biological testing labs can tell for nutrients and blocks root-eating nematodes. And mycorrhizal fungi bring how much VAM you have in your existing lawn soils. Obviously, if you are just putting in a lawn, you have an opportunity to esthe you

store it in a dark, cool spot. VAM will help achieve a healthy lawn that does not need watering or feeding as frequently as those without mycorrhizal fungi. Twenty-four hours prior to seeding a lawn, roll wet grass seed in VAM and

## What if you need a quick fix?

Some lawns are seemingly hopeless, and while soil food web management eventually prevails, quicker action is sometimes desired. Consider first the use of heat, vinegar, or manual labor to get rid of weeds in lawn; if weeds are so bad ing (say, for an emergency backyard wedding), then you should take remedial that you need to use a herbicide, or if the lawn needs an instant nitrate green-

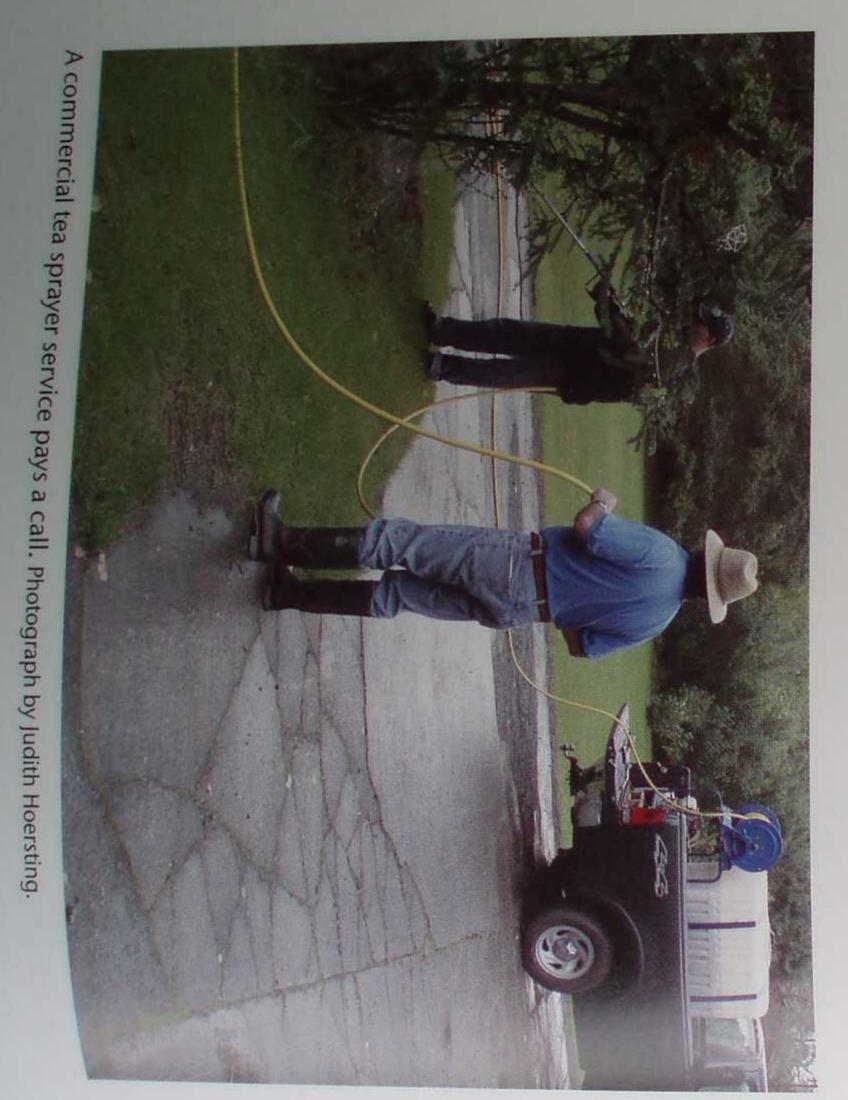
action to restore the soil food web. apply the tea. The microbes in the tea will immediately start to detoxify the soil with an application of compost tea. Give the stuff a few days to work, and by breaking down the remaining chemicals and repopulating it. Repeat week, and check the status of soil food web life. Always practice Rule #15: follow any chemical spraying or soil drenching

sources with complex proteins (the kind fungi like), such as kelp, fish hydroltherefore need to inoculate contaminated soil with lots of organic food rethat attack and break up these complicated chlorinated carbon rings. You ysate, and humic acids. Both bacteria and fungi can degrade pesticides, but it is mostly the fungi

# Applying compost teas to lawns

ing it yourself. don't have the right equipment. A commercial tea sprayer service is the easiest to admit that applying compost tea to a large lawn can be problematic if you bacterial aerated compost tea at a rate of five gallons per acre. One of the best ways to establish the right biology in lawns is way but can be more difficult to arrange and much more expensive than applyto use a slightly We are the first

you should consider a traveling sprinkler (one that follows along a hose laid soluble fertilizers) attached to your water source. Instead of holding fertilizer, out on the lawn) with an inline fertilizer dispenser (a tank made for applying to the sprinkler as it travels across the lawn. the dispenser can be filled with actively aerated compost tea, which it will feed Concrete sprayers (see chapter 17) are fine for a small area. For larger areas,





work. Photograph by Judith Hoersting. A traveling lawn sprinkler and a fertilizer dispenser make applying tea to a lawn easy

If you plan on applying tea to a really large lawn, you might want to consider renting or buying a gas blower (and using its lowest, most gentle setting). You can mist an acre of lawn in about five to ten minutes and spray up into 30-foot trees. Rental is the best idea, as you will only need applications in the spring and autumn once the soil food web is established. Do ensure the tank is free of any residual herbicides, pesticides, or other harmful chemicals.

to care for. You will no longer have to thatch or rake clippings or leaves. You will need to water less, mow less frequently, and best of all, have the satisfaction of being able to play and work on your lawn without worrying about dangerous chemicals. Once your lawn has a thriving soil food web system, it will be much easier

#### Chapter 19

### Maintaining Trees, Shrubs, Perennials

shrubs, and perennials. shrubs and some perennials run under the lawn, and they are and shrubs receive, and all many perennials get as well. The roots of trees and food web, you have to become their defenders and continue to feed trees. kill even the beneficial organisms that protect plants. With a fic and by the use of nonselective herbicides, which besides killing lawn weeds with the lawn. Whatever fertilizer goes on the grass is usually all the trees scaping. Yet they seldom get specialized care and are instead lumped in REES, SHRUBS, AND PERENNIALS are the mainstays of affected by trafany yard's landdiminished soil

# Trees, shrubs, and perennials prefer fungally dominated soils

and therein lies the problem. If the soil is very heavily bacterial, many trees their nitrogen in the form of ammonium, not nitrate. This means fungal soils. lawn? Remember, Rule #3 dictates that trees, shrubs, and perennials prefer when you planted it in the middle of your beautiful green, nitrate-fertilized have a difficult time establishing themselves. Ever wonder why the lilacs never bloom? or why that spruce didn't survive Lawns, on the other hand, do best with nitrates or slight bacterial dominance

scape, and that a conifer, for example, that craves ammonium that trees and shrubs in particular often function as specimens in the landtices provide a different soil food web specifically where they grow. We realize be sited in the middle of a lawn that prefers nitrates. The trick, create an island around each tree and shrub with a fungally Being surrounded by lawns may not be a good thing for trees, shrubs, and -or the gardener—unless some soil food web management pracdominated soil then, is to try to nitrogen might

old growth forest. The most familiar of these are cottonwoods, birches, and transitional in the successional development of ecosystems from desert through The few exceptions to Rule #3 are the trees and shrubs normally considered



mulch that will attract fungi. Photograph by Judith Hoersting. Trees growing in a bacterially dominated or balanced environment should benefit from

aspen. These do well in bacterially dominated soils when they are young because at that stage of their development they can easily utilize nitrates. Once mature, however, even these prefer ammonium nitrogen.

# shrubs, and perennials dislike compacted soils

Trees, shrubs, and perennials are frequently the victims of compacted soils, especially when they are planted in lawns (as is often the case with trees and shrubs) or in pathed gardens (as with perennials). Every precaution should be taken to prevent this condition (and every step taken to correct it), as roots (and thus plants, obviously) do best in soil with good structure, and good soil structure as you now know absolutely requires an active soil food web.

Larger organisms cannot survive in compacted soil—they cannot move through it in search of food because transportation pathways have been destroyed; if the compaction is really severe, it may be impossible to establish new ones, or not worth the bother. With the nematodes and many of the protozoa gone, nutrients accumulate in fungal and bacterial biomass instead of being released and available to plants. At the same time, the fragile mycorrhizal fungi

full of fungi as trees and shrubs prefer. through even compacted soil. The food web is not in good shape and surely not tunistic fungi and protozoa that are so small in size they are able to move ter a while, the only soil food web organisms left are the bacteria and opportwo fungi that cause stem and root rot problems, for example, are missing. Afor drowned; mycorrhizal fungi that compete with Pythium associated with the roots of trees, shrubs, and perennials are and Rhizoctonia, literally crushed

trients is limited. They become even more stressed. nitrogen they prefer, but their access to water and phosphorus and other nuface a double whammy in compacted soils: they not only don't get the kind of they can no longer rely on mycorrhizal fungi to bring back Plant roots too have trouble moving through compacted soil. And since nutrients, plants

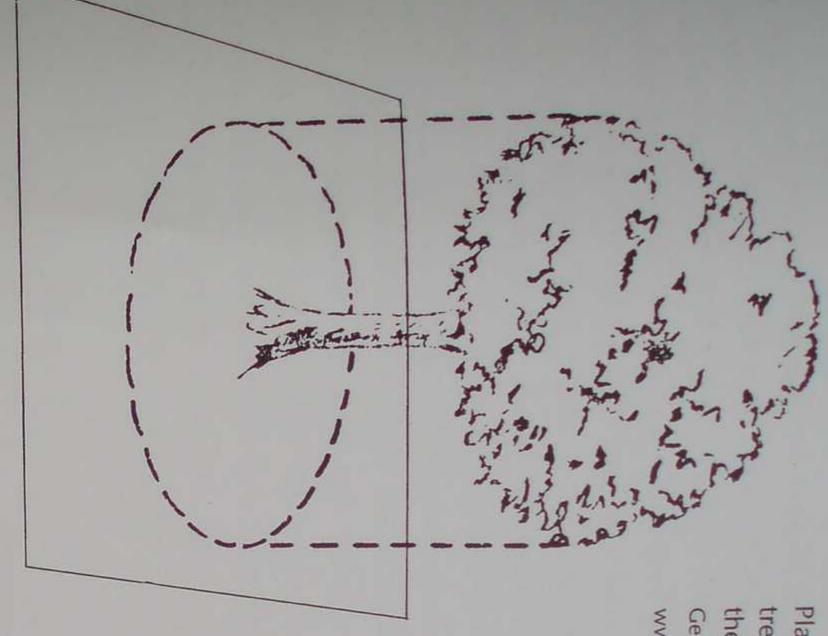
appear. No mycorrhizae, no beneficial fungi, harmful elements galorenot a healthy situation. tunnels and burrows through which water flows, pulling and pushing air, distake over. Anaerobic bacteria produce metabolic products that kill roots, The It gets worse. Compaction reduces oxygen levels, and anaerobic bacteria -this is

prove compacted soils, the benefit of aeration will be short-lived. The solution compacted soils. If you don't have the proper soil food web needed to build and maintain soil structure. Mulches, compost, and compost is to apply food web management practices and return the organisms that are teas are all very effective when it comes to treating compa trees, shrubs, and perennials. Plug aeration of the affected area is only a first step toward remediation of organisms to imcted soil around

# All three soil food web tools apply

and shrubs and around all perennials to a depth of 1 to 2 inches (2.5 to 5 cenfor trees, shrubs, and perennials. Start with compost and place it under all trees Brown mulches and fungal compost and compost tea work the microbes in the compost don't attack the bark). Obviously, you should give compost doesn't touch the stem or trunk of any of these plantimeters). Go at least out to the drip line of the tree or shrub, but make sure the up on trying to grow grass under trees. best when caring ts (so that, again,

if you don't have compost to put under your plants. Start with should too \_\_\_\_\_\_\_ the plant. Nature places mulch over tree roots; you The nitrogen and carbon in these leaves is naturally recycled, and some Gravity isn't the only reason trees and shrubs drop their leaves where they -again, to at least the drip line—using brown mulches. Mulch even the plant's own



Place compost and mulch under trees and shrubs at least as far as the drip line. Diagram by Tom Hall, Georgia Forestry Commission, www.forestryimages.org.

leaves if you can (open these up for bacteria and fungi by running them over with a lawn mower); don't remove them. Add to nature's mulch with brown mulches of any kind, but don't let it get too deep. A few inches is all that is needed to support a healthy population of fungi. The mulch has the added benefit of keeping down weeds and grass by blocking the light.

perennials, once at the beginning of the growing season (two weeks before are in place under the plants. The microbes in the tea will really speed up detrees and shrubs leaf out) and again at the end, just as leaves finish falling and cay during the winter months and support a good, fungally dominated food sprays, except for perennials, which in addition to the two soil drenches should web community. You can simply soil drench, and don't need to bother with be sprayed at least once after their leaves appear to add microbiology to the phyllosphere. Finally, consider an application of compost tea around trees, shrubs, and

### Mycorrhizal relationships

Before planting trees, shrubs, and perennials, inoculate them with mycorrhizal fungi. These can be purchased at nursery centers. Remember, there are two basic types of mycorrhizae--those associations where roots are invaded, and

and hardwood trees (birch, oak, beech, hickory) form mycorrhizae with ectorhizae with endomycorrhizal fungi. These rules are based upon the research of mycorrhizal fungi; most shrubs, softwood trees, and perennials form mycorcorrhizal fungi to use on what is answered by Rules #16 and #17: most conifers those where they are notsoil scientists, who now have the tools to assess what types of fungi naturally associate with particular plants and have codified these assessments. There are exceptions to these rules. For example, plants in the heath family, which inthese rules, you should be on stable (but, we hope, not compacted) ground. rhizae, which are not yet commercially available. Nonetheless, if you stick with rhododendrons, azaleas, and blueberries, require ericaceous mycor--so it is important you get the right ones. Which my-

with various materials to help in their delivery), so they are easily tions that contain mycorrhizal fungi are always dry powders or grains (mixed 24 hours of being exposed to moisture in order to grow. Commercial prepara-Mycorrhizal fungi spores must come into direct contact with applied when roots within



Mycorrhizal spores. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.

The pine on the left was treated with mycorrhizal fungal spores when planted; note the increased size of both the seedling and its root ball. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.

new plant as usual. plants are about to be put into the ground. Simply sprinkle them on the roots or dip the roots directly into the spores before you plant, and then water in the

soils have not been degraded to the point that natural mycorrhizal fungi have ing trees have mushrooms under their drip line, you most probably are lookoften form an association with the fly agaric, Amanita muscaria. If your existof mushroom growing near the same kind of tree. Birch trees, for example, been affected. Look for signs of mycorrhizae in the form of one particular kind Existing trees and shrubs are a bit more difficult to colonize. Let's hope your

ing at an existing mycorrhizal association and don't have to add to create one. If you have a yard with really compacted soils, have not seen mushrooms roots of existing plants with the appropriate mycorrhizal fungi. In the case of using a root feeder or long syringe (the kind used to apply glue) to inoculate the around your trees and shrubs, or have noticed they are not doing well, consider most perennials and shrubs, you can carefully dig into the root zone with a spade or trowel and apply endomycorrhizal spores whenever you come across roots



Judith Hoersting. Birch trees often form mycorrhizae with the mushroom Amanita muscaria. Photograph by

# Unstressed plants are healthier

and they are able to produce extra pitch and sap to trap any invading beetles. phorus and wash it down with ample water. with beneficial bacteria and fungi to outcompete disease. Their Stressed trees put out a signal recognized by aphids and other insects; they formed mycorrhizae that increase their reach and allow them to dine on phos-Their exudates attract all the right microorganisms. Their leaves know the tree is weak and attack it. Unstressed trees don't emit this message, roots have are coated

soil food web tools, especially compost teas, at the first sign of any remain under the plants from which they drop. And, obviously, use all three fungally dominated compost, mulches, and teas to and around them. Let leaves nials: try to plant them in soils that are already fungally dominated. If not, apply The bottom line when it comes to caring for your trees, shrubs, and perendiseases.

#### Chapter 20

# Growing Annuals and Vegetables

and vegetables; and the vicious cycle that develops in lawns treated with chemsame high concentrations of soluble nitrates that work on the lawn, with their amounts of chemical fertilizers because no longer are there microbes to procling of nutrients ends. You have to feed the plants you grow with increasing ical fertilizers will also occur in your flower and vegetable beds. The natural cypercentages tweaked a bit, work quite well when it comes to feeding flowers vide them with nutrients, and in the absence of microbes, soil structure deteriorates. Without a healthy soil food web, opportunistic pathogens and animals appear, and these seemingly require other chemicals to keep them at bay WHOLE INDUSTRY is built around fertilizing annuals and vegetables. The lawn might be the number one dump for chemical fertilizers, but homegrown tomatoes and marigolds are not that far behind. The

### Annuals and vegetables prefer bacterially dominated soils

What are the soils in your vegetable and flower beds like? Look for earthworms. lots of earthworms and earthworm castings in your soils, then you probably They survive by eating protozoa and bacteria, and, as with lawns, if you have have bacterially dominated soils with plenty of nitrates, which are what most vegetables and annuals prefer (remember Rule #2). Set up the Berlese funnel lots of bacteria-eating mites and good diversity of animals. Measure your soil's and see what kinds of microarthropods are roaming the soils. You want to pH in the rhizosphere. If it is decidedly alkaline, you most probably have bacably fungal dominance. Finally, get your soil tested for its microbiology; this is terial dominance. Similarly, an acidic reading means you have fungi and probthe best way to know what is missing, if anything. Sure, an NPK test won't hurt, but it is really the biology you need to know about. see

### No more rototilling

soil food web tools. But there is one traditional organic practice we must ask If you are an organic gardener you probably already employ one or you to drop. With one exception we recommend the no-dig principle: never rototill again. This is a real shocker to those who regularly rototill or otherwise that Rule #18 is a special rule against it: rototilling and excessive soil disturturn their soils. Soil turning is so ingrained in the psyche of the home gardener bance destroy or severely damage the soil food web. They are outmoded pracble digging as ways to mix organics back into the soil; indeed, rototiller manumost gardening circles. Many organic gardeners advocate rototilling and doufacturers are major advertisers in magazines that promote organic and should be abandoned in established garden beds. This is heresy in gardening. two of the

southern England and invented a seed drill that mechanically placed seed at a steam, so to speak, when lawyer Jethro Tull (1674-1741) inherited a farm in set depth in a premade hole, replacing hand-broadcasting. Tull also actively enetables did better in loosened soil and from this concluded that plant roots couraged farmers to loosen soil before planting crops; he had noticed that vegpossessed little mouths and ate soil particles (how else could a plantrients?). Believing that loose soil consisted of smaller particles theory into practice. His writings later caught the attention of more easily fit into root mouths, he developed a horse-drawn hoe to put his fellow Americans to break up soils. The end result is that most home gardenfarmers like George Washington and Thomas Jefferson, who encouraged their ers still break up and turn over their soil at least annually, even know plant roots don't eat soil. The age-old agricultural practice of plowing the earth really that would t ingest nuthough we gentlemen picked up

better in soil that had first been loosened and to which manures were added. This had nothing to do with tiny particles of soil; it was because breaking up the soil supports Rule #2. Breaking up forest soil in order to plant a tually does more than make a treeless field; it reverses the results of years of succession, destroying the network of fungi in the soil. With fewer and row crops. The addition of manures by these early American fa fungi, soils become bacterially dominant, a boon to nitrate-loving greatly increased bacterial populations, as these are great bacterial food. For reasons unknown to Tull and his contemporaries, vegetables did grow rmers also vegetables garden acyears and

in manure made soils suitable for agriculture; however, rototilling or turning soil also destroys soil structure and displaces soil biota, disrupting the So, in the short term, breaking up America's virgin forest soils and mixing otherwise

dog's name, not a soil description. The first time water hits disturbed soil, it bein bacterially dominated soils. Worm tunnels and the pores between soil food web. It completely chops up the miles of fungal hyphae that exist even rains or the bed is watered. gins to compact, a spiraling, downward course that continues every time it are all blown apart. Sure, the soil is fluffy after rototilling, but that's a

and vegetable gardens, unless you are trying to establish a vegetable or annual quires that the soil be disturbed as little as possible when it comes to annual crete holes for plants or seed. You can also lightly pull a hoe or the corner of a garden in fungally dominated soils. Use a trowel, dowel, or dibble to make dis-2-by-4 board along a row and plant in the limited disturbed wake, backfilling method because you are not opening up the soils and exposing weed seeds to the light that is required for germination. structure and microbial diversity. Soil food web gardening practice Even bacterially dominated soils need to contain some fungi good bacterially dominated compost. You will get fewer weeds using this to maintain

# Soil food web workers are great farmers

How do you encourage the bacterial domination needed for your annuals, veg etables, and row crops if you cannot rototill? Like everything in the soil fooc web, if you feed them, they shall come. Green mulches promote bacteria. Ir this case, not only does green mulch provide nutrients for the proper and necessary soil food web organisms, it also prevents weeds from germinating and holds moisture in, preventing it from evaporating. Too, bacteria like the easy-Since soil bacteria also favor dampness, wetter mulches—to a pointto-digest stuff, so the finer the green mulch, the higher the bacterial growth. mulch that fosters anaerobic conditions, however, so be careful. Use your nose as the tester. If there is a bad smell, you put in too much water and need to aerpromote bacteria. There is a fine line between damp, aerobic mulch and wet ate the mulch and back off a bit on the water. -will also

that fragile fungi are not killed. You can put these in the root zone when ganic microbe food—with all three of the NPK numbers below 10ally dominated teas as both a soil drench and foliar spray to prevent or contro diseases and to keep microbial populations in the soil at high numbers. In addition to bacteria-supporting mulch, your soils should have plenty of organics to feed the microbes that are feeding your plants. Use any oror side-dress before you mulch and then add as needed. Apply bacteri

Lawn clippings are a terrific green mulch to use around your annual flow-

all the nitrogen they need with available carbon, without interfering with any spring planting. Try alfalfa meal, straw, or grass clippingsbe over by spring. food. The bacteria get started in autumn; during this season, they can combine garden soils in autumn so they have a chance to start to break down before faded. The same is true of straw. And it is still a good idea to add organics to they were cut, they contained sugars that remain even after the chlorophyll has color and turn "brown," they are still considered "green" mulch because when plant's needs. Nitrogen tie-up at the soil-mulch interface, if it occurs at all, will ers and your vegetables during the growing season. Even though the -all good bacteria y lose their

atode products have hit the home horticultural market, but these are usually mechanism. Apply protozoa soup as a soil drench to help increase nutrient reprotozoa and nematodes are part of the equation as well, as they are tions of nutrient-cycling nematodesspecific for garden pests such as slugs. Your best bet for increasing the populaof bacterial food with an immediate dose of protozoa soup. Comme protozoa to find the bacteria in the rhizosphere, so wash down any a cycling in your vegetable and flower gardens. It may take a week or good compost and compost tea. When it comes to growing plants that require nitrates, good pop -and by far the most economicalthe cycling ulations of rcial nempplication so for the -ıs still



Vegetable garden with straw mulch on the beds. Courtesy National Garden Bureau.

your gardens if you follow soil food web practices. Mycorrhizae even help plants grown in containers. The longer the season, the bigger their role. This is because it takes time for these fungi to establish and grow. Rule #19 requires that soil food web gardeners always mix endomycorrhizal fungi with the seeds of annuals and vegetables at planting time or apply them to roots at transplanting time. Of the plants that do not form mycorrhizae, many are vegetables. In particular, the families Brassicaceae (which includes cabbages, mustards, and And, of course, you will have the benefit of mycorrhizal fungi working in



The potted marigolds on the right show the benefit of endomycorrhizal fungi. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.



Root balls are considerably larger when corn plants (family Gramineae) are treated with endomycorrhizal fungi, as was the one shown here on the right. Courtesy Mycorrhizal Applications, www.mycorrhizae.com.

plants is a waste of time and money. mycorrhizal associations; using mycorrhizal products on these broccoli) and Chenopodiaceae (spinach, beets, lamb's-quarters) do not form particular

will a bacterially dominated compost tea as a soil drench. If you fail to attract ally dominated compost in early fall will help attract and support worms, as your vegetable and flower gardens. An application of a few inches of bacteriif you want to speed things up. You can soil drench your plants once a week to earthworms, it is a sign that you need to increase bacteria and protozoa popuonce a month, depending on their performance. lations. Do so, and then add some worms to your annual and vegetable gardens Once you stop applying chemicals, you will eventually find earthworms in

#### Weeds

sound soil food web practice. Applications of powerful nonselective herbicides den is to douse it with whatever herbicide is suggested and often a bit more All too often the reaction of the gardener to a weed in a flower or vegetable garmicro- and macroarthropods, as well as microbes. Instead, carefully hoe weeds harm the soil food community in much the way chemical fertilizers do, killing than the directions call for, for good measure. For obvious reasons this is not methods that have fewer and more temporary consequences to the microbiolup or use vinegar, heat, boiling water, corn gluten, and other weed-controlling ogy in the soil. Should you ever need to resort to an herbicide (and we sincerely #15 again). Let the poison take its toll and then take steps, using hope you won't), you must take remedial action as soon as prac food web tools, to get the biology back where it belongs. ticable (Rule all three soil

mulches. The nitrogen, phosphate, and sulfur weeds need to germinate and a physical barrier to their growth, they are given a poor supply makes it doubly hard for weeds to do well, as in addition to facing no light and grow are tied up by the biology at the interface of the mulch and and compost teas? Put down 2 to 3 inches (5 to 7.5 centimeters) of a bacteria-Really, when you think about it, why fuss around with the other tools, compost supporting mulch before weeds appear, taking care to leave a bit of "bare" around the stems of your plants. When it comes to preventing weeds in the first instance, nothing beats of nutrients. the soil. This soil

never worry about weeds again. Indeed, our experience has convinced us that returning the appropriate microbiology to your soils may be the only step you'll need to control many of your annual weeds, those that thrive on the high Other than the work it takes to apply mulch, soil food web gardeners need

seeds buried under mulch and not exposed to light because we don't rototill. web. Chickweed, our nemesis, completely vanished, as plants no longer got we had in our gardens disappeared once we started working with the soil food concentrations of nitrates found in chemical fertilizers. Many of the plant pests their fix of high nitrates and had trouble germinating in the first instance, their

nuals use to help obtain water and nutrients, particularly phosphate, are killed. The host plant doesn't do as well; the surface-feeding, nitrate-loving weeds ample supply of nitrates, an unwanted plant suddenly has the food power to grow faster and overrun the garden, outcompeting the main crops for light. really take over. Adding to the injury, the mycorrhizal fungi your veggies and an-High-nitrogen fertilizers encourage opportunistic annual weeds. Given an

will come from the natural course of cycling. Instead of being poured on in a concentrated, chemical form and killing off the soil food web, the only nitrates chemicals and with a bit of inoculationbeing used will be those produced by the soil food web itself. And-Once you get the soil food web humming, any nitrates needed by plants -mycorrhizal fungi will return.

#### "Pests"

loosely to include spiders and others that are not truly insects) we encounter It is never an ideal world, unfortunately, but most insects (we use the term in our flower and vegetable gardens are helpful in lots of ways. Who needs to nutrients. In most instances, insects get out of hand in your gardens because and aerate it, and insects eat each other and participate in the recycling of plant be reminded that insects pollinate flowers? Their larvae tunnel through soil something is wrong with the soil food web, which normally maintains a bal-



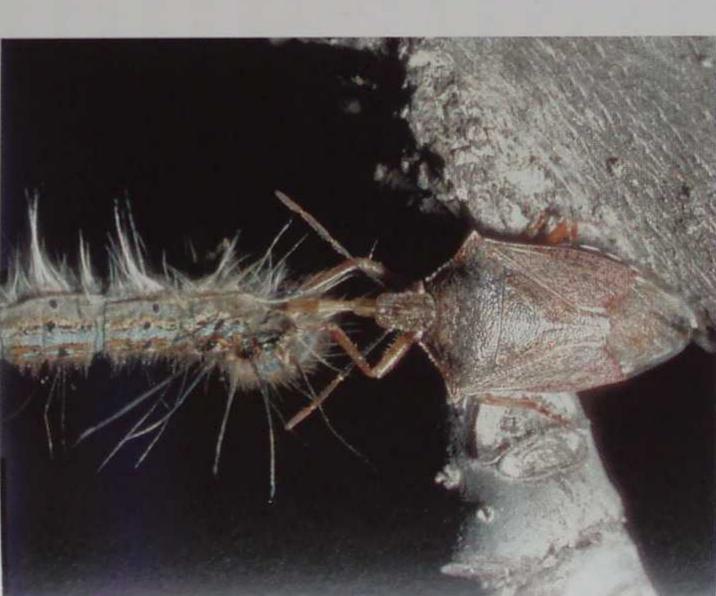
A spined soldier bug makes a meal of the Mexican bean beetle larvae on this snap bean. Courtesy USDA-ARS

ance between pests and predators. But you are not going to have a totally pesttain the good-guy populations. insect pest. If there are a few bad guys, you need to realize that these help main-If your soil food web is healthy, this community will help plants overcome any free garden even with the soil food web in place. Accept it as part of the science.

area is part of learning to garden with the soil food web. Ladybird beetles and distinguishing beneficials from pests: learning about the beneficials in your Every gardener has access to local agencies that will provide assistance in



A ladybird beetle larva devours aphids.
Courtesy Clemson University, USDA Cooperative
Extension Slide Series, www.forestryimages.org.



A stink bug does in an eastern tent caterpillar. Photograph by Robert L. Anderson, USDA Forest Service, www.forestryimages.org.

Braconid wasp larvae parasitize a hornworm. Courtesy R. J. Reynolds Tobacco Company, R. J. Reynolds Tobacco Company Slide Set, www.forestryimages.org.



aphids, spider mites, whiteflies, and caterpillars. Hornets take out flies. The soil aphids, mites, slugs, snails, and nematodes. Assassin bugs are adept at getting the good ones. food web gardener observes and learns what relationships existsflies, mosquitoes, and caterpillars. worms, root maggots, slugs, and snails. Rove beet their larvae feed on aphids, scale, and spider mi-Green lacewings and larvae gobble up tes. les eat fly maggots and eggs, Ground beetles eat cut--and fosters

aging as chemical insecticides. of which have varying impacts on the soil food web, but usually none as damyour action, if you have to use a pesticide). However, don't forget the lesser rejuvenate the microbial universe in the soil and flagrantly negative impact on soil food webs (again, Rule #15 will see that you than we like the use of herbicides. These very nonselective We don't like the use of pesticides in flower and vegetable gardens any more -insecticidal soaps, botanical insecticides, Bacillus thuringiensis (Bt)break down the residues of substances have a

# Schedule for restoration and maintenance

If you habitually used chemical fertilizers in your vegetable and flower gardens, you will need all three soil food web tools. Apply timeters) of bacterially dominated compost before you plant annuals and vegto 2 inches (2.5 to 5 cen-



Applying compost to flower and vegetable aph by Judith Hoersting

plant, nated compost tea. These measures will restore or maintain the soil food web and any seedlings with mycorrhizae right before you plant them. After you etables. Spray seeds with bacterially dominated compost tea and treat them organisms in your vegetable beds. lay down green mulch. Start weekly applications of bacterially domi-

Spray a third application on the debris left over from the growing season. first leaves appear and at least one more time a few weeks before harvest. Spray your vegetables with a bacteria lly dominated compost tea as soon as

is bacterially dominated, you cannot apply too much. pathways through them. Side-dress and ever possible, and put compost on garden beds before the winter. As long as it Avoid compaction; try to stay out of top-dress plants with compost whenthe garden beds, and limit and direct

fungi, protozoa, and nematodes can work during the winter to cycle nutrients. Finally, it is important to mulch garden beds in autumn so that the bacteria,

soil food web. duce will only dens. If we are not mistaken, the great size and taste of organically grown pro-Restore and maintain the soil food webs in your flower and vegetable garmatch the particularly lovely glow of annuals raised using the

# Chapter 21

# A Simple Soil Food Web Garden Calendar

When it is very cold, compost teas are definitely not in a drought situation could prevent the soil underneath from absorbing water. the best time to apply compost tea, and putting down mulch at the wrong time temperatures freeze up compost and mulch. Times plays a big part in when and even how you ap different, and so are the various soil food webs in them. Climate, too, HERE IS NO ONE WAY to garden with the soil going to work, and colder ply soil food web science. of drought might not be food web. Each garden is

crobes and other animals in your soil food webs as and garden care is no longer just about plants. You have to pay attention to the microbes if you are going to team with them. Still, no matter where you garden, you should each season rolls by. Yard at least consider the mi-

#### Spring

Spring is when you first check things out and give your soils a microbiological boost. The compost pile should be cranked up so you'll have ample supply of room, start a new pile designed to be fungally dominated. Use the organic decompost throughout the growing season. Turn last bris that accumulated during the winter and some of last fall's leaves. Use the first grass clippings to get good bacterial compost going as well. fall's pile, and if you have

put back and supplemented. Use compost teas on seedlings both drench and a foliar spray. Inoculate all seeds and transplants with the appro-Mulches should be pulled back to let soil warm up if necessary and then as a soil

priate kind of mycorrhizal fungi. microbiology. You don't have to do this every year, first year or two of gardening with the soil food web. Thereafter, your plants will let you know how you are doing. You might want to have your compost piles tested as well. This is also the time to test things yourself, using Berlese funnel soil traps and your own eyes. You want to be Three weeks before leaves appear, have your soils able to correct any gaps in but you surely should the and tea tested for their

your soil food webs before you plant.

done every year, but it is definitely a consideration the first year after you stop spring every three or four years, depending on the amount of traffic your yard using chemical fertilizers. Thereafter, you only need to aerate in the early receives; the amount of ice that accumulates each winter, if any; and the state of the soil food web as evidenced by worm, mite, and mushroom activity. Two weeks before leaf-out, aerate your lawns. Again this doesn't have to be

to lawns. If you experienced too many mushrooms (or mushrooms of only one species) the previous year, apply some alfalfa meal instead, as it will feed more aerate), apply an appropriate organic After aeration (or two weeks before leaf-out of trees and shrubs, if you didmicrobe food, such as soybean meal,

bacteria than fungi.

lawn created by winter traffic should anced compost tea, at the rate of at least f fungally dominated compost tea to restore structure. applications, things will be downright spongy. Even without tea, make sure the teas, throw the leftover compost and any organic microbe food in these areas is sufficient to support existing microbial populations. You can't burn the lawn applying these organics, so don't worry. This is also the right time to spray lawns with a slightly bacterial or balbe ive gallons of tea per acre. Paths in the cordoned off and sprayed with a excess on these paths. After a few When you finish making

nials and refresh it if you need to. This is why you should save leaves in the autumn when they drop: they can be hard it with mulch to control weeds. Apply a fungal food (humic and fulvic acids, have leaves, bark chips will do. You can spread compost at this time and cover cold-water kelps, phosphate rock dusts) perennial, and shrub a soil drench of your most fungal compost tea. Spray a fungal tea on your perennials at least once after their leaves appear. Tidy up the brown mulch layer under trees and shrubs and around perento your plants, and then give each tree, to come by in the spring. If you don't

possible soak transplants in aerated compost tea before planting. Spray com-Treat any seeds or transplants with the appropriate mycorrhizal fungi first.

post tea on seeds before planting, and apply a soil drench after germination. Apply 4 lbs per 100 square feet soybean meal as soon as you can after the soils thaw, and spray with a bacterially dominated tea. When planting, drill holes for mulch after a seeds or disturb just the row where they will be planted. Use lots of green mulch after the soil warms up. Neither till the vegetable garden nor turn over the soil in the annual beds.

### Summer

chemicals. program started in the spring, especially the first During the summer months you need to continue with the spray and drench year after you stop using

of water is not the cause, spray or sprinkle on a protozoa soup. A second applimulating at a noticeable rate, or the lawn is not greening up enough and lack Berlese funnel tests to see what is going on. Keep records for later comparisons. cation of soybean meal or other microbe food is in order. It is useful to do more Microbial activity should be taking care of lawn clippings. If they are accu-

gardens. Apply microbe food once every two weeks plenishment of green mulches will keep weeds down in vegetable and annual Liberal applications of bacterially dominated compost and frequent reneeded.

shrubs, and perennials. Mix in any twigs or sticks these plants drop. You might make them look neater. run these over with a lawn mower, in place, just to open them up a bit and Fungal compost and mulch should be applied liberally around trees,

sprayed with compost tea followed by a soil drench plants showing signs of disease or stress of tea. should be immediately

### Autumn

fall composting, which should begin while the Just before the tree leaves start to drop, gather up a load of grass clippings for the season is coming to an end. Use mycorrhizal fungi on the roots of any can also put some of this green mulch on annual tumn transplants. grass is still fresh and green. You and vegetable beds, even if au-

have to run over them more than once). Leave them in place. This will provide to the lawn. Gather the rest of the leaves, every single one you can. Brown leaves some fungal balance to the bacterially dominated teas you have been applying are always in short supply when it comes to spring and summer composting. Build your compost pile and store the rest. Turn leaves that fall on lawns into a fine mulch with your mower (you may

shrubs, trees, Mulch vegetable and flower garden beds. After leaf drop, make sure all your and perennial plants are properly mulched, too, and if possible,

fungally dominated compost first.

making sure to In the first year of using the soil food web, spra inoculate mulches and leaves. Microbial action should decay y 20 gallons of tea per acre,

about half the leaf mass within a month or so if it is warm (and by the end of

crobes go to sleep with full stomachs, wake up early, and start cycling nutrients. spring, even if it is cool). After harvests, have your soils tested again and make some Apply a good organic microbial food of the appropriate type. Let the mi-Berlese funnel

runs, if it is not too cold; compare these tests to those you took in the spring and summer. This will allow you to manage your soils during the winter months so they are ready come next spring.

ing libraries with that subject in mind. This is a new science, and Spend winter reading up on the soil food web, surfing the Internet and browsto the home gardener are ever expanding. New products, such as specialized introduced all the time. All sorts of new compost tea makers, sprayers, and nutrient ingredients are hitting the market. There is a lot out there to help you predatory bacteria and nematodes that take out pests and patho team with microbes, and you need to keep abreast of the latest developments. its applications gens, are being

compost teas. You can have an abbreviated soil food web system working for support the microbial life you are adding. your indoor plants; make sure the potting soils contain ample organic foods to Of course, just because it's winter doesn't mean you should stop using

able in the winter. Give it a few turns. You know the saying: a will make you a better gardener. Finally, depending on where you live, your compost pile may still be worktew good turns

## Chapter 22

# No One Ever Fertilized an Old Growth Forest

member visiting. You can almost hear a stream nearby, the wind running nearest forest. Or simply close your eyes and visualize any wooded area you rethrough the leaves. It is beautiful, majestic—and no one ever fertilized any of The beautiful plants in these beautiful areas are completely controlled by the the plants there. Not one single time. How can this be? You know the answer. soil food webs in which they live. OES THE SOIL FOOD WEB really support plants? Will it work in your to use what you have learned, we point you in the direction of the yard and gardens? Just to give you confidence and to encourage you

full force of the realization hit: every single plant you are seeing produces exudates and attracts microbiology to its rhizosphere. This community in turn attracts micro- and macroarthropods, worms, mollusks, and the rest of a complete soil food web. It is a natural system, and it operates just fine without interference from man-made fertilizers, herbicides, and pesticides. Tall oaks grow from small acorns with no blue powders to feed them or nasty smelling protozoa, nematodes, and the rest of the soil food web gang. sprays to protect them. Plants flourish nonetheless, thanks to bacteria, fungi, It often comes as a surprise when gardeners so reflect. Only then does the

in your yard. Long before construction, traffic, rototilling, the application of return it. You can even improve it. Once you work with the microbes at the fertilizers and other chemicals, a healthy soil food web existed there. You can base of the soil food web, you will reestablish that soil food web. We know. We We know it is possible to let the very same kind of soil food webs take over

and thousands of our neighbors and friends have done it.

how the system works, and you have been exposed to its benefits. With the microbiology returned to your yard, soil structure improves. Mycorrhizal fungi will help your lawn, trees, shrubs, perennials, annuals, and veggies get the nutrients they need. Pathogens face fierce competition. Plants get more of the kind of nitrogen they prefer. Water drainage and retention are improved. Pollutants are decayed. Food tastes better. Flowers look better. Trees are less You have been introduced to the basic science of soil food webs. You know

stressed. And you don't have to work so hard; you will have lots of of all, you won't have to worry about the affects of chemicals on you or your tamily, pets, or friends. helpers. Best

that biology into your soils and working for you. Gardening with many of them. What are you waiting for? Start teaming with microbes and get You have been given the rules to garden using the soil food web. web is the natural way to grow. Remember: no one ever fertilized an old growth forest. They d There are not lidn't have to. the soil food



### Appendix

# The Soil Food Web Gardening Rules

- Some plants prefer soils dominated by fungi; others prefer soils dominated by bacteria.
- 2. Most vegetables, annuals, and grasses prefer their nitrogen in nitrate form and do best in bacterially dominated soils.
- Most trees, shrubs, and perennials prefer their nitrogen in ammonium form and do best in fungally dominated soils.
- Compost can be used to inoculate beneficial microbes and life into soils around your yard and introduce, maintain, or alter the soil food web in a particular area.
- Adding compost and its soil food web to the surface of the soil will inocu late the soil with the same soil food web.
- 6. Aged, brown organic materials support fungi; fresh, green organic materials support bacteria.
- 7. Mulch laid on the surface tends to support fungi; mulch worked into the soil tends to support bacteria.
- 8. If you wet and grind mulch thoroughly, it speeds up bacterial coloniza-
- 9. Coarse, dryer mulches support fungal activity.
- 10. Sugars help bacteria multiply and grow; kelp, humic and fulvic acids, and Phosphate rock dusts help fungi grow.
- 11. By choosing the compost you begin with and what nutrients you add to balanced. it, you can make teas that are heavily fungal, bacterially dominated, or
- 12. Compost teas are very sensitive to chlorine and preservatives in the brewing water and ingredients

- 13. Applications of synthetic fertilizers kill off most or all of the microbes. soil food web
- Stay away from additives that have high NPK numbers.
- 15. Follow any chemical spraying or soil drenching with an application of compost tea.
- 16. Most conifers and hardwood trees (birch, oak, beech, hickor orrhizae with ectomycorrhizal fungi. form myc-
- 17. Most vegetables, annuals, grasses, shrubs, softwood trees, and perennials form mycorrhizae with endomycorrhizal fungi.
- 18. Rototilling and excessive soil disturbance destroy or severely soil food web. damage the
- 19. Always mix endomycorrhizal fungi with the seeds of annuals and vegetables at planting time or apply them to roots at transplanting time.

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order@alaskagiant.com, http://www.alaskagiant.com/ Alaska Bountea / Alaska Bounty, Box 1072, Palmer, AK 99645, 907.745.8234,

bob@bobsbrewers.com, http://www.bobsbrewers.com/ Bob's Brewers, 6515 W. Marginal Way SW, Seattle, WA 98106, 206.767.7816,

Keep It Simple (KIS), Inc., 2323 180th Ave. NE, Redmond, WA 98052-2212, www.kisbrewer.com 866.558.0990, kis@simplici-tea.com, www.simplici-tea.com,

www.soilsoup.com Soil Soup, 305 9th Ave. N, Seattle, WA 98109, 877.711.7687,

# Labs that perform biological testing

info@agrienergy.net, http://www.agrienergy.net/. AgriEnergy Resources, 21417 1950 E. St., Princeton, IL 61356, 818.872.1190,

bbclabs@aol.com, http://bbclabs.com/. BBC Laboratories, Inc., 1217 N. Stadem Dr., Tempe, AZ 85281, 480.967.5931,

Soil Food Web, Inc., 980 NW Circle Blvd., Corvallis, OR 97330, 5 sh@soilfoodweb.com, http://www.soilfoodweb.com. 41.752.5066

# Mycorrhizal fungi

Mycorrhizal Applications, Inc., Box 1181, Grants Pass, OR 97528, 866.476.7800, http://www.mycorrhizae.com/index.php?cid=60.

Spokane, WA 99205, 509.327.7670, http://www.tandjenterprises.com/. T and J Enterprises, Thomas Giannou, 2328 W. Providence Ave.,

#### Index

Boldface page ranges indicate the main discussion of a topic.

acids 25, 29, 30, 41, 57, 58, 100 AACT. See compost tea acids, carbonic 35, 66 acids, butyric 46 acids, amino 25, 45, 48, 55, 100, 120 Aceria anthocoptes 79 acids, nitric 29 acids, humic 141, 156 acids, fulvic 141, 176 actinomycetes 46, 47, 121, 123 Actinomycetales 46 actively aerated compost tea. See active transport 45, 56 aeration 99, 128, 144, 153, 176 aerobic 32, 46, 51, 115, 120, 135, 167 air pollution 60 Agrobacterium tumefaciens 51 air pump 136 air stone 136, 137 Albugo 62 alders 103 alcohols 32, 47, 50, 120, 122, 135 algae 28, 60, 64-66, 82, 93 alfalfa meal 124, 127, 131, 152, 168, 176 algae, blue-green 66 algae, green 59, 65 algae, yellow-green 65 aloe vera 141 aluminum 29, 34, 36, 39 Amanita muscaria 53, 163 compost tea

ammonium 40, 49, 50, 57, 73, 99, 10 apples 51 anaerobic 32, 34, 46, 50, 71, 115, 120 ammonia 46, 126 amoebae 70, 71, 72, 135 antibiotics 25, 49, 51, 63, 119 annuals 26, 61, 101, 102, 103, 114, 1 anion 40, 41, 42, 100 aphids 11, 164, 172, 173 ants 19, 80, 82, 123 apical growth 55 ant lions 80 Aporrectodea 85 Arthrobacter 121 Armillaria mellea 63 Arachnida 79 arthropods 22, 27, 74, 78-84, 95, 99 aspens 103, 159 Arthrobotrys dactyloides 58 azaleas 103 autumn 168, 174, 177 autotrophs 71 Ataenius 146 Ascophyllum nodosum 141 Azospirillum 48 Azotobacter 48 160, 167 102, 154, 158 143, 165-174, 176, 177, 179 124, 125, 126, 135, 136, 140, 143, 106, 107, 128, 130, 145, 151

Bacillus 120

Bacillus thuringiensis 173

Bacillariophyta 65

bacteria 19, 21, 22, 24, 25, 26, 28, 29, 39,

42, 43-51, 52, 54, 55, 56, 57, 62, 64,

66, 69, 70, 71, 74, 75, 76, 82, 86, 87,

88, 89, 99, 100, 101, 102, 103, 105,

108, 109, 114, 117, 118, 119, 120, 121,

122, 123, 124, 127, 128, 130, 132, 133,

136, 139, 140, 141, 143, 144, 148, 149,

150, 151, 152, 156, 160, 161, 162, 165,

167, 170, 174, 176, 178, 179

bacteria, active 111, 112, 135

bacteria, aerobic 46

bacteria, anaerobic 46, 50, 84

bacteria, denitrifying 48

bacteria, nitrifying 57, 58, 66, 73, 76, 100

bacteria, pathogenic 24, 46, 51

bacteria, psychrophilic 121

bacterial slime 23, 26, 26, 37, 49, 50, 57,

72, 99, 100, 135, 139, 149

bacterivores 75, 76

baking soda 139

bark 124, 131

bark chips 129, 131

basidiomycetes 120, 123

beach 102

beeches 103, 162

bees 80, 84

beetles 24, 39, 66, 78, 80, 82, 105, 106,

108, 127

beetles, ground 173

beetles, ladybird 11

beetles, Mexican bean 171

beetles, pine shoot 81

beetles, predatory 81

beetles, rove 93, 123, 173

beets 170

Berlese, Giovanni 106

Berlese funnel 106, 107, 108, 109, 151,

175, 177, 178

biofilm. See bacterial slime

biomass, bacterial 25, 102, 103, 109, 111,

biomass, fungal 25, 101, 102, 103, 109,

110, 154, 159, 160

bioslime. See bacterial slime

Bipolaris 146

birches 11, 12, 158, 162

birds 19, 20, 24, 89, 93, 94-**95**, 150

black spot 51, 149

blood meal 152

blueberries 141, 162

Botrytis cinerea 62

Brassicaceae 169

branches 119, 124

broccoli 103, 170

brown material 44, 47, 122, 123, 124, 128

brown patch 146

brown rot 120

Bt. See Bacillus thuringiensis

bugs 80

bugs, assassin 173

bugs, pill 80

bugs, sow 80

bugs, spined soldier 171

bugs, stink 172

Burkholderia cepecia 51

burrows 89

butterflies 78, 80

C:N ratio 123, 124, 131, 132

cabbages 169

calcium 29, 39, 40, 61, 87, 9

calcium carbonate 87

cane syrup 140

carbohydrates 21, 61, 88, 102, 122, 128

carbon 15, 19, 22, 44, 47, 48, 55, 115, 119,

121, 123, 124, 132, 140, 160, 168

carbon dioxide 29, 32, 47

cardboard 128

carrots 103

Carson, Rachel 11

caterpillars 78, 173

cation 40, 41, 100 caterpillars, eastern tent 172

cation exchange capacity 14, 41, 87, 109

chafers 146 centipedes 19, 80, 105, 106, 123 cellulose 47, 52, 55, 56, 63, 64, 84, 88, 90, cedar chips 131 cation exchange site 41 chemosynthesizers 19 chemoautotrophs 47 chemicals 14, 26, 179, 180 chickweeds 147, 154, 171 Chenopodiaceae 170 Cellulomonas 47 CEC. See cation exchange capacity chlorine 140, 153 chloride 40 chitin 47, 52, 55, 56, 75, 78, 93, 123 chipmunks 94, 95 Chilopoda 80 chlorophyll 52 chloromine 140 Chlorophyta 65 ciliates 70, 71, 72, 135 cicadas 81 clay 34, 35, 36, 37, 40, 41, 100 citrus canker 51 clover 147, 153 Clostridium 46, 48 cole crops 103 cockroaches 80 Coleoptera 80 compaction 153, 159 Collembola 83 compost 114, 115, 117-128, 133, 134, competition 24 compost, bacterially dominated 128, 174, compost, fungally dominated 128, 160, compost, cold 115, 127 102, 120, 122, 131 135, 136, 137, 138, 139, 140, 141, 147, 148, 154, 155, 160, 164, 168, 173, 174, 175, 176, 179

compost, hot 126, 127

diatoms 64, 65

Dictyosteliomycota 66

cyst 72 diatomaceous earth 65 depolymerization 120 decomposition 11, 34, 76, 84, 88, 124 dandelions 11, 153 damping off 146 decay 23, 24, 46, 47, 55, 56, 66, 88, 93, Darwin, Charles 86 damselflies 80 daddy longlegs 79 deer 94 cytoplasm 54, 55, 68 cutworms 78, 146, 173 cucumbers 51 crickets, Mormon 80 crickets, mole 81 cottonseed meal 152 cotoneasters 103 copper 57, 61 Cyanophyta 66 crickets 80 cottonwoods 103, 158 corn gluten 153, 170 corn 103 concrete sprayer 144 compost tea brewers 136, 137, 178 compost tea, fungally dominated 146, compost tea, bacterially dominated 146, compost inoculum 121 compost extracts 134 compost tea 114, 115, 134-147, 153, 154, compost leachates 134 Curvularia 146 compost, instant 127 161, 177, 179 119, 124, 125, 129, 132, 133, 145, 152, 176 156, 167, 174, 175, 176, 177 155, 156, 160, 161, 164, 168, 176, 177,

diversity 24, 127, 135, 140, 150, 154, 165, dollar spot 146, 149 Diplopoda 80 diffusion 56

dominance, bacterial 25, 26, 86, 100, 101, 158, 162, 159, 166, 167, 170, 173 103, 124, 130, 132, 139, 146, 153, 154,

dominance, fungal 25, 26, 101, 102, 103, 130, 147, 153, 154, 158, 161, 164, 167,

dragonflies 80 drip line 160, 161

earthworm castings 89, 105, 129, 165 earthworms 19, 24, 26, 28, 37, 39, 66, 73, 85-90, 93, 94, 99, 105, 106, 108, 117,

123, 127, 128, 130, 138, 142, 148, 150, 151, 165, 167, 170, 176, 179

earwigs 80 earthworms, Wisconsin red wiggler 85

Eisenia fetida 85 E. coli. See Escherichia coli

electrical charge 39, 40

Enchytraeus doerjesi 85

enzymes 43, 45, 47, 55, 56, 57, 63, 70, 83, endospores 120

87, 120, 124, 141

euglena 71 Erysiphe graminis 146 Eukarya 52, 69 Escherichia coli 46, 119, 135

exoskeleton 22, 70, 78, 82, 84 eukaryotes 52 exudates 19, 20, 22, 25, 45, 57, 60, 61, 62, 133, 142, 164, 179

facultative anaerobes 46 facultative aerobes 46 fats 119 F:B ratio 103, 145 fairy rings 146, 154

fungi, bracket 52

fertilizer, chemical 11, 23, 26, 2 fertilizer 22, 56, 57, 87, 104, 152, 156, fecal pellets 87, 88 feather meal 152 158, 179 145, 148, 149, 154, 164, 170, 171, 173,

flagellates 70, 71, 72, 135 flagella 49 fungi 12, 13, 19, 21, 22, 24, 25, 26, 28, 29, truit pulps 121, 141 forest, old growth 101, 158, 180 forest, deciduous 103 food, bacterial 124, 141, 166, 168 fly agaric 163 flies, scorpion 80 flies 19, 78, 80, 173 Fleming, Alexander 63 fleas 80 fish hydrolysate 141, 156 fish emulsion 141 fish bone meal 152 fire-blight 51 fire ants 146 fertilizer dispenser 144 fertilizer, salt-based 109, 114 fertilizer, organic 151 fertilizer, nitrogen 12, 171 fertilizer, inorganic 124 fruit juices 140 fruit 62 Frank, Albert Bernhard 60 forest, conifer 103 food chains 20, 106 food web. See soil food web 30, 37, 39, 42, 44, 46, 52-63, 64, 66, 100, 101, 103, 104, 105, 108, 73, 74, 76, 80, 82, 86, 88, 90, 176, 179 118, 120, 121, 123, 124, 127, 151, 152, 153, 156, 160, 161, 132, 133, 136, 139, 144, 148, 149, 150, 130, 131, 165, 174, 93, 99, 109, 114,

glomalin 37 gophers 94 glucose 120 gastropods 91-93, 106, 107 gamasids 82 fungus gnats, dark-winged 81, 82 grass 26, 61, 84, 101, 133 glycoproteins 92 fungus, oak root 63 grass, quack 147, 153 grass, lawn 128, 130, 131, 152, 158, 160 fungivores 75, 76 grass clippings 11, 115, 119, 124, 129, grass, bent 147 Glomales 37 fusarium wilt 63 Fusarium oxysporum 63 fungicides 27, 60, 95, 109, 114, 124 fungi, rust 62 fungi, puffball 52 grasshoppers 80 Gramineae 169 Gaeumannomyces 146 fungi, pathogenic 62 fungi, parasitic 62 grasslands 102 gray mold 149 grass seed 155 fungi, endomycorrhizal 60, 61, 155, 162, green material 44, 121, 122, 123, 124 green lacewings 173 fungi, mycorrhizal 25, 60, 61, 102, 133, groundhogs 92 fungi, ectomycorrhizal 60, 61, 162, 176, fungi, coral 52 grubs 75, 146 163 133, 149, 151, 152, 156, 167, 168, 175, 171, 175, 177 142, 151, 155, 159, 162, 163, 169, 170, ivy 147 kale 93 kiwi 121 kitchen scraps 119, 124 king bolete 53 kelp 141, 176 katydids 80 Jefferson, Thomas 166 iron 19, 29, 34, 36, 39, 40, 57, 61 ions 40, 44, 57 insecticide 12, 173 Insecta 23, 56, 79, 80, 99, 146, 164, 171, Ingham, Elaine 10, 13, 25 immobilization 23, 25, 44, 56, 59, 73, 76, hyphae, fungal 12, 14, 19, 23, 27, 37, 52, hydrogen sulfide 46 hydrogen peroxide 139 hydrogen 40, 41 humus 31, 33, 36, 37, 40, 100, 120 humic acid 141, 156, 176 humate 142 hornworms 172 hornets 173 hormones 99 hickories 162 heterotrophs 71 herbivores 75, 76, 99 hermaphrodites 92 herbicides 11, 27, 95, 114, 124, 157, 158 hemicelluloses 121 heath 162 Heliospirillum 120 gypsum 34, 155 guano 89 99, 132 54, 55, 58, 75, 99, 102, 117, 135, 144 170, 173, 179

lamb's-quarters 170 ladybird beetles 19, 172 lacewings, green 173 lacewings 11, 80 lawns 11, 103, 104, 105, 114, 128, 130, larvae 19, 66, 78, 95, 99, 105, 171, 173 Laetisaria 146 143, 158, 159, 165, 176, 177, 179

leaf curl 51 leaching 50

leaf spots 146

leaves 115, 124, 126, 128, 129, 130, 131,

175, 176 132, 134, 143, 145, 156, 160, 162, 174,

leaves, autumn 119, 149, 176, 177

lettuce 93, 103 Leptosphaeria 146

lice 80

lichens 30, 59, 60, 66, 82, 93

lignin 47, 55, 56, 63, 88, 102, 122, 123,

131

lilacs 103, 158

lime 155

Limonomyces 146

lizards 93

loam 36

Lumbricus terrestris 85

macroarthropods 78, 84, 105, 106, 108, 127, 129, 154, 170, 179

MacroScope 107, 151

maggots, fly 173

maggots, root 81, 173

Magnaporthe 146

magnesium 29, 34, 36, 40, 61

Malacostraca 80

malt 141

mammals 24, 28, 94-95, 99, 105

manganese 34

mantids 80

mantids, praying 11

manure 12, 119, 129, 148, 166 manure tea 134, 135

maples 103

maple syrup 140

maturation stage 122, 123

mayflies 80

meats 119

melons 51

mesophilic stage 120, 121, 122

methane 71, 84

mice 92, 154

microarthropods 59, 73, 78, 84, 94, 104,

106, 108, 117, 127, 128, 129, 130, 151,

154, 165, 170, 179

microbe food 151, 152, 176, 177

microbes 19, 26, 31, 60, 108, 114, 115, 116, 117, 119, 120, 125, 127, 131, 132,

142, 143, 144, 147, 148, 149, 150, 153, 133, 135, 137, 138, 165, 139, 140, 141,

microbial populations 86, 117

155, 160, 161, 170, 175, 178, 179, 180

microbiology 12, 14, 26, 100, 109, 134, 143, 144, 145, 147, 148, 150, 151, 161,

165, 170, 175, 179

Microdochium 146

microorganisms 19, 25, 40, 42, 86, 88, 89,

microscope, electron 12, 13, 21, 35, 71, 94, 108, 114, 115, 119, 162

104

mildew 149

mildew, downy 62, 146

mildew, powdery 62, 146 millipedes 80, 105, 106, 127

minerals 31, 33

mineralization 23, 25, 44, 73, 74, 75, 76

mites 39, 78, 79, 81, 82, 84, 123, 165, 173,

mites, dust 80

mites, gamasid 82, 83

mites, oribatid 82, 83

mites, rust 79

miticides 95, 124 mites, spider 173

molasses 140, 143

mold, gray 62, 149

mold, leaf 149
moles 89, 94, 95
Mollusca 91
mollusks 91, 179
mosquitoes 173
mosquitoes 173
moths 80
mucilage 66

mulch 108, 115, **129–133**, 134, 139, 152, 160, 164, 167, 175, 177

mulch, bacterial 170
mulch, brown 130, 131, 133, 160, 168
mulch, fungal 177
mulch, green 133, 167, 168, 176, 177
mulch, organic 115, 129, 130
mushrooms 54, 58, 108, 152, 154, 163, 176
mustards 169

mycelia 52, 108, 141 mycorrhizae 60, 152, 161, 163, 164, 169,

mycorrhizae, ericaceous 162 mycorrhizal. See fungi, mycorrhizal mycorrhizal spores 162 myxamoebae 66, 67, 68 Myxomycota 66

necrotic ring spot 146
nematodes 12, 13, 14, 19, 21, 22, 24, 26, 39, 49, 54, 58, 72, 73, **74**–**77**, 78, 82, 84, 86, 90, 93, 99, 100, 105, 108, 109, 111, 114, 117, 120, 122, 130, 133, 135, 136, 139, 146, 148, 151, 154, 159, 168, 173, 174, 178, 179

nematodes, bacteria-eating 74, 75
nematodes, ectoparasitic 75
nematodes, endoparasitic 75
nematodes, fungi-eating 74, 75
nematodes, plant-eating 74, 75
nematodes, predatory 74, 75
nematodes, root-eating 75, 11
newspaper 121
night crawler 85

papaya peptidase 141

papain 141

nitrate 26, 40, 48, 49, 57, 58, 73, 76, 99, 100, 101, 147, 148, 152, 158, 159, 165, 166, 168, 171

nitrite 48, 49

Nitrobacter 49

nitrogen 12, 15, 19, 26, 44, 47, 57, 58, 76, 87, 115, 119, 120, 151, 154, 160, 168, 170, 179

170, 179 nitrogen, ammonium form 26, 76, 100, 10, 119, 158

nitrogen, nitrate form 26, 101, 119 nitrogenase 66 nitrogen cycle 48, 147 nitrogen-based fertilizers 11, 26, 100, 148 nitrogen fixation 48 *Nitrosomonas* 49

NPK 14, 151, 162, 167 nucleic acid 48 nucleus 43, 52, 69 nutrients, microbial 115 nut sedges 147

oats 62 oligochaetes 85 organic matter 19, 20, 28, 31, 33, 34, 36, organics. See organic matter oranges 141 operculum 91 oatmeal 141 oat bran 141 oaks 62, 63, 103, 162, 179 oyster mushroom 58 oxygen 27, 29, 31, 32, 72, 99, 120, 121, osmotic shock 148 osmosis 45, 140 onions 51 37, 41, 43, 45, 52, 56, 57, 65, 82, 84, 93, 108, 114, 119, 120, 121, 123, 124, 126, 128, 130, 175, 176 143, 160

paper 124, 128, 129
paramecia 69, 70
pathogens 24, 27, 51, 63, 115, 121, 127, 146, 150, 165, 179
pears 51

pears 51
peat moss 130
penicillin 25, 63
perennials 26, 61, 103, 117, 133, 143,

158–164, 176, 177 pesticides 19, 27, 60, 95, 108, 114, 124, 130, 156, 157, 173, 179, 179

pH 14, 26, 41, 42, 47, 49, 57, 63, 99, 100,

109, 118, 124, 148, 154, 155, 165

phenology 147
phenology 147
phenology 147
phenol oxidase 55
phosphate 40, 87, 130
phosphate rock dusts 141, 176
phosphorus 25, 57, 61, 151, 152, 160, 164
photoautotrophs 64
photosynthesis 20, 71

psocids 80

Puccinia 146

Pythium 146, 160

pseudopods 70

phyllosphere 25, 134, 146, 161

Physarum 67

Physarum 67

Phytophthora 62, 146 pill bugs 80 pine needles 129, 131

pine needles 129, 131 pines 60, 62, 162 pink patch 146

Placentonema gigantissima 74 plantains 147 plant succession 25, 101

plasmodia 68

Plasmopara 62

Pleurotus ostreatus 58

plug aeration 152, 153, 160

polysaccharides 37, 128

plug aeration 152, 153, 160
polysaccharides 37, 128
poplars 103
pores. See soil porosity
potash 87
potassium 29, 34, 40, 151
potatoes 51
pot worms 85

powdered algae 141

roundworms 74

prairie dogs 94
predators 13, 79, 127, 144, 172
primary decomposers 43, 44
primary producers 64
prokaryotes 43
prostomium 86, 87
proteins 44, 92, 120, 122, 123, 128, 138,

156
protozoa 19, 21, 22, 24, 26, 28, 43, 49, 50, 56, 58, 66, **69–73**, 74, 76, 82, 86, 89, 90, 99, 100, 102, 105, 108, 111, 114, 117, 120, 130, 133, 139, 146, 148, 149, 151, 159, 160, 165, 170, 174, 179
protozoa soup 154, 168, 177
Pseudomonas 51, 121
pseudopodia 70

rabbits 94
red thread 146
reptiles **94–95**Rhizobium 48
Rhizoctonia 160
Rhizoctonia cerealis 146
Rhizoctonia solani 146
rhizosphere 21, 22, 23, 25, 42, 45, 76, 99, 132, 132, 165, 168, 179

76, 99, 132, 132, 165, 168, 179 rhododendrons 103, 146, 162 rice 66 robins 81, 95

robins 81, 95
rock crawlers 80
rock crawlers 81
root hairs 81
root tip 21, 22, 41, 45
rots 149
rots, crown 146
rots, stem 160
rots, root 62, 146, 160
rototilling 11, 25, 27, 89, 95, 104, 166, 167, 171

rye 62 sawflies 80 sawdust 119, 124, 131 sand 34, 35, 36, 41 salts 148, 149 salamanders 82, 93 rusts 146 row crops 99, 167 Sclerophthora 62, 146 scale 146, 173 rusts, white 62 scorpions 79 shrews 154 shredders 26, 79, 81, 88, 129 septa 52, 54 seeds 148 seaweed 129 Sclerotinia 146 shrubs 26, 61, 105, 117, 133, 134, 143, silicon 29 silverfish 80 silt 34, 35, 36, 37, 41 slime molds, cellular 66 slime molds 64, 66-68 slime molds, plasmodial 66, 67 slugs 19, 26, 75, 91, 105, 106, 123, 168, 173 slugs, red 92 snails 91, 105, 123, 173 snakes 93, 94 snow mold, gray 146 snap beans 171 snow mold, pink 146 soaker hose 137 sodium 29, 40 soil, alkaline 41 soil, acidic 41 soil, fibric 33 soil, sapric 33 soil, humic 33 soil compaction 60, 95, 152, 159, 160 soil color 34 158-164, 176, 177, 179 soil food web gardening rules 100, 101, soil drench 144, 145, 161, 167, 168, 170 soil science 28-42 soil profiles 33 soil porosity 14, 32, 36, 89, 90, 99, 167 soil peds 37, 38 soil food web 19-27, 99-103 Soil Foodweb, Inc. 109, 111, 112, 113 spinach 170 spiders 19, 23, 39, 78, 79, 83, 93, 105, 123, sprayers, garden 144 sprayers, electrostatic 144 sprayers, concrete 144, 156 spores, fungal 54, 54, 55, 62, 63, 66, 120 sow bugs 80, 123 soybean meal 141, 176 soil texture 14, 34, 35, 36, 37, 41, 51, 76 soil structure 23, 37, 39, 99, 150, 159, soil horizon 33 sugars 21, 44, 45, 55, 92, 102, 121, 140, stripe smut 146 streptomycin 25 strawberries 62 straw 119, 129, 133, 168 stoneflies 80 squirrels 94 spruces 11 springtails 19, 39, 59, 80, 82, 83, 105, 108, spring 176, 177 sporangia 68 Spitzenkörper 55 succession 25, 65, 158 Streptomyces 46, 121 Staphylococcus 63 175, 176 123 117, 119, 124, 128, 130, 132, 133, 139, 147, 148, 151, 155, 158, 162, 166, 169, 165, 166, 167 180, 181-182 141, 152, 168 170, 171, 173, 174, 175, 177, 178, 179

sulfate 40 sulfur 19, 47, 48, 130, 155, 170 summer 177, 178 summer patch 146

take-all 146
tannin 124
termites 71, 80, 84
terpenes 131
Thanasimus formicarius 81
thermophilic stage 120, 121, 122, 123
thrips 80

ticks 79 toadstools 62 tomatoes 13, 51, 63, 103, 165

trees 26, 95, 103, 105, 117, 133, 134, 143, 158–164, 176, 177, 179

web spinners 80

traveling sprinkler 144, 156, 157

trees, coniferous 60, 101, 102, 104, 158, 162

trees, deciduous 103 trees, hardwood 60, 101, 162 trees, orchard 104 trees, softwood 61

Tull, Jethro 166

twigs 124, 152, 177

Typhula 146

Tyrophagus putrescentiae 80

Ustilago 146 ultraviolet rays 143, 144 UV. See ultraviolet rays

VAM. See vesicular-arbuscular mycorrhizae vegetables 26, 61, 101, 102, 133, 143, 165–174, 176, 177, 179

vermicastings 87, 128, 140
vermicompost 85, 128
vesicular-arbuscular mycorrhizae 155
vinegar 46, 126, 155
vitamins 63, 99
voles 94

walking sticks 80
Washington, George 166
wasps 75, 80, 84
wasps, braconid 172
water 31, 32, 132
water, capillary 32, 35, 36, 37
water, gravitational 32, 35
water, hydroscopic 32, 72
weathering 29, 30, 33, 34, 66

weeds 124, 128, 129, 148, 158, 167, 170
weevils 75, 146
wheat 51, 62, 103
whiteflies 146, 173
winter 174, 178
wood chips 115, 119, 124, 129, 130, 131, 132

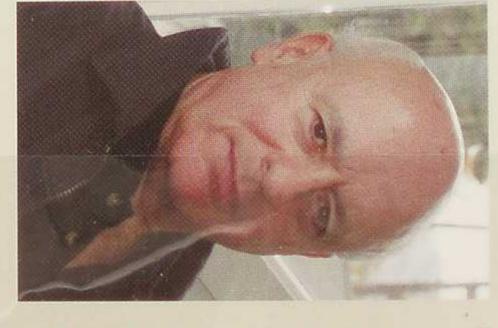
worms. See earthworms

Xanthophyta 65

yellow patch 146 yucca 141

zeolites 141 zinc 57, 61, 143 zorapterans 80





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Wayne Lewis is a lifelong
Alaskan gardener. He has
worked with Jeff on many
projects over the past 20
years, including the now
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(started in Anchorage by
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gardeners to donate a

portion of their harvest to charitable organizations in their community.

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