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Soil food web - opening the lid of the black box

by Bart Anderson

> *We know more about the movement of celestial bodies than about the soil underfoot.*
> *- Leonardo da Vinci, circa 1500s*
>
> *Any sufficiently advanced technology is indistinguishable from magic.*
> *- Arthur C. Clarke*

"Magic" is how humans have customarily described the soil's natural cycles of decay and growth. Without a scientific understanding, our ancestors relied on observation and traditional practices to grow crops.

Modern chemical agriculture has been only marginally better at understanding the soil. Unable to control the natural cycles, it bypasses them with synthetic fertilizers and pesticides. Despite the outward successes of modern agriculture, its heavy-handed approach brings with it pollution, soil degradation and other ills.

In contrast, organic methods like permaculture have attempted to work with natural cycles. Despite the many insights and successful practices that have emerged, a rigorous scientific model is still lacking. Permaculture and its brethren are accused of being belief systems rather than science. It's hard to make progress without having a common understanding of how things work.

Recently, however, soil ecology has developed to the point where we can open the lid on the black box of underground processes. We can begin to understand how micro-organisms maintain the structure and fertility of the soil. We learn that symbiotic relationships between plants and micro-organisms are not the exception but the rule.

It is no longer just compost-lovers who are excited about soil. The respected journal *Science* devoted an issue to "Soils: the Final Frontier" (June 11, 2004), saying:

> "In many ways the ground beneath our feet is as alien as a distant planet. The processes occurring in the top few centimenters of Earth's surface are the basis of all life on dry land but the opacity of soil has severely limited our understanding of how it functions.... However, perspectives are beginning to change... Interest in soil is booming, spurred in part by technical advances of the past decade."

Waiting for Dr. Ingham

It's a chilly winter day at the San Mateo Garden Center in Northern California. Several dozen of us are drinking tea and coffee, waiting to hear soil microbiologist Dr. Elaine Ingham talk on the soil food web. We're drawn by the promise that by understanding soil ecology, we can grow healthier plants without relying on pesticides and synthetic fertilizers. And in the long run, we're told, it will be cheaper and easier.

Actually most of us don't have to be convinced -- we're a cross-section of greenies from the San Francisco Peninsula: landscape designers, horticulture teachers, nursery owners, Master Gardeners, Master Composters and permaculture activists. We know Ingham's reputation and are here to listen to the master.

At last Dr. Ingham steps to the front and we're off. For the next two days we are inundated with dense, high intensity information that's very different from the usual. It's like having your head unscrewed.

She's the kind of professor you wish you had in college. She loves her subject and invites you to share it with her.

Dr. Elaine Ingham
(Photo: Alane Weber / Botanical Art)

Much of the talk around organics is vague -- but not with Dr. Ingham at the helm. Ask a question or raise an objection, and she'll come back with a detailed response, complete with references in the scientific literature. As we say in Master Gardeners: "science-based gardening advice."

Ingham has been researching soil microbiology for over 25 years, having received her PhD in 1981. She taught at Oregon State University (Corvallis) from 1986 to 2001. She left academia to devote herself to Soil Foodweb, Inc, the consulting and testing service she started in 1996. She has published over 50 articles in refereed journals.

Years spent peering through a microscope have given her a perspective that is ... different. As one aside, she remarked that humans, if viewed from outer space, would bear a remarkable resemblance to rod-shaped bacteria. As with many good biologists, she has an affection and respect for the organisms she studies.

She also has a gift for the apt metaphor that makes a technical concept come alive:

- Pests and disease are "garbage collectors" that take away stressed plants growing in the wrong habitats.
- When adding water to compost, follow the "Goldilocks Principle" (not too little, not too much - just the right amount).

After several days of lectures, I had taken over 100 pages of notes and was in danger of getting lost in the details. How to summarize Ingham's message? One attempt:

> **Life on earth is sustained by a complex underground ecological system - the soil food web.**

Through ignorance, we've disrupted the food web, in particular with ill-advised farming and gardening methods.

We can return the food web to health by restoring the soil biology.

The picture of the soil food web that Ingham presents seems to be widely accepted. Rarely however are the ideas synthesized into a coherent whole. No wonder. The concepts come from many different fields -- microbiology, ecology, soil science and agronomy. Specialists absorbed in their own fields often find it difficult to see the big picture.

Beyond the big picture, Ingham does differ from other scientists. She has a higher level of passion than one expects in academia. Also, some of her specific methods and recommendations are different than the usual. For example, she and her associates developed methods of assessing soil health by making direct counts of organisms under a microscope. Among the public, she is probably best known for advocating the use of aerobic compost tea.

The rest of this article gives highlights from Ingham's presentations, then discusses the implications of the vision. To learn more, see the list of resources at the end of this article. Especially recommended is the Soil Biology Primer, which Ingham co-authored.

Soil food web

Learning about the soil food web is like entering an alternate reality. We see the results of the microbial world in decomposition, in foods (wine and cheese, for example) and in diseases. However this world operates with numbers and at a scale that is disturbingly alien. One handful of good garden soil can contain more organisms than the number of human beings who have ever lived: 1 trillion bacteria (10 to the 12th), 10,000 protozoa, 10,000 nematodes and 25 km of fungi, according to Young and Crawford in *Science* magaziney.

As far as alien-ness, let's not even talk about bacterial sex!

I had known the numbers were high and thought that the picture was hopelessly complex. What I learned, though, is that the organisms in the soil belong to a manageable number of functional groups. These can be studied and we can make generalizations about them. Ingham's colleague, Andrew Moldenke, says:

> "All soils everywhere are comprised of the same basic critter groups. What's different about a desert, the tundra, a rainforest or a cornfield are numbers (relative densities of critters)."

The concept that ties the different groups together is the soil food web.

The Soil Food Web: Eat and be eaten.
(Figure: USDA)

Energy and nutrients are passed as one group of organisms feeds on another.

At the bottom level of the food web is the decaying organic matter in the soil that ultimately came from plants. Roots are a source of nourishment for some organisms.

Feeding on the organic matter are bacteria, fungi, root-feeding nematodes (microscopic round worms) and other organisms.

Feeding on them are the first-level predators such as protozoa (one-celled organisms like amoebae), some species of nematodes and arthropods ("bugs" with jointed legs like mites and insects).

Above them are higher level predators such as those pictured.

Even in this highly simplified diagram, you can see the multiple interconnections characteristic of a food web.

Bacteria and fungi - decomposers and mutualists

The stars of the underground are the bacteria and the fungi.

Bacteria are small bundles of protein with a high percentage of nitrogen. They're "like power plants," according to Andrew Moldenke. If the nutrients they need are "at the precise site of the bacterium, then bacterial metabolic rate is unequaled. But everything has to be present, just like the coal and oil at a power plant."

In contrast, Moldenke describes fungi as being "like railroad systems. They are immensely long systems of threadlike hyphae that can mobilize carbon from one region, nitrogen from another region..."

Before learning about soil ecology, I had thought that bacteria and fungi were bit players. Some caused plant diseases, I knew, but the rest seemed innocuous and uninteresting. Several things Ingham said made me realize how wrong I was.

- Bacteria and fungi evolved one billion years before plants, according to Ingham.
  -- Since plants developed in a world already inhabited by bacteria and fungi, wouldn't they evolve to take advantage of those micro-organisms?
- About 80% of plants have fungi associated with their roots (mycorrhizal fungi). The figure is from *Science*).
  -- Something about the plant-fungi relationship must be extremely important for it to be so widespread.
- Plants can release through their roots as much as 20% of their photosynthetic production. (Figure from *Science*; Ingham quotes higher figures.)
  -- Why would plants make this substantial investment, unless they were getting something vital from the bacteria and fungi attracted by these foods?

Among the services that bacteria and fungi provide for plants:

- **Building soil structure.** Bacteria glue together small aggregates (clumps of soil); fungi glue them into larger aggregates.
- **Storing nutrients and releasing them in forms plants can use.** A "microbial sponge" Moldenke calls the phenomenon. One way micro-organisms do this is by incorporating nitrogen and other nutrients in their own bodies - a much less leachable form than if the nutrients were in their inorganic forms
- **Protecting plants against diseases and pests.** Beneficial bacteria and fungi out-compete pathogens and occupy potential sites of infection on the plant.

One of the most intriguing portion of the soil is the "rhizosphere" -- the soil around the plant roots. It's a zone of intense activity, with bacteria and fungi attracted by the sugars, carbohydrates and proteins exuded by plant roots.

As usual, Ingham has striking images to describe the process. Noting that the exudates contain the same basic ingredients as used for baking (sugar, carbohydrates (flour) and protein (eggs)), she calls them "cakes and cookies." No wonder they're attractive.

The bacteria and fungi attracted to the roots are "the white knights fighting off the bad guys."

(Photo: Soil Foodweb International)

Symbiotic Fungus:

Wheels within wheels... life within life.

Feeder root of a plant containing the nutrient-absorbing parts (dark blue) of a symbiotic fungus. Vesicular-arbuscular mycorrhizae ("VAM") fungi like this one colonize the root systems of most plants, providing nutrients and water to the plants, as well as protection against parasitic nematodes and root rot fungi.

Fungal vs bacterial soils

Moving back from the microscopic view, the distinction between fungi and bacteria has practical consequences for farmers and gardeners. Different plant communities have different ratios of fungi to bacteria.

Bacteria dominate in early succession communities such as bare earth, weeds and vegetable. For flowers and most row crops, fungi and bacteria are in equal balance. Late succession communities such as shrubs and trees are dominated by fungi.

Knowing the bacteria/fungal ratio for the crop you're raising, you can employ different practices to encourage one or the other. Tilling or digging, for example, favors bacteria over fungi. (Most farmland is bacteria dominated.) Ingham suggests applying compost that is right for the plants you are growing, such as fungal-dominated compost around fruit trees (very fungal around conifers) and bacterial for grass. To build soil, she says, encourage fungi.

Predators, engineers, taxicabs and shredders

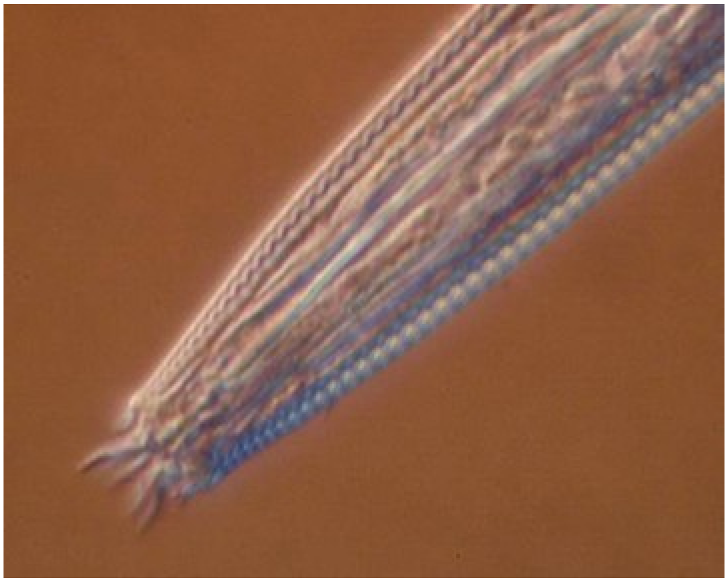
The larger organisms play a variety of roles in the soil food web.

Many are predators who keep prey populations in balance.

Some of the large organisms, especially earthworms, are "engineers", improving the architecture of the soil by creating air passages and hallways with their burrowing.

Micro-arthropods are "taxi cabs" for the less mobile smaller organisms such as bacteria, helping them spread throughout the soil and onto the leaf surfaces. In this way, they bring bacteria to where the nutrients are.

Andrew Moldenke points out that some arthropods shred dead plant parts, so that the nutrients become accessible to bacteria.


(Photo: Soil Foodweb International)

Beneficial nematode:

Many species of nematodes (microcopic roundworms) in the soil are beneficial. This is an example of a nematode that feeds on bacteria. By eating the nitrogen-rich bacteria and then excreting excess nitrogen, the nematode returns nitrogen to the soil in a form which plants can use. Other species of nematode feed on fungi, on plant roots, or on other nematodes.

Restoring the soil food web

Unfortunately, scientific knowledge of the soil food web has only come in recent decades. We haven't appreciated what the soil food web can do for us, and Ingham says that many of our common practices degrade it:

- Compacting the soil.
- Tilling, turning and digging.
- Pollution.
- Pesticides.
- Synthetic fertilizers.

The degraded food web invites pests, disease and nutrient problems. In a vicious cycle, we attack the problems with chemical solutions which further degrade the food web.

The solution, according to Dr. Ingham, is to restore and enhance the soil biology. In her words:

> "Over the last 50-60 years, the attitude has been to get rid of the bad guys through pesticides, not understanding that if you destroy the bad guys, you also get rid of the good guys. When we nuke soils and destroy life, what comes back are the bad guys.
>
> "Put your workforce back into place. They don't need holidays. Just make sure they're in your soil and feed them. .... Our job is to make sure there is a diversity of micro-organisms, so plants can choose which organisms they need."

Monitoring the soil life

The first step in restoring the soil biology is being able to diagnose it. Since we can't look at the soil food web directly, we must rely on indirect methods. Some have suggested nematodes and springtails as indicators of soil health.

Ingham advocates a "direct count" method, in which individual organisms in a sample are counted under a microscope. Following a protocol, a trained technician counts the number of different classes of organisms (bacteria, fungi and protozoa, for example). The result is a report on the organisms estimated to be in the sample. The numbers indicate possible problems in the soil. For example, a high number of ciliates (a group of protozoa) suggests anaerobic conditions - harmful to plant life.

Other researchers have used plate counts. A soil sample is placed in a growth medium like agar, typically in a Petri dish. The number of bacterial or fungal colonies that grow from a soil sample are then counted.

Ingham maintains that this method grossly underestimates the number and variety of soil organisms. She says that the method was designed to detect and grow human disease organisms such as E. coli. In contrast, soil organisms need different conditions than the laboratory setting and growth media can provide. Only about .01 percent of soil organisms can be detected with traditional plate counts, she estimates.

Compost

Restoring soil biology requires a source of micro-organisms, and compost is ideal for that purpose. The compost should have a huge species diversity. Not just bacteria but fungi, protozoa, nematodes and microarthropods, as well as organic matter for them to feed on. The compost should be made locally, so that its soil biology is similar to the soil on which it is applied.

To people already involved with compost, Ingham's discussion on compost-making should be familiar, if more rigorous than the usual. Most of her information comes from an Austrian family, the Luebkes, who developed the Controlled Microbial Composting (CMC) method. CMC is a thermal (hot) method, which involves frequent turning and close monitoring.

You can control the fungi-to-bacteria ratio of the compost by the raw materials you start with, and by your methods. Frequent turning, for example favors bacteria, since every time you turn a compost pile you "slice and dice" the fungal hyphae.

(Photo: Soil Foodweb International)

Fungal Strands in Compost:

Not all the life in the soil food web is microscopic. Some fungi can be seen with the naked eye, as can earthworms and arthropods (such as insects, spiders and centipedes).

One thing you learn quickly about compost from Ingham: Aerobic GOOD! Anaerobic BAD!

Anaerobic bacteria - those that thrive at low levels of oxygen - are on her list of "bad guys." Some are pathogens. The foul-smelling compounds produced under anaerobic conditions are bad for plants. Bad compost has foul odors like:

- rotten eggs (hydrogen sulfide)
- sour milk (butyric acid)
- decaying flesh (putrescine acid)
- vomit (valeric acid)
- ammonia
- vinegar (acetic acid)

Just reading the list of smells is motivation enough to keep a pile from going anaerobic.

In addition to thermal compost, Ingham's presentation covers static (cold) compost and worm compost, which she recommends highly.

Compost tea

A keystone of Dr. Ingham's approach is compost tea (CT), made by soaking compost in water. It's a convenient way to the apply organisms that have grown in compost. The effect is similar to solid compost, but it's easier to transport, and it's the only way to apply compost organisms to leaves (foliar application).

One disadvantage is that compost teas lack the solid organic matter contained in regular compost. Without this food for the micro-organisms, the effects of compost tea do not last as long (5 years of biology vs 5 months, says Ingham).

Compost teas are not a recent invention. Ingham says they have been used in traditional agriculture since before the Roman Empire. With the chemical era, compost tea was dropped, probably because the results were variable.

Many different kinds of compost tea exist, including leachates, manure teas, anaerobic teas and passive aerobic teas. What Ingham studies and recommends is one particular variety: actively aerated compost tea (AACT). Conditions are kept aerobic by agitating the liquid or with a bubbler.

Actively aerated teas brewed from good compost make for results that can be duplicated, she says. Traditional teas, made without aeration, have variable results. And if compost tea goes anaerobic, you've lost most of the aerobic micro-organisms. On the other hand, she said she was interested in studying anaerobic teas and their possible benefits.

Machines for brewing compost tea in various sizes are available from manufacturers. "Caveat emptor," (Buyer beware) Ingham says. She encourages people to read reviews and ask for data from the manufacturers. You can also make your own brewing apparatus. Ingham wrote an article explaining how for *Kitchen Gardener* magazine.

Some of the hints proferred by Ingham for good tea:

- Good compost.
- Good (potable) water without chlorine or chloramine.
- Good brewing machine, easy to clean.
- Appropriate temperatures
- Appropriate food for desired organisms
- Brewing times variable (about 24 hours)
- Prompt application.

To encourage bactera, add bacterial foods like sugars. For more fungi, add fungal foods like humic acid, corn meal, oatmeal and fish hydrates.

One question that puzzled me was how micro-organisms stay on plant leaves after a foliar application of compost tea. Dr. Ingham replied that bacteria quickly make slimey glue to stick to surfaces," so they aren't washed away.

(Photo: Rick Weber / Botanical Art)

Brewing Compost Tea:

Permaculturalist Alane Weber in the middle of a compost tea brew cycle. She's checking the smell ("Very important!" she says) and the flow in and around the mesh bags holding the compost. The brewer is a 100-gallon model from KIS, and is located at Lyngso Garden Materials, Redwood City, California.

Perspective on the soil food web

(*Note: this last part of the article reflects my own point of view rather than Dr. Ingham's.)*

Is compost tea the answer?

The part of Ingham's approach that has aroused the most enthusiasm has been compost tea. It promises all the benefits a healthy food web can bring -- resistance to pests and disease, better yields, more vigorous plant growth, etc. Many compost tea users seem to be happy with the results.

On the other hand, skeptics point to the paucity of scientific validation and are dubious of claims that compost tea is a cure-all. Some are suspicious of the commercialization of the process.

Dr. Ingham wisely points out the limitations of compost tea:

> Compost tea is not a "silver bullet" for the problems in your yard. Other practices, such as

organic fertilizing, soil amending, mulching, aeration, etc., are also important to build and sustain a healthy garden. The soil, environmental and prior chemical condition of your yard all play a role in its overall health.

So far, most of the evidence for the effectiveness of compost tea is anecdotal, she says. She doesn't have replicated scientific studies, adding that such studies require money and resources. However, she does point to scientific studies which confirm the underlying concepts of the food web.

Determining the effects of compost tea may be complicated by the many variables in the process:

- Many preparations have been called compost tea, and the brewing process has many variables. Dr. Ingham has provided details on what she means by compost tea.
- The biology (micro-organisms)in the compost tea is wildly variable. Adding sugars or fungal food will change the nature of fungi:bacteria ratio. If compost is non-local, the resulting tea may not contain organisms adapted to the environment.
- Nature of the plant problem and the environment. For example. soils with few micro-organisms would seem to respond more dramatically to compost tea than those soils with a thriving food web.

A second difficulty is that the effects of compost tea are probably indirect rather than direct. For example, a pesticide or antibiotic tends to have a direct action on the target, perhaps by disrupting a key biological process. In contrast, a compost tea might provide resistance to disease by adding organisms that would occupy potential infection sites.

It seems rather early in the study of compost tea to make categorical pronouncements. We should remember that many organic methods that are now accepted, such as compost and non-chemical pest controls, were derided when first introduced.

With our new understandings of soil ecology, the opportunities for investigation are wide open - not only for compost tea, but for other organic and traditional practices.

Chemical and environmental models of agriculture

The soil food web gives a firmer scientific foundation for the ecological view of agriculture. The table below highlights the differences between the conventional or chemical model and the ecological model.

Conventional/chemical	Ecological
A mechanical model: • Inputs: fertilizers, pesticides • Outputs: crops • Problems: pests, diseases • Side effects: pollution, wastes • Simple systems (e.g. monoculture)	Natural cycles: • Nutrient recycling • Natural checks and balances • Pests seen as symptoms of underlying problems • Waste from one process is food for another • Complex systems (biodiversity)

Many ecological ideas have been incorporated into conventional gardening and agriculture. For example Integrated Pest Management (IPM) has become part of many Ag extension programs. (see the the IPM website and the manual Pests of the Garden and Small Farm from University of Californa).

One can imagine a combination of the two models, in which environmental thinking prevailed but chemical solutions might be used on a temporary basis for intractible problems. Dr. Ingham, while fiercely opposed to the overuse of chemicals, admits that in a few cases they may be necessary as a first step in restoring some farmlands.

End of the chemical era?

A shift to a more ecological agriculture may happen sooner than we think. And the reasons may be economic and political rather than environmental.

Modern agriculture developed during the 20th century, a period of cheap energy. Oil and natural gas have been abundant, and our current food system uses both freely. Estimates are that it takes 10 or more calories of fossil fuels to grow one calorie of food. Food writer Michael Pollan says that the American diet with its emphasis on corn and corn products is really an oil diet:

> "Corn is the SUV of plants. Growing it the way we do requires it to guzzle fuel in the form of fertilizer, about a quarter to a third of a gallon of petroleum for each bushel." (Interview from the UC Berkeley News Service)

The basis of modern agriculture is nitrogen fertilizer manufactured by the energy-intensive Haber process. Since its invention in the early 1900s, the Haber process has helped avert famines as world population rose from 2 billion to 6.6 billion. Making this fertilizer requires 1% of the world's energy supply, estimates Science magazine. (Natural gas is the usual feedstock for fertilizers; petroleum is the feedstock for many pesticides.)

Arguments aside about its successes and shortcomings, modern agriculture needs cheap fuels. Without them, it is in trouble.

Are we facing energy shortages? An increasing number of people think so. The followers of Peak Oil believe we will soon reach the peak of oil production, after which supplies will shrink and prices will go up and up. David Holmgren and others in permaculture are talking about "energy descent" - preparing for a low-energy future. Even members of the U.S. elite are worried about disruptions to the oil supply; their number includes ex-Fed Director Alan Greenspan and ex-CIA heads James Schlesinger and James Woolsey.

Supply distruptions can happen whether or not oil production has reached its peak. When the Soviet Union disintegrated in 1989, Cuba lost its source of cheap oil and other imports required for to maintain its conventional, chemical-based agriculture. It got through the crisis by turning to organic methods and restructuring its large-scale farms.

In an era in which oil, natural gas and energy in general will probably become more and more expensive, it would seem prudent to develop an agriculture that is not so dependent on them. Soils, plants, microbes and water are everywhere. The processes of ecological agriculture may be tricky (for example, the turning and monitoring of compost), but they are do-able, and they don't require imports from far-off countries.

What to do?

Assuming the scientists are right and the soil ecology picture is correct, what next?

As a start, let's make soil ecology a part of the culture. If people don't know about the soil food web, they won't value it. Are there any visionaries who can see this as a subject for science fiction or children's books? It will take imagination, since ciliates and springtails don't have the cuddle factor of baby mammals. The BBC had an example of what is possible, in their wild radio segment "Soil Safari" available on the Web.

Some good basic texts would be helpful. The subject cries out for photos, figures and diagrams to make the concepts vivid. The Soil Biology Primer is a good example of what can be done. Generalizations should be linked to supporting studies, so we can sort out myth from science.

A knowledge of micro-organisms and the environment will be increasingly important in public debates. Although this article has only discussed gardening and agriculture, soil ecology plays a part in global warming (a healthy soil sequesters more carbon); in trawling and disturbance of the ocean floor; in invasive organisms and restoration ecology. A few popular science books on soil ecology have been published (see List of Resources), but there is room for many more.

As I researched this article, I kept hoping to see more work by agriculture extension programs and researchers. They have the resources to do the research and education we need. Perhaps we'll see them adopt soil ecology as a cause, as they previously took up Integrated Pest Management.

For permaculturalists and organic gardeners, the news about soil ecology should be gratifying. Many of our practices have a scientific basis and are good for the soil food web. The way is now open for more research and experimentation.

Learning more

An article, a set of CDs or even a weekend seminar can do no more than scratch the surface of soil ecology. However excellent resources are available online and in print.

A good place to start is the Soil Biology Primer, an inexpensive ($15) 48-page booklet with clear explanations and vivid photographs. Elaine Ingham is one of the co-authors. You can read the book online, but the printed version is much easier to follow (and the pictures are better!).

Dr. Ingham makes much information available free on the website of her organization, Soil Foodweb, Inc.: http://www.soilfoodweb.com/. A good entry point is "The Soil Foodweb Approach". The website also has details on CDs, classes and other services.

Most gardening books don't cover soil ecology well. Either they skip over it completely, or speak in vague mystical terms. Exceptions include chapters in the permaculture-oriented Edible Forest Gardens by Dave Jacke with Eric Toensmeier; and Gaia's Garden by Toby Hemenway.

A book to look for is Teaming with Microbes: A Gardener's Guide to the Soil Food Web by Jeff Lowenfels, due out August 15, 2006.

Two popular science books give background on soil microbiology and the environment: Under Ground: How Creatures of Mud and Dirt Shape Our World by Yvonne Baskin and Tales From the Underground: A Natural History of Subterranean Life by David W. Wolfe.

To get deeper into the science, see Soils: the Final Frontier a special issue of *Science* magazine (June 11, 2004). More science references are available from Elaine Ingham's website (SFI: Recent academic and popular information sources). Several scientific journals and textbooks are devoted to soil ecology.

Soil food web in brief

- Soil food web - basis for life on the land.
    - Breaks down dead plants and animals and recycles nutrients.
    - Numbers and varieties of organisms are staggering.

    - Reproduction rates are high (especially bacteria), and populations tend to boom and bust with different levels of oxygen, nutrients, heat, pH and water.
    - Complex ecological relationships.
- Soil food web is composed of several classes of organisms.
    - Plants - roots and organic matter from plants.
    - Bacteria and fungi - many varieties and functions. Most are decomposers, while many others are mutualists.
    - Other members of the food web - protozoa, nematodes, arthropods, earthworms and higher predators.
    - Predators eat other organisms and make nutrients available.
- Soil food web is important for plant growth:
    - Builds soil structure.
    - Stores nutrients and releases them in forms plants can use.
    - Protects plants against diseases and pests.
    - Can tie up salts and harmful chemicals.
    - Provides resilience and adaptation to changing conditions.
- Some bacteria and fungi form mutualistic associations with plant roots. Both plants and micro-organisms benefit.
    - Plant roots exude proteins, sugars and carbohydrates ("cakes and cookies") which attract beneficial micro-organisms.
    - Nitrogen-fixing bacteria inhabit the roots of leguminous plants.
    - About 80% of world's plants have symbiotic relationships with fungi (mycorrhizae).
- Ratio of bacteria to fungi is different for different plant communities.
    - Bacteria-dominated in early succession communities (bare earth, weeds, vegetables).
    - Fungal-dominated in late succession communities (shrubs, trees, old growth).
    - Equal balance of bacteria and fungi for most row crops and garden flowers.
    - Bacteria/fungal ratio can be changed to favor different kinds of plants.
- Soil food web is degraded in disturbed land.
    - Enemies of the soil food web: compaction, tilling (turning), pollution, pesticides, synthetic fertilizers.
    - Degraded food web invites pests, disease and nutrient problems.
    - Chemical solutions aggravate the problem.
    - Need to restore and enhance the soil biology.
- Monitoring soil biology.
    - Ingham advocates a "direct count" method, in which individual organisms in a sample are counted under a microscope.
    - The result is a report on the numbers/biomass of different classes of organisms estimated to be in the sample.
    - These numbers give indication about the health or problems with the soil. For example, a high number of ciliates (a group of protozoa) indicates anaerobic conditions.
    - Many problems can be solved or alleviated by applying compost or compost tea, according to Dr. Ingham.
- Compost
    - Aerobic good, anaerobic bad. It should not stink (stink=anaerobic).
    - Three methods discussed: thermal (hot), worm, and static (backyard).
    - The balance between fungi and bacteria can be controlled by different feedstocks and

methods.
    - Monitoring compost quality is important - all composts are not created equal.
- Compost tea is a convenient way to apply compost.
    - Actively aerated compost tea (AACT) is what Ingham studies and recommends.
    - Other compost teas and liquid amendments exist (some anaerobic).
    - Process
        - Good compost.
        - Good (potable) water without chlorine or chloramine.
        - Good brewing machine, easy to clean. Ask manufacturer for data.
        - Appropriate temperatures
        - Appropriate food for desired organisms
        - Brewing times variable (about 24 hours)
        - Prompt application.

Resources - Short list for print version

- *Soil Biology Primer* by Elaine R. Ingham, Andrew R. Moldenke and Clive A. Edwards. Soil and Water Conservation Society (in cooperation with the USDA Natural Resources Conservation Service). 2000.
  Print version available through SWCS or Earth Fortification.
  Online Version available.
- Soil Foodweb Inc. website: http://www.soilfoodweb.com/
- Teaming with Microbes: A Gardener's Guide to the Soil Food Web by Jeff Lowenfels. Timber Press. Publishing date: August 15, 2006.
- Edible Forest Gardens by Dave Jacke; with Eric Toensmeier. Chelsea Green. 2005. Monumental two-volume work. Chapter 5 in volume 1 covers "Structures of the Underground Economy" and describes Elaine Ingham's soil food web concepts (pages 216-234).
- Gaia's Garden: A Guide to Home-Scale Permaculture by Toby Hemenway. Chapter 4 is devoted to "Bringing the Soil to Life."
- Under Ground: How Creatures of Mud and Dirt Shape Our World by Yvonne Baskin. Island Press. 2005. (Amazon).
- Tales From the Underground: A Natural History of Subterranean Life by David W. Wolfe. Perseus Publishing. 2001. (Amazon).
- Soils: the Final Frontier - Special issue of *Science* magazine (June 11, 2004).

Many online resources are listed in the web version of this document.

Resources - Extended List for Web Version

Dr. Elaine Ingham and Soil Foodweb, Inc. (SFI)

- Soil Foodweb, Inc. (SFI) homepage
- SFI Approach (treasure chest of information; also has photos of microsopic organisms)
- SFI: FAQs on compost tea, vermicompost and others

- SFI: Recent academic and popular information sources
- SFI: Ezines
- The Soil Foodweb: Its Importance in Ecosystem Health by Dr. Elaine Ingham (older essay, useful because it has references to the literature for specific claims about the soil foodweb.)
- The Sacred Balance (TV program by Dr. David Suzuki, with appearance by Dr. Ingham (Ingham bio)

For gardeners & farmers

- Jeff Lowenfels, long-time gardener and gardening columnist.
    - Teaming with Microbes: A Gardener's Guide to the Soil Food Web by Jeff Lowenfels. Timber Press. Publishing date: August 15, 2006.
    - Notes on soil food web
    - Life long gardener is now an uprooted man (article about)
- Edible Forest Gardens by Dave Jacke; with Eric Toensmeier. Chelsea Green. 2005. Monumental two-volume work. Chapter 5 in volume 1 covers "Structures of the Underground Economy" and describes Elaine Ingham's soil food web concepts (pages 216-234).
- Gaia's Garden: A Guide to Home-Scale Permaculture by Toby Hemenway. Chelsea Green. 2001. Chapter 4 is devoted to "Bringing the Soil to Life." Chelsea Green. 2001.
- University of California at Santa Cruz," Center for Agroecology & Sustainable Food Systems
    - Soil Biology and Ecology (PDF) a chapter in a training manual available online and in printed form.
    - Resources: Soil Biology and Ecology (PDF)
- Steve Diver of ATTRA - National Sustainable Agriculture Information Service
    - Alternative Soil Testing Laboratories
    - Soils & Compost (list of resources)

Soil ecology

- *Soil Biology Primer* by Elaine R. Ingham, Andrew R. Moldenke and Clive A. Edwards. Soil and Water Conservation Society (in cooperation with the USDA Natural Resources Conservation Service). 2000.
  Print version available through SWCS or Earth Fortification.
  Online Version available.
- The Soil Food Web: Tuning in to the World Beneath Our Feet (PDF) from ACRES about Ingham
- Under Ground : How Creatures of Mud and Dirt Shape Our World by Yvonne Baskin. Island Press. 2005. (Amazon).
- Tales From the Underground: A Natural History of Subterranean Life by David W. Wolfe. Perseus Publishing. 2001. (Amazon).
- Soils: the Final Frontier - Special issue of *Science* magazine (June 11, 2004). Many of the online articles are only available to subscribers, however one can see an interactive map of the earth's soils and the factors that threaten them. Accompanying article: Soils in trouble. To see all nine articles, you need to pay or get a print copy.
- Soils and atmosphere intricately linked by Dr. David Suzuki (comments on articles in *Science* magazine issue on soils)
- Soil Safari (audio from BBC)
- Compost Microbiology and the Soil Food Web - California Integrated Waste Management

Board
- Soil Biodiversity - FAO
- Soil Biological Communities - Bureau of Land Management (BLM)

Soil ecology (researchers)

- SFI: Recent academic and popular information sources
- Andrew Moldenke (Department of Entomology, Oregon State University). / slides from a soil biology workshop.
- Mary Eleanor Power (UC-Berkley) - food webs in rivers and their watersheds
- Diana H. Wall (Coloradu State University) - Soil Biodiversity and Ecosystem Functioning
- Howard Ferris (UC-Davis) - Nematology and soil ecology. Content-rich website: Nemaplex
- Soil & Root Ecology, Jackson Lab UC Davis

Compost tea

- Compost Tea: Promises and Practicalities (PDF) by Elaine Ingham in ACRES
- Brewing Compost Tea by Elaine Ingham in *Kitchen Gardener* magazine
- Compost Tea - Just What the Doctor Ordered (PDF) from ACRES
- Steve Diver of ATTRA - National Sustainable Agriculture Information Service
    - Notes on Compost Teas (includes extensive list of information sources) / PDF version
    - Compost Teas: A Tool for Rhizosphere + Phyllosphere Agriculture (slideshow)
- Mary Applehof "Wormwoman" - articles in her WormEzine, all PDF
    - An Introduction to Compost Teas, Part I (issue 2-5)
    - "Compost Teas, Part II -- Tests for Microorganisms" (issue 2-7)
    - "Worm Bins and Compost Teas" (issue 3-Aug)
- Tinkers Garden Forum on compost tea (heading says "Daylilies" but posts are about compost tea)
- Compost Tea Yahoo Group (login required)

Compost tea - industry & research

- Organic Teas from Composts and Manures (Organic Farming Research Association. Richard Merrill, Cabrillo College, Calif.) -PDF. Has extensive list of articles in the literature about Compost Tea.
- Notes on Compost Teas (includes extensive list of information sources) / PDF version - Steve Diver of ATTRA - National Sustainable Agriculture Information Service
- Commercial experiences: Time for (compost) tea in the northwest (also posted here)
- FAQs about Compost Tea International Compost Tea Council
- Compost Tea - an Industry Overview PDF (Brian Rosa, North Carolina Division of Pollution Prevention and Environmental Assistance (DPPEA), NC Dept of Environment and Natural Resources
- Compost Tea Task Force Report (National Organic Standards Board, USDA)
- An Update on Compost Tea: Benefits, Risks, Regulation by Eric Sideman, Maine Organic Farmers and Gardners Association
- Evaluating the Benefits of Compost Teas to the Small Market Grower (Greenbook 2003, Energy and Sustainable Agriculture Program, Minnesota Dept. of Agriculture)
- Compost Tea to Suppress Plant Disease (Vern Grubinger, University of Vermont extension)

- Dr. Linda Chalker-Scott (WSU) (compost tea skeptic): 1 | 2 | 3

Bart Anderson has been a reporter, high school teacher and technical writer. He now gardens and writes on sustainability and energy issues. He is co-editor of Energy Bulletin (http://energybulletin.net).

Bart has no connection with any business or group involved in compost tea. He has made worm compost and backyard compost for his own use for years, but has not tried compost tea.

~~~~~~~~~~~~~~~ Editorial Notes ~~~~~~~~~~~~~~~~~~~

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UPDATE (Oct 27, 2008): Added Creative Commons logo.
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