Chapter One
What is Soil Health?

The Soil is Alive!

Introduction

The story of "soil health" starts with the realization that soil is alive -- not like an individual is alive, but in the sense of a community, or ecosystem. A single handful of healthy soil will contain thousands of species of organisms and millions of individuals. So, when we speak of heathy soil, we are not referring to the physical elements, such as particles of clay, silt or sand; we are actually speaking of the health of a community of organisms, living in the physical environment we call "soil".

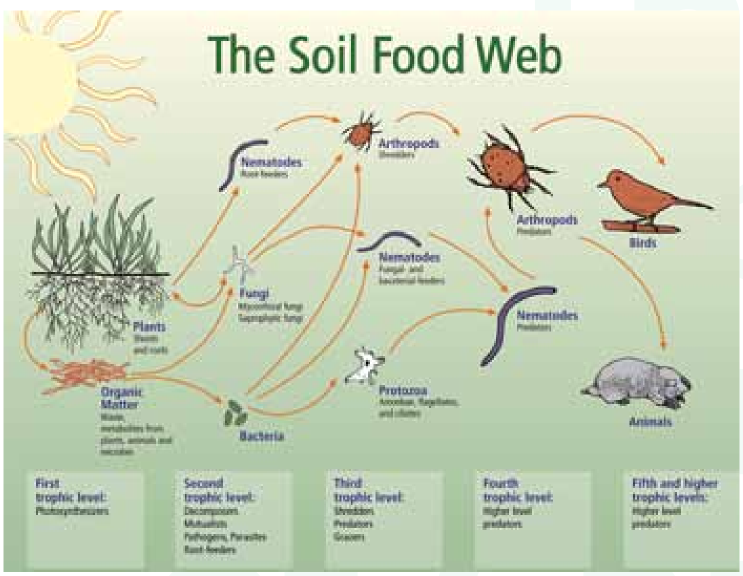
But what does the health of such a "community" really mean? What does a living community of organisms require in order to be healthy? And what are the implications of these needs for us, as human beings? This primer attempts to answer some of these questions. We will be basing our answers on the latest science, but we will be presenting them in a more user-friendly and practical manner than you will find in a scientific paper or textbook. We will be referring to this underground community as the soil food web and using the following as a working definition of soil health:

> "It is estimated that 99 per cent of the world's food comes from the terrestrial environment. But soils are also home to over a quarter of global biodiversity. Millions of soil-dwelling organisms promote essential ecosystem services – from plant growth to food production. They support biodiversity, benefit human health, promote the regulation of nutrient cycles that in turn influence climate, and represent an unexplored capital of natural sources."
>
> – Global Atlas of Soil Biodiversity

Soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans.

- Natural Resources Conservation Service, USDA.

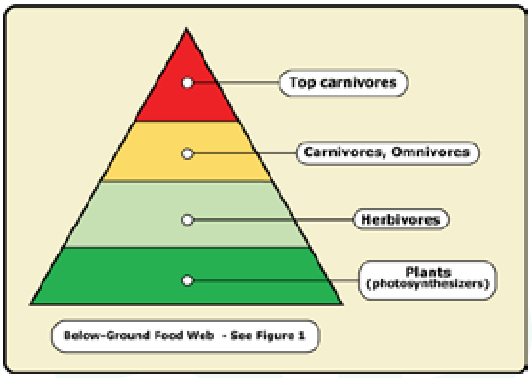
What is the "Soil Food Web"?



Soil Food Web *(Figure 1)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

The "soil food web" is a term used by scientists to describe the various life forms in the soil and the relationships between them. Like the above-ground food web, the soil hosts a hierarchy of organisms, with those at higher trophic levels[1] consuming those in the lower levels. This "who eats whom" story is very important (particularly for fertility, as we will see in Chapter 3). However, it is only part of an even greater story. Just as in our own communities, "who does what, and how they do it" really matters, not just to the organisms in the soil food web, but to those of us above ground as well.

Figure 1 shows the soil food web diagram created by the United States Department of Agriculture (USDA). Plants are the original (primary)



Above Ground Food Web *(Figure 2)*
Trophic levels diagram by the Compost Council of Canada.

energy producers, and the creatures below ground are fed by that energy, beginning with the bacteria and fungi at the lowest level (the decomposers) and continuing up to the insects and worms at the top of the underground world.

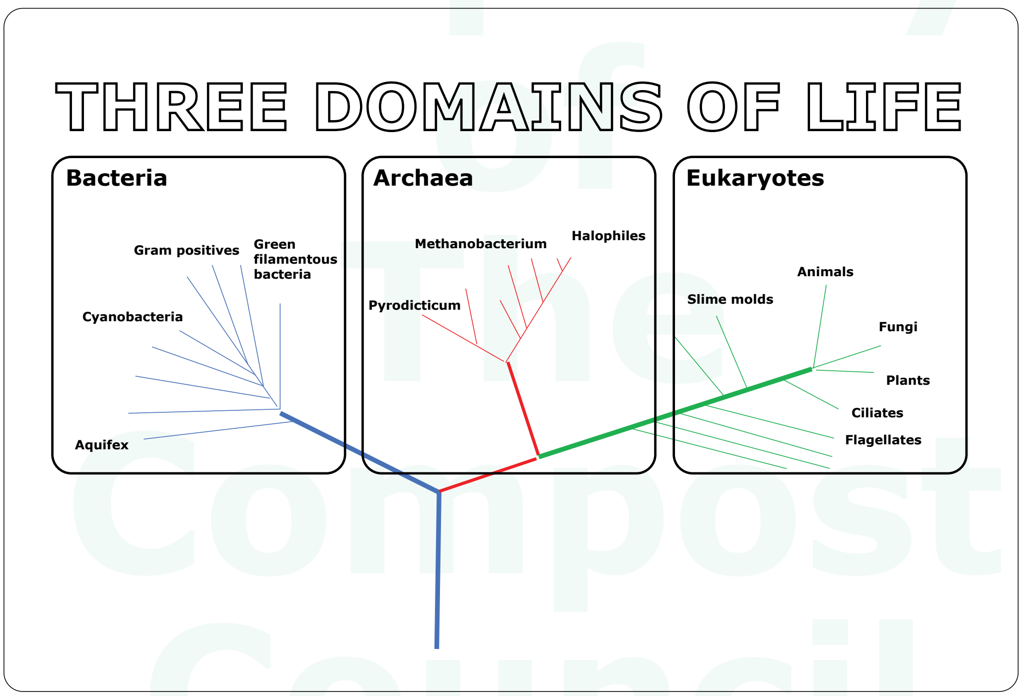
Figure 2 illustrates, for comparison purposes, the general structure of the above-ground food web.

In this chapter, we will look at the various members of the soil food web, describing in general terms what they look like, where they get their energy and resources, and what their primary roles are within the soil food web. In later chapters, we will expand on these descriptions, specifically as they relate to the soil functions of most interest to farmers.

Key Members of the Soil Food Web

Classifying Life forms

Before we jump in to descriptions of the organisms in the soil food web, we should pull back for a quick look at how scientists have classified life forms in general (see **Figure 3**). Classifications such as this are always in flux and may not be accepted by all scientists at any given point in time. However, the basic set of three domains described below, although fairly recent, appears to be the current consensus on the subject.



Classification of Life Forms *(Figure 3)*
Source: NASA

Figure 3 shows the basic classifications of our planet's life forms organized by the highest category, known as domains. Until fairly recently, scientists recognized two domains, which they named prokaryotes (bacteria) and eukaryotes (everything else). Prokaryotes are defined as single celled organisms with no nucleus or other internal organs. The eukaryotes consist of all single celled organisms that do contain a nucleus and defined "organelles", such as amoebae, plus all multi-celled organisms (such as you, your dog, your potted plant, the tiny aphid eating your plant).

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With the advent of better methods of assessing genetic material, a new domain was born – the archaea. These are also prokaryotes and are pretty much indistinguishable from bacteria under the microscope; however, genetically, they are as different from bacteria as they are from plants and animals. They tend to live in extreme environments, such as undersea vents and salt marshes, as they can withstand extreme conditions. Archaea are also present in soils but their contributions to the functions of the soil food web are not significantly different from those of bacteria.

So, for all intents and purposes, and to make the discussion less complicated, the two domains we will consider are the bacteria and the eukaryotes. Within these two domains are five kingdoms: bacteria comprise the sole kingdom in their own domain, whereas the prokaryotes boast four kingdoms. These are: protists, fungi, plants, and animals. Of particular note in Figure 3 is the fact that fungi are more closely related to plants and animals than to either protists or bacteria.

Bacteria – the Resilient Workforce

Bacteria are the smallest members of the soil food web, but the most numerous. You can think of them as the boots-on-the-ground workforce, because they can "take a licking and keep on ticking". In part, this resilience is because they reproduce very quickly, so knocking their populations back is usually a temporary phenomenon. However, like all the other underground organisms they do need a regular source of energy to thrive and perform their various functions effectively.

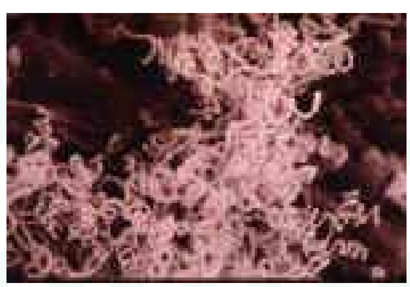
The most obvious fact with respect to bacteria is that they are very, very small. In general, they are a fraction of a micron in diameter and up to a few microns in length (a micron = one millionth of a meter). How small is this? If you lined them up side-by-side in one row on one of your fingernails, like a military unit, you would need between 10,000 and 20,000 of them to stretch from one side to the other (depending on the size of your nail).

Yet the total weight of bacteria in the soil can amount to 1 - 2 tonnes per hectare in temperate grasslands, so there must be a lot of them in the soil. In fact, as little as one gram of healthy soil (about a teaspoon) will contain millions of individual bacteria and thousands of different species. They also come in a variety of shapes and sizes, with spheres, rods, and spirals among the most common types. One of the characteristics scientists use to categorize soil microbes is by how they get their energy. A few types are what scientists call autotrophs. Like plants, they are able to photosynthesize, thereby getting their energy (in the form of carbon) from sunlight and the air. However, for the majority of soil microbes, there are three main routes. They can get energy by:

- consuming organic residues – these are called decomposers
- forming a mutually beneficial relationship with another organism, usually a plant – these are known as mutualists
- feeding off living organisms – commonly called parasites or pathogens.

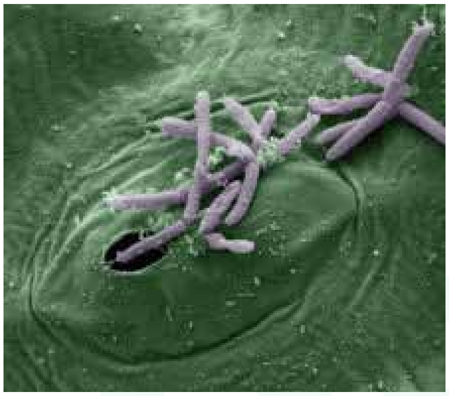
Figures 4, 5 and **6** are microphotographs of examples of each of these types of bacteria.

- **Figure 4** shows actinomycetes, a decomposer commonly found in compost as well as soils, and known for secreting a chemical that gives soil its pleasant, "earthy" odour.
- **Figure 5** shows the nodules on the roots of a leguminous plant that house the mutualist rhizobium bacteria (see below).
- Finally, **Figure 6** shows Pseudomonas syringae bacteria,



Actininomycetes – decomposer bacteria *(Figure 4)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

Rhizobium nodules on roots of legume – mutualist bacteria *(Figure 5)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

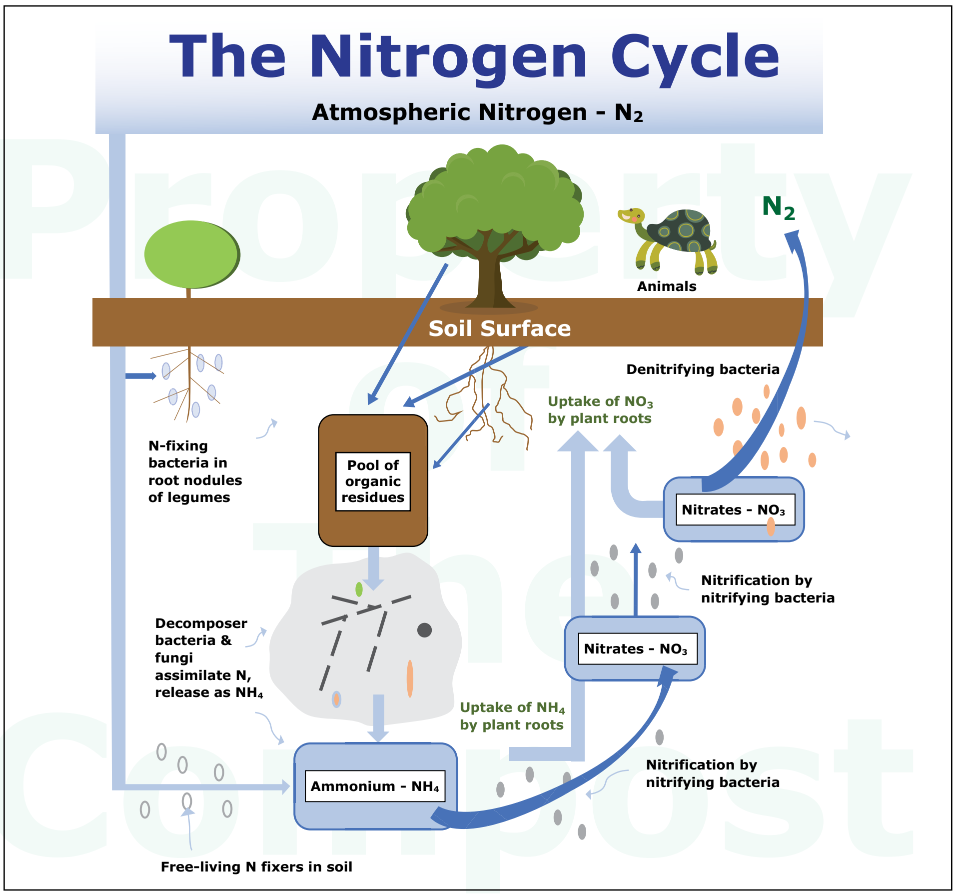


Pseudomonas syringae – pathogenic bacteria *(Figure 6)*
Image credit: James Kremer and Sheng Yang He. Reproduced with permission.

a plant pathogen, entering a plant leaf through a stoma.

There are many types of pathogenic or parasitic bacteria; fortunately, the first two categories greatly out-number the last one, at least in healthy soils -- more on this in Chapter Four.

In general, decomposers are the most well-known bacteria. Just about every one understands that bacteria are what cause rot and decay. In addition, the bacteria that colonize the roots of legumes (Rhizobium, Figure 5) and fix nitrogen from the atmosphere into a form useable by plants are also well known and appreciated, especially by farmers. Not so well known, however, are the several types of free-living nitrogen fixers, who perform the same function while working as free-lancers, as opposed to being "under contract" to specific plants. These are also mutualists, as they do their work in return for payment in the form of plant root exudates – more on this in Chapter Three.



Nitrogen Cycle *(Figure 7)*

Bacteria and the N Cycle

Nitrogen (N) is an essential element of life. It is required by all living organisms, since it a key ingredient in the synthesis of proteins, nucleic acids and other compounds basic to living processes. The Earth's atmosphere is fortunately very rich in nitrogen -- it is almost 80 per cent nitrogen gas. However, as a gas N is unusable by most living organisms. It must first be converted into a different form, called ammonium, a process we refer to as "fixing nitrogen".

The N cycle is a series of natural processes that convert nitrogen gas to organic substances and back, as part of a continuous cycle. This cycle is maintained by the decomposers and nitrogen bacteria. The nitrogen cycle can be broken down into four types of reaction and micro-organisms play roles in all of these, as the above diagram shows.

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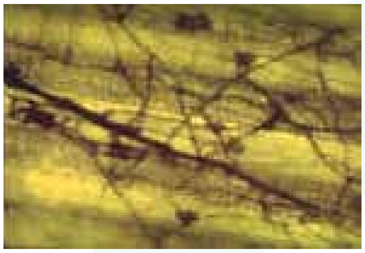
Bacteria are also fundamental to the nitrogen cycle in soil, as described in "Bacteria and the N Cycle" (see Box above, including **Figure 7**).

Bacteria perform many other functions in soil as well. They are able to secrete chemicals that can break down minerals, releasing nutrients that they then take into their bodies. Some can produce antibiotics that kill other organisms, including pathogenic bacteria. Also, given the proper conditions, they out-compete the destructive organisms in soil, ensuring overall ecosystem health.

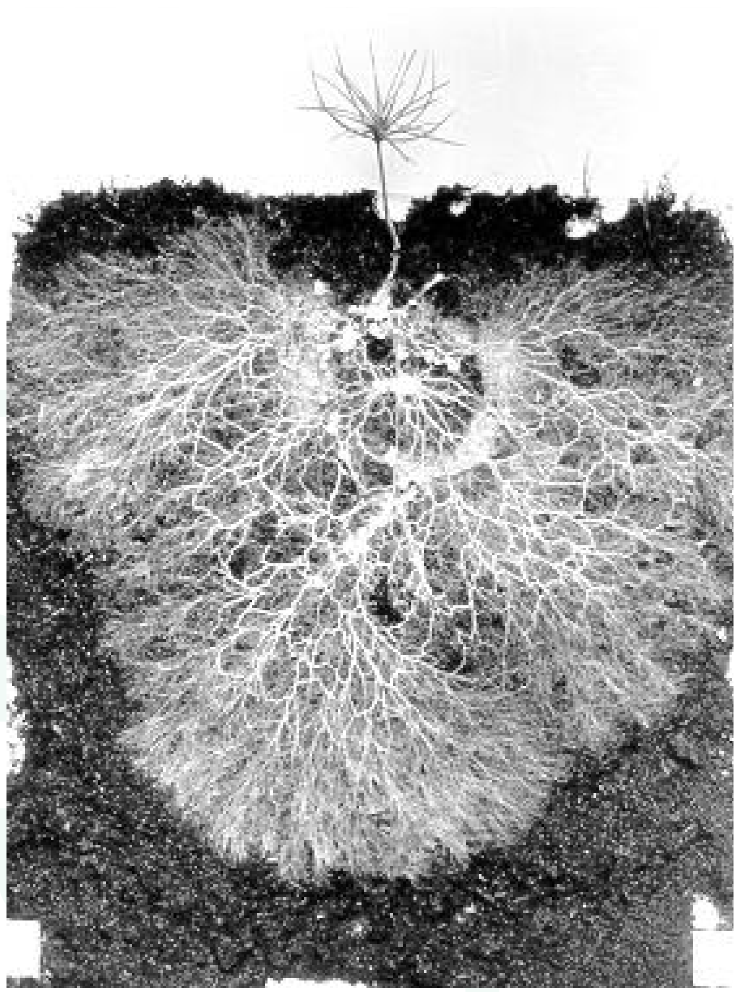
Fungi – the Networkers



Decomposer fungi *(Figure 8)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

The other organisms sharing this important niche at the base of the soil food web are the fungi. As mentioned above, fungi are more closely related to plants and animals than they are to bacteria. In fact, some scientists consider them more closely related to animals than plants, which may seem counter-intuitive to most of us. They are more complex than bacteria, beginning with the fact that most types have many cells, rather than just one. They spread through the production of long, thin filaments, known as hyphae, which can have considerable length but are only a few microns in width. When we see their white strands in soil, particularly forest soils, we are not seeing individual hyphae, which are microscopic. We are actually looking at mycelia, which consist of many intertwined hyphae, numerous to the point of being visible to the naked eye.

Like bacteria, when classified by energy source there are three main types of fungi: decomposers, mutualists, and pathogens. The decomposers are important because they are able to break down some of the tougher organic materials, things that resist bacterial break down, such as lignin (one of the main components in woody material). Fungi and bacteria are therefore complementary factions of the decomposition process of organic residuals; you need both in most soils to get efficient nutrient turnover. **Figure 8** shows decomposer fungi hard at work attacking the veins of a dead leaf.



Mutualist fungi - mycorrhizae *(Figure 9)*

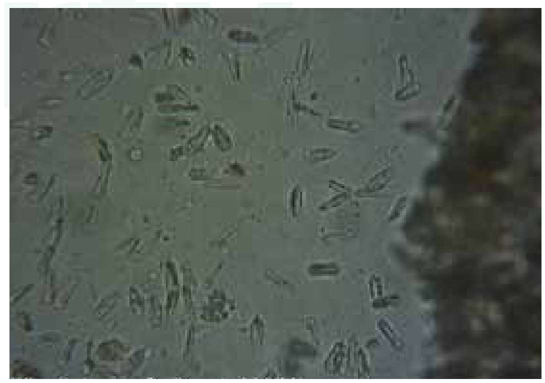
Again, like bacteria, fungi also include an important group of mutualists. These are known as mycorrhizal fungi, and there are many different species. The word "mycorrhiza" means "fungus root" in Greek and it refers to the fact that these fungi form an association with plant roots that is beneficial to both parties. The plants feed the fungus directly, through these root contacts, providing it with the energy-rich products of photosynthesis. In return, the fungus uses its spreading network of hyphae to scavenge for nutrients and water, which it uses to "pay" the plant for its sugar. These fungi are also able to solubilize nutrients out of minerals, so they have a complex, vital set of roles in the underground community. As we will see in later chapters, mycorrhizal fungi are more than just recyclers – they are also miners, truck drivers, traders, and water managers. **Figure 9** shows an extensive network of mycorrhizal hyphae radiating from the roots of a larch seedling.

Of course, pathogenic fungi are also extremely important, but for all the wrong reasons. Fungal species of both Verticillium and Fusarium, for instance, are the cause of major crop losses every year. **Figure 10** shows a microphotograph of Fusarium graminearum, a plant pathogen that causes fusarium head blight on wheat and barley.

Fungi have an enormous impact on soil functions, and these impacts appears to grow stronger as soils become healthier. Like bacteria, fungi's base-of-the-food web counterparts, they are very important for nutrient cycling, soil building (see Chapter 3), and certain symbiotic activities. However, fungi are much more complicated organisms than bacteria, and the list of the ways they impact soil and soil health is impressive. We will be discussing fungi in more detail in later chapters, but the following is a quick summary of some of the benefits fungi bring to soil.

- Approximately 80 to 90 percent of all plants form symbiotic relationships with mycorrhizal fungi, in which the latter assist the plant in acquiring nitrogen, phosphorus, micronutrients and water in exchange for sugar produced by the plant through photosynthesis.
- Some fungi help to control diseases.
- Fungi can also help to control predators (e.g., nematode-trapping fungi help to control root-feeding nematodes).
- In fact, many fungi can be used as biological controls.
- Beneficial fungi benefit most plants by suppressing plant root diseases and attacking plant pathogens with fungal enzymes.
- Some fungi produce vitamins that promote plant growth.
- Fungi also protect plants by supplying both water and phosphorus to the plant roots during droughts.

Parasitic Fungi – Fusarium species
(Figure 10)
By fk (Own work) [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC BY-SA 3.0 (http://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons



Protozoa - Flagellates *(Figure 11)*
Source: Tim Wilson, Microbe Organics

Protozoa and Nematodes – the Predators

Protozoa inhabit the next trophic level up in the soil – they are the smallest predators. Like bacteria, they are one-celled organisms; however, they are larger than bacteria and their cells have a nucleus and organelles (in other words, a higher level of organization than bacteria). This makes them eukaryotes (see **Figure 3**), more closely related to plants and animals than bacteria (but less closely related than fungus).

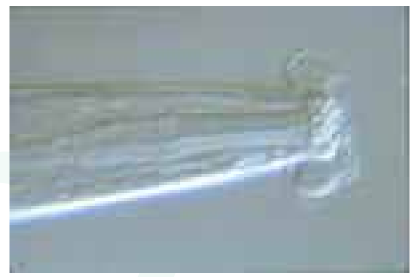
They eat bacteria – lots of them. They scoop them up and assimilate the nutrient-rich bacterial bodies, creating their own larger pool of nutrients, many of which are secreted (in plant-available form) in their wastes (or when they die). There are three basic categories of protozoa in soils: flagellates, amoebae, and ciliates. They are differentiated by their structure (see **Figures 11, 12, and 13**). Bacteria are the primary diet of protozoa; fungi are a much less common food source.

Protozoa - Amoeba *(Figure 12)*
Source: Tim Wilson, Microbe Organics

Protozoa - Ciliate *(Figure 13)*
Source: Tim Wilson, Microbe Organics

Parasitic Nematode Cysts (eggs) on Roots *(Figure 14)*
Figure credit: Bonsak Hammeraas, Bioforsk—Norwegian Institute for Agricultural and Environmental Research, Bugwood.org.

Nematodes are the other major microscopic predators of the soil food web, but they are very different from protozoa. Full-fledged, multi-cellular eukaryotes, nematodes are non-segmented, microscopic worms. While they do not make up the largest organism (as measured by biomass) in the soil, they are very common in all environments and they are the most abundant multi-cellular organism on the planet.



Bacteria-feeding nematode *(Figure 15)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

The agricultural perspective on nematodes has generally been coloured largely by the damage done by the pest variety, that is, root feeders (see **Figure 14**). However, that is only one type, and most nematodes are beneficial in soils. The beneficial nematodes get their energy by consuming other organisms: bacteria, fungi, protozoa, and other, smaller nematodes. In doing so, they perform a similar function to protozoa: collecting and releasing nutrients (textbooks call this nutrient cycling). **Figure 15** shows a type of nematode that feeds on bacteria. This function of nematodes is discussed in more detail in Chapter 3.

Some nematodes are also useful for controlling insect pests. These are the type that are available commercially and sometimes used by turf managers. They burrow into the larvae of insect pests and eat them from the inside out – a form of parasitism. Other predatory nematodes attack smaller nematodes, including the root feeders (see **Figure 16**).

Predatory Nematode Eating Another Nematode *(Figure 16)*
Credit: Nikki Seymour

Nematodes' beneficial functions are discussed in more detail in Chapters 3 and 4.

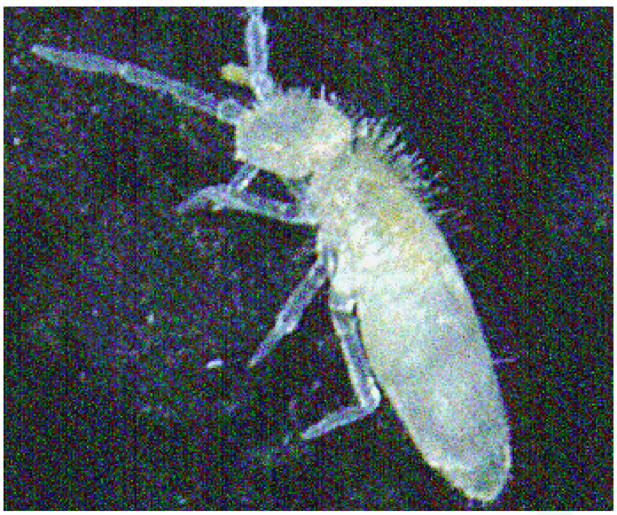
Arthropods – the Facilitators

Arthropods comprise a group of organisms that includes insects, arachnids (spiders and scorpions), and myriapods (centipedes and millipedes). They are very numerous in healthy soils, although being higher trophic level organisms that are quite large relative to microbes, they do not have anywhere close to the same total numbers as bacteria, fungi, protozoa or nematodes. They are not microscopic and are easily visible to the naked eye and range in size from barely visible (mites) to hard-to-miss (spiders, centipedes, etc.).

These creatures perform many valuable services in the soil, including:

- reducing the size of organic matter by chewing, making more surface area available to bacteria and fungi
- excreting nutrient rich material in their wastes (again, making more food available for further processing by the smaller members of the food web)
- keeping pathogenic organisms under control through predation and competition
- loosening the soil and making air and water passages by means of their burrowing
- providing "transportation services" to microbes, who will hitch a ride to other areas of the soil, either on arthropod surfaces or inside their digestive systems (they are excreted in the fecal pellets).

As with other members of the soil food web, these creatures thrive when the environment is good for their movement, reproduction, etc. The beneficial ones are usually much more numerous than the



Microarthropod - springtail
(Figure 17)
Source: Illinois Natural History Survey

Arthropod - pill bug
(Figure 18)
Source: Illinois Natural History Survey

pests when the soil is healthy. As conditions deteriorate (compaction, reduced oxygen, etc.), their numbers tend to drop relative to pest numbers, resulting in more crop damage. **Figure 17** (springtail) and **Figure 18** (pill bug) illustrate two very common soil arthropods.

Earthworms – the Soil's Heavy Hitters

Earthworms are generally considered to be at the very top of the underground food web. They perform all of the benefits listed above and are particularly prized for their ability to both improve soil structure and enhance fertility.

Earthworms are synonymous with healthy soil, and for good reason. They are both important indicators and promoters of soil health. According to Dr. Jill Clapperton, one of North America's leading experts on soil health and the soil food web, a farmer should have five or more earthworms per spade or shovel full of top soil. Moreover, this is a minimum – the more the better.

Farmers often state that one of the ways they can tell that the health of their soil is improving is the appearance of worm middens (see **Figure 19**), which are little piles on the soil surface made up of a mixture of organic residues and worm casts (feces). It appears as though the worms magically appear

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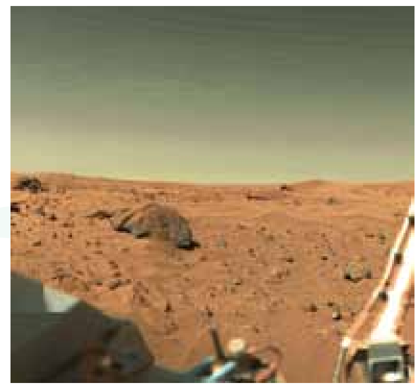
Earthworm middens (Figure 19)
Source: Glenn Munroe

as the soil gets better, but in fact it is a "virtuous circle" that is occurring, because the worms are also improving the soil as they migrate in and reproduce.

Worm turn the soil, but not in the destructive way that tillage often does. The worms' turning is gentle and slow and does not destroy soil structure; in fact, it improves it. Worms' burrows provide roots with easy channels for growth. Those same channels also allow easier infiltration of water during rainfalls and better infiltration of air (and thus oxygen) all of the time.

Last, but not least, worms fertilize soils. Their casts are rich not only in nutrients but also in beneficial microbes. When worms consume organic matter, it goes into their intestinal tracts, which act like hothouses for beneficial soil microbes. Accordingly, the casts they release hold orders of magnitude more beneficial microbes than the ambient soil. As they travel through the soil, they inoculate it with microbial activity. By doing this, they spread the greatly increased numbers of beneficial organisms all around the farm field, increasing its fertility significantly.

How do worms know to come to farms with healthy soils? From how far away do they come? Or are the increased number of worms that farmers soon see when they apply soil-health practices simply a result of increased levels of reproduction of the worms already there? Or perhaps an increase in hatching of cocoons (i.e., worm eggs) that have been in the soil for some time? We don't know for sure, but it certainly seems to be that if you build a good soil, they will come.



Surface of Mars *(Figure 20)*
Source: NASA and the NSSDCA

What are "soil functions"?

Healthy soils provide humans (and in fact all life on the planet) with many benefits. These include: clean and abundant water; the fertility necessary to grow our food; enhanced above-ground biodiversity; clean air; and last but not least, a moderate climate. If you think these claims may be extreme, think about the planet Mars (see **Figure 20**). The soils there (as far as we can tell) are dead, and almost certainly, as a consequence, the planet has no life above ground either. As those of you who read science fiction will know, any future plan to "terraform" Mars (i.e., make it like Earth, holding abundant life), will probably begin with the parachuting in of carefully selected varieties of soil microbes. Get the soil working and the rest of the planet will follow.

Back here on Earth, we can define soil functions as simply the processes through which the soil supplies a number of specific benefits, of value both to the creatures living in the soil and those above ground (including us). Given this primer's agricultural mandate, we will focus here on four sets of functions:

- Chapter 2- soil structure and its importance to water management
- Chapter 3- soil fertility
- Chapter 4- pest and disease suppression
- Chapter 5- soil carbon, along with its relationship to climate.

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1 The phrase "trophic levels" refers to the question of where an organism gets its food. The first trophic level is that of the producers – plants and certain other organisms that are able to photosynthesize – these are the primary producers. The second level refers to organisms that eat plant material, living or dead (e.g., herbivores above ground, decomposers below ground). The third and higher levels are composed of predators and omnivores of various kinds.

2 In fact, there is a 4th option: chemotrophs are able to obtain energy from certain chemical reactions. However, this type of bacterium is not very important for this discussion.

3 Not all fungi are multi-cellular, but all are eukaryotes. For instance, yeast is a single celled eukaryotic organism classified as a fungus.

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