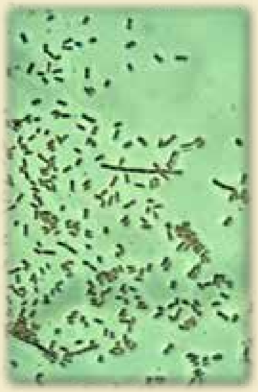
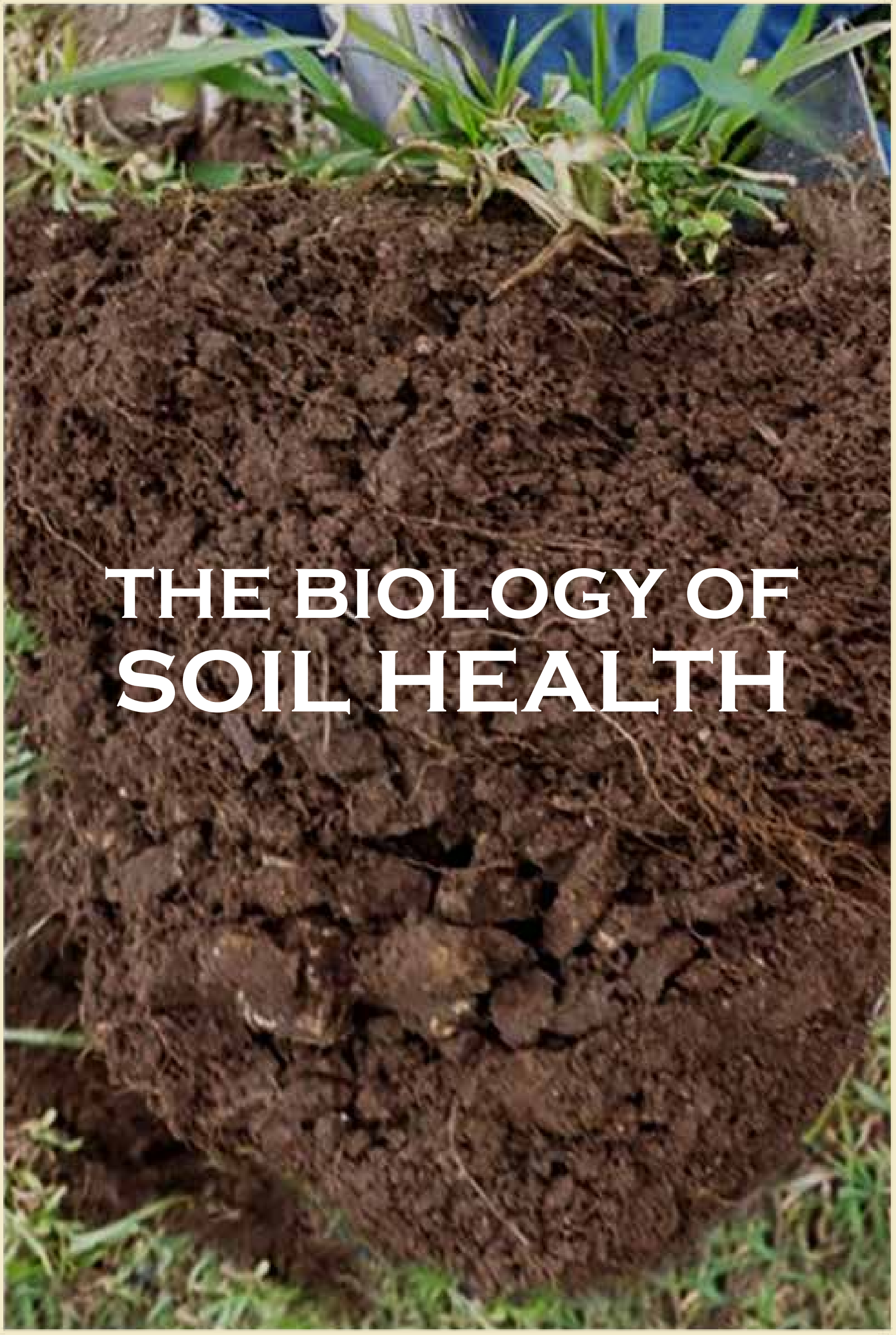
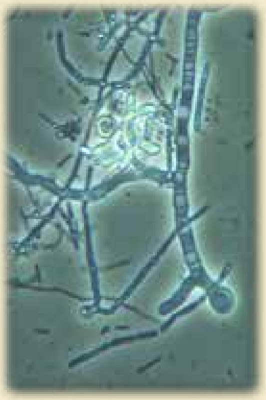
SOILS AT WORK





THE BIOLOGY OF SOIL HEALTH



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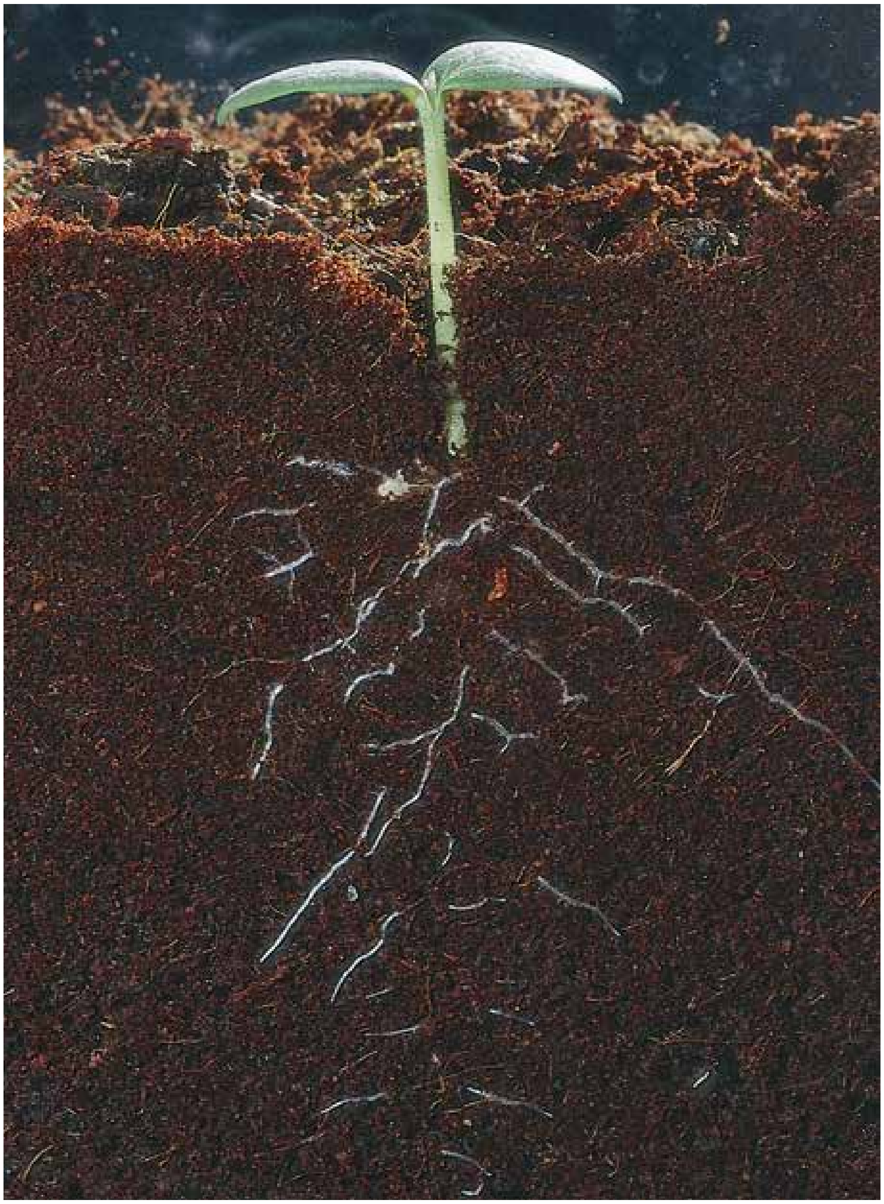
Lois Hole. From her book, *I'll Never Marry a Farmer*.



“The soil is the great connector of lives, the source and destination of all. It is the healer and restorer and resurrector, by which disease passes into health, age into youth, death into life. Without proper care for it, we can have no community, because without proper care for it we can have no life.”

— Wendell Berry

SOILS AT WORK: THE BIOLOGY OF SOIL HEALTH
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Introduction

About the "Biology of Soil Health" Project

The Primer

This primer, along with workshops based on its content (see below), are the products of an initiative originally conceived by The Compost Council of Canada. The project was funded in part through *Growing Forward 2 (GF2)*, a federal-provincial-territorial initiative. The Agricultural Adaptation Council assists in the delivery of *GF2* in Ontario.

The objectives of the project are to provide information that will help farmers:

1. Make farming more profitable, by decreasing input costs while maintaining or increasing yield;
2. Make farming more sustainable, by protecting the principal resource – soil;
3. Ensure that the overall impact of farming on the general environment is positive, rather than negative.

It is also important to state what this project is not, that is:

- An attempt to promote any particular system of farming, other than the use of generic best management practices (BMPs) related to soil health.
- An attack on synthetic inputs, other than the general idea that reducing the need for them helps farmers be more profitable and may reduce, at some times and to some degree, the negative environmental impacts of farming.
- An attempt to tell any farmer how he or she should farm (as opposed to providing good, balanced scientific information a farmer needs in order to make their own decisions).

The emphasis here is on the science – the biology and ecology of soil health. The coverage of best management practices (BMPs) consists of general principles only. For instance, subjects such as which cover crops to use or which type of conservation tillage works best in different situations is not covered. The basic idea is to tie the science of soil health to the general value of the BMPs, so that the scientific and practical logic of the use of cover crops (for instance) is clearly illustrated.

Finally, please note that Chapter Eight, which goes into more detail on the role of compost in soil health and climate change, was added after the initial project was completed. This means that responsibility for the content of Chapter Eight lies with The Compost Council of Canada alone and that none of the original project sponsors had any input. However, please be assured that the same standards of transparency, use of credible sources, and adherence to scientific accuracy were applied to Chapter Eight as were to the rest of the document.

The Workshops

Workshops based on the content of this primer have been developed, tested, and delivered across the Province over the spring and summer of 2017. The Compost Council of Canada has partnered with a number of different organizations, from individual farmers and businesses to several Conservation Authorities and the Timmins Economic Development Corporation. The workshops are usually one day in length, but can be adapted for specific audiences, such as two-hour summary presentations for a general audience and we have expanded to home gardeners and other users/workers of soil.

If you or your organization is interested in partnering in the delivery of one or more workshops or presentations, please visit The Compost Council of Canada's website at www.compost.org.

Chapter One

What is Soil Health?

The Soil is Alive!

Introduction

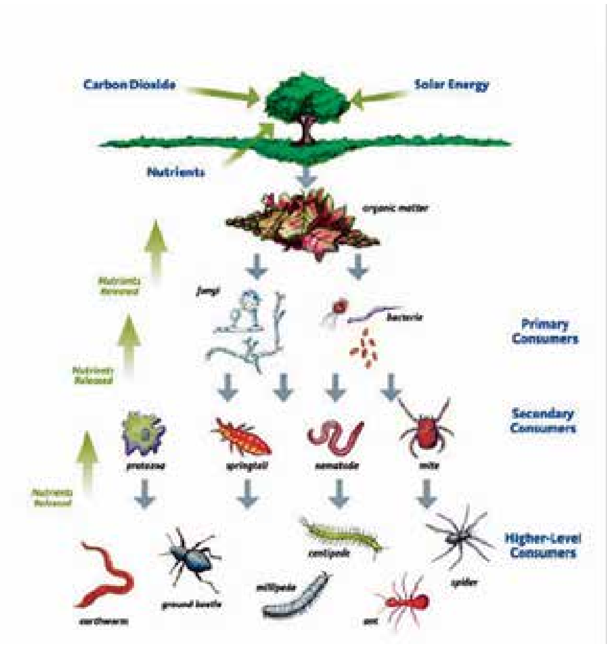
The story of “soil health” starts with the realization that soil is alive -- not like an individual is alive, but in the sense of a community, or ecosystem. A single handful of healthy soil will contain thousands of species of organisms and millions of individuals. So, when we speak of heathy soil, we 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.

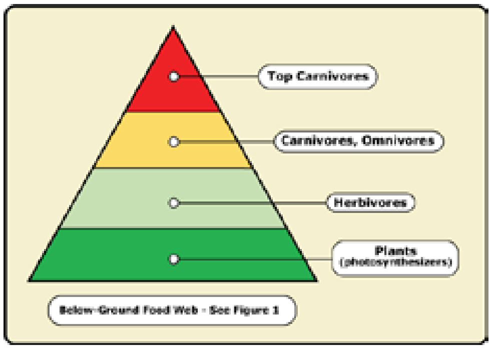


The Soil Food Web *(Figure 1)* is the community of organisms living in the soil, all or part of their lives.

What is the “Soil Food Web”?

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 Three). 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 illustrates the various levels of the soil food web. Plants are the original (primary) 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.



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

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

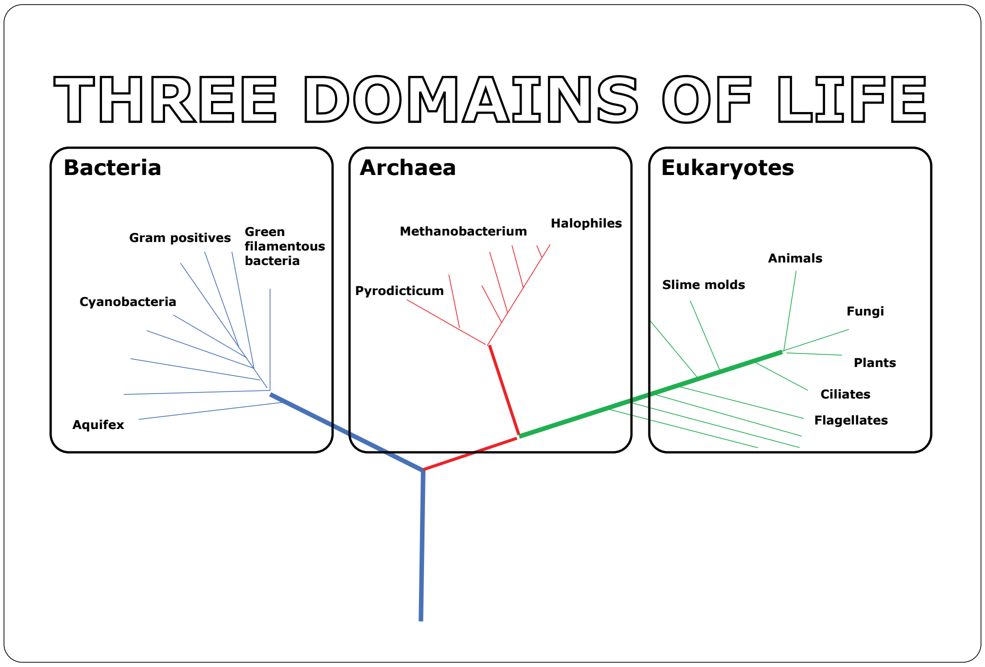
In this chapter, we will look at the various members of the soil food web, describing in general terms what they look like, where they get their energy and resources, and what their primary roles are within the soil food web. In later chapters, we will expand on these descriptions, specifically as they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

Key Members of the Soil Food Web

Classifying Life Forms

Before we jump into 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.

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).



Classification of Life Forms *(Figure 3)*
Source: Figure by The Compost Council of Canada, adapted from NASA

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 often 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 eukaryotes 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.

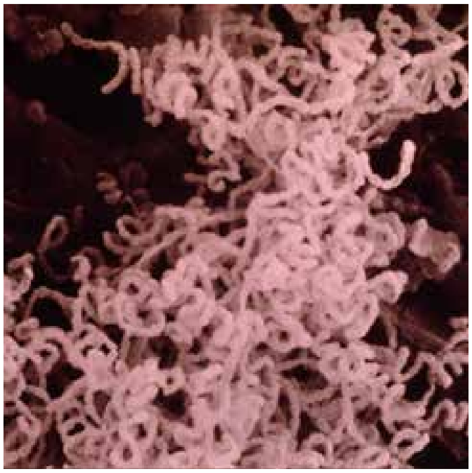
The most obvious fact about them is that they are very, very small. In general, they are a fraction of a micron in diameter and up to a few microns in length (a micron = one millionth of a meter). How small is this? If you lined them up side-by-side in one row on one of your fingernails, like a military 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).

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.[2] 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; and,
- 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.

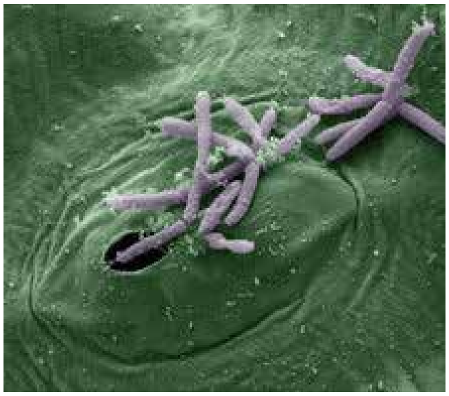
- **Figure 4** shows *actinomycetes*, a decomposer commonly found in compost as well as soils, and known for secreting a chemical that gives soil its pleasant, "earthy" odour.
- **Figure 5** shows the nodules on the roots of a leguminous plant that house the mutualist *rhizobium* bacteria (see below).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



Actinomycetes – decomposer bacteria *(Figure 4, left)*

Rhizobium nodules on roots of legume – mutualist bacteria *(Figure 5, right)*

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

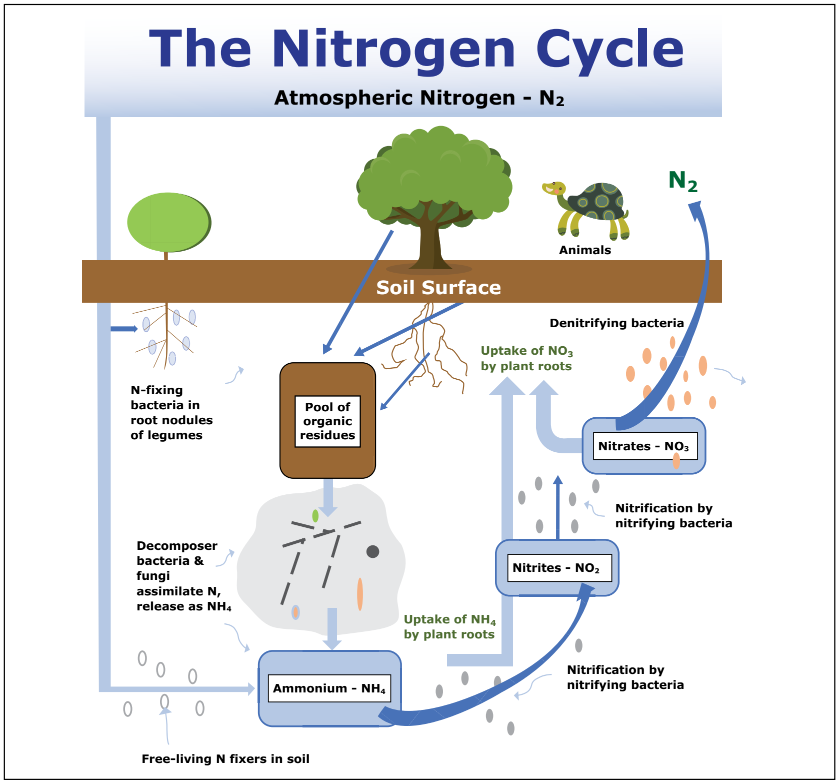


Pseudomonas syringae – pathogenic bacteria *(Figure 6)*
Image credit: James Kremer and Sheng Yang He. Reproduced with permission.

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. It is common knowledge that bacteria 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 freelancers, 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.

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



Nitrogen Cycle *(Figure 7)*
Diagram by The Compost Council of Canada,
adapted from U.S. Environmental Protection Agency original.

Bacteria and the N Cycle

Nitrogen (N) is an essential element of life. It is required by all living organisms since it is 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.

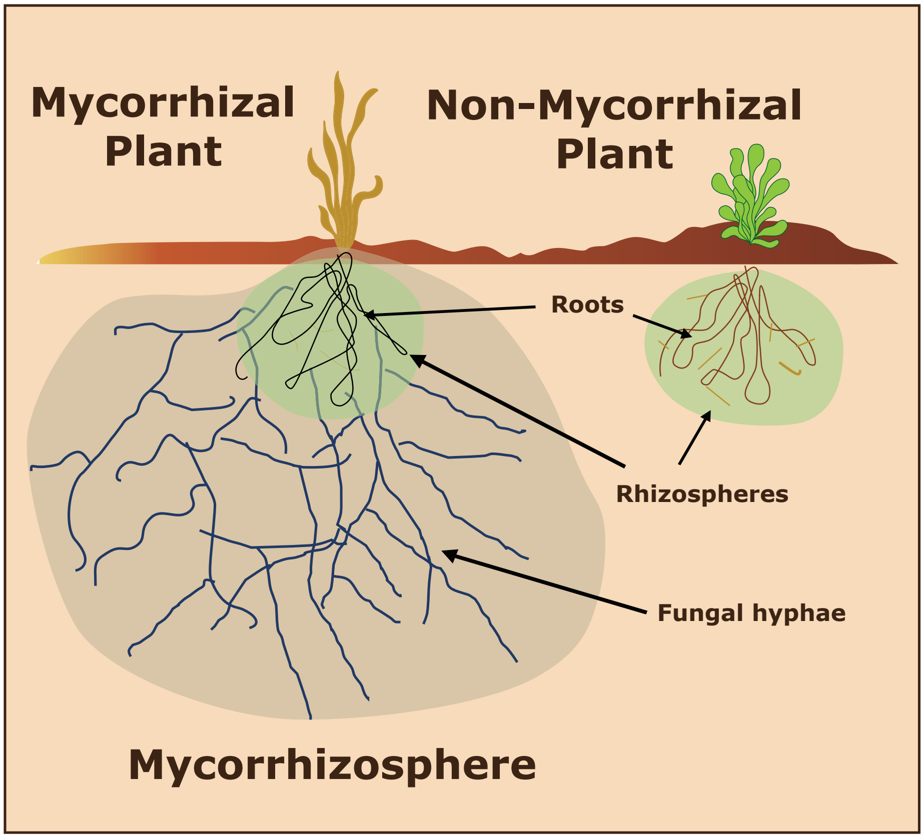
Bacteria perform many other functions in soil as well. They are able to secrete chemicals that can break down minerals, releasing nutrients that they then take into their bodies. Some can produce antibiotics that kill other organisms, including pathogenic bacteria. Also, given the proper conditions, 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 decomposer 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. They are more complex than bacteria, beginning with the fact that most types have many cells, rather than just one[3]. 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 breakdown, 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)*
Diagram by The Compost Council of Canada

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, referring 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 how Mycorrhiza extend the range of a plant's root system.

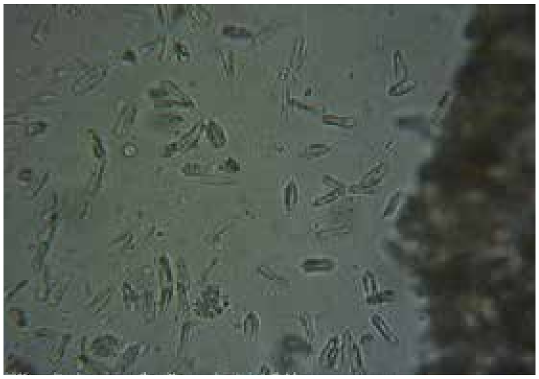
Of course, pathogenic fungi are also extremely important, but for all the wrong reasons. Fungal species of both *Verticillium* and *Fusarium*, for instance, are the cause of major crop losses every year. **Figure 10** shows a microphotograph of *Fusarium verticillioides*, a plant pathogen.

Fungi have an enormous impact on soil functions, with these impacts appearing to grow stronger as soils become healthier. Like bacteria, fungi are very important for nutrient cycling, soil building (see Chapter Three), and certain symbiotic activities. However, fungi are much more complicated organisms than bacteria.

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, which assist the plant in acquiring nitrogen, phosphorus, micronutrients and water in exchange for sugars produced by the plant through photosynthesis.
- Some fungi help control diseases.
- Fungi can also help to control predators (e.g., nematode-trapping fungi help to control root-feeding nematodes).
- 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.

Fusarium verticillioides -- a common pathogen on maize *(Figure 10)*
Photo credit: Wikipedia, Public Domain



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.

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.

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

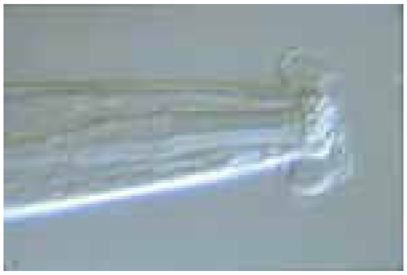
Protozoa - Amoeba *(Figure 12)*
Source: Tim Wilson, Microbe Organics

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.

Predatory Nematode Eating Another Nematode *(Figure 16)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

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 Three.



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

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**).

Nematodes' beneficial functions are discussed in more detail in Chapters Three and Four.

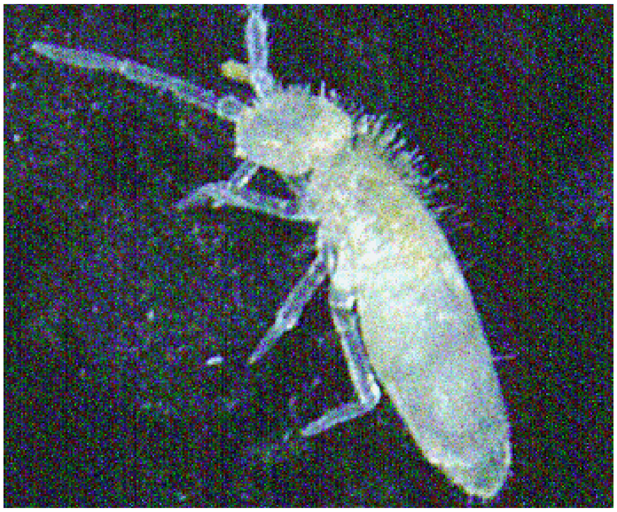
Arthropods – the Facilitators

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 — they 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, 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 then 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 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.



Microarthropod - springtail
(Figure 17)
Photo Credit: Michel Vuijlsteke

Arthropod - pill bug
(Figure 18)
Photo Credit: Franco Folini

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 topsoil. 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 as the soil gets better but in fact it is a virtuous circle: 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, not destroying soil structure but, in fact, improving it. Worms' burrows provide roots with easy channels for growth. These same channels also allow easier infiltration of water during rainfalls and better infiltration of air (and thus oxygen) all of the time.

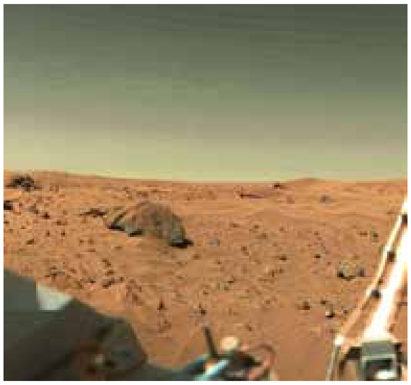
Earthworm middens (Figure 19)
Source: Glenn Munroe

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. 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.

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.



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

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 Two - soil structure and its importance to water management
- Chapter Three - soil fertility
- Chapter Four - pest and disease suppression
- Chapter Five - 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 get their energy directly from the sun – 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.

Chapter Two

The Biology of Soil Structure

Soil – A Complex Environment

The Basic Stuff of Soils

Soil has five basic constituents:

- minerals
- gasses
- water
- organic materials
- microorganisms

Minerals usually comprise just under half of the volume of soil. Minerals in soil are generally the result of weathering - the process of the gradual breakdown of rock by the acids and salts contained in rain and soil water, substances released by plant roots, soil animal activity, ice formation, and other impacts resulting from changes in temperature and moisture.

The other half (roughly) of the volume of healthy soils consists of the spaces between soil particles, which are filled to varying degrees with air and water.

The fraction of soil occupied by organic matter is usually measured by weight and ranges generally from 1 to 10 per cent (higher in organic soils). The last category, microorganisms, come in at less than 1 per cent by volume.

Even though the volume occupied by organisms is relatively small, we will see later in this primer that they play a very important role in how all of the other materials are managed and utilized in the underground community.

Bathtubs and Basketballs

Dr. Rattan Lal, one of the world's foremost soil scientists, uses the following analogy to describe how the various mineral components of soil relate in size. Think about a bathtub full of basketballs. In relative terms, this is what a soil comprised entirely of sand (e.g., a beach) is like. The large sand particles (0.5-2.0 mm) leave so much space between them that water flows right through the soil and runs out along whatever hard surface underlies it. Now imagine that the tub is filled with marbles (the average size of silt particles, which lie between .002 and 0.5 mm, relative to sand). This would slow the water down but would not stop it running through. Finally, imagine the tub filled with tiny beads, ranging in size from a pea (at the large end) to less than the period at the end of this sentence (in real terms, from .002 mm down to the size of bacteria). Now we would see some serious impediment to water flow. Perhaps, if the smallest beads were very tiny, and if they filled in all of the spaces between the larger beads, the flow might be blocked completely.

Soils, of course, are at a much smaller scale, so it is easy to imagine how even loam soils, which are considered the best for agriculture, can become compacted. A good loam soil has a rough composition of 40 per cent sand, 40 per cent silt, and 20 per cent clay. Settling of the particles into a compacted state can be due to several factors, including the pull of gravity, the lateral and downward movement of water as it flows through soil, and downward pressure from the wheels of farm equipment and the hooves of grazing animals. These forces and others can cause silt to fill the spaces between the sand particles and tiny clay particles to fill the spaces between them both, creating a solid barrier that water (and plant roots) cannot penetrate. Fortunately, nature has a way to prevent this from happening via the creation of what is called soil structure.

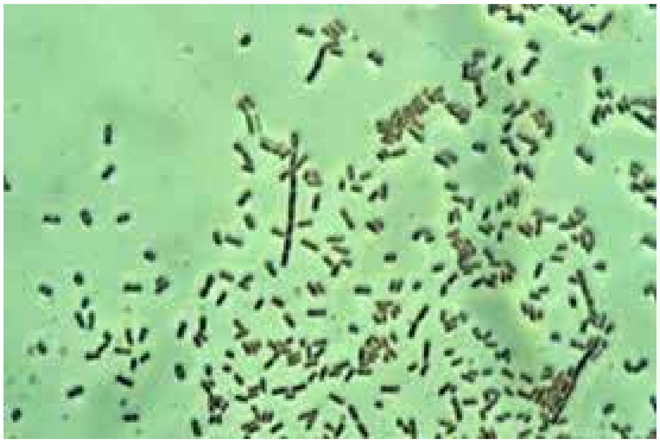
Soil Structure and Water Management

What could be more important than managing water? Soil is the filter through which much of our rainwater passes on the way back to the ocean; the soil slows its progress, holds it and cleans it. If the soil has structure, it lets the rain infiltrate easily, absorbs and holds it like a sponge, allowing plants of all kinds to access water as it is needed. Alternatively, when soil is compacted, it rejects much of the rainwater, and with flooding often the result. Compacted soil can't accept or hold much water so plant life is extremely limited and unproductive. For natural ecosystems, water is the essence of life and soil is the undeniable manager of that essence.

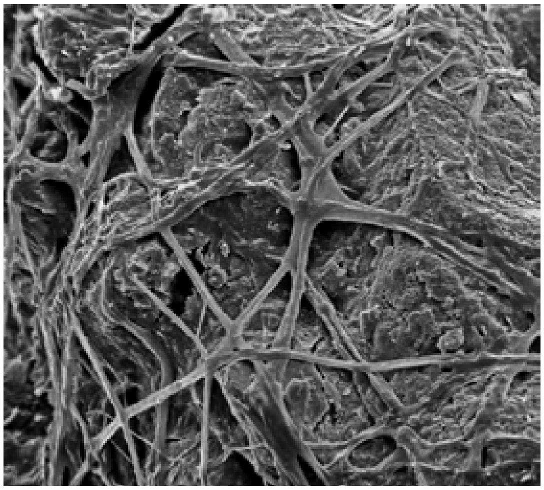
For farmers, water is a major key to productivity. No amount of nutrient will grow a good crop if water is lacking. Moreover, farmers have long understood that for soil to hold significant amounts of water, it needs to have good amounts of organic matter. However, the specific processes within the soil that open it up and create the structure that allows better infiltration of rainfall and increased water-holding capacity have not been that well understood in the past. We now know that good soil structure is the direct result of *stable soil aggregate* formation. To better understand how stable aggregates are formed in soil, we have to go back to talking about the largely invisible creatures of the soil food web.

Soil Aggregate Formation

Soil aggregates are primarily made by microbes. Although tiny mineral particles (particularly clay) do form small aggregates due to chemical attractions, the real work of making soil come together in clumps falls to the various forms of soil life. Bacteria secrete glues as a matter of survival. It allows them to stick themselves to a particle, be it mineral or organic, so that they are not washed away with the rainwater as it passes through the soil. When you look in a microscope at a soil sample (see **Figure 21**), you will see some bacteria floating free (shaken free during the sample preparation, for the most part), but many are attached to something. The glues that they produce to do this work also benefit the entire community, result in the establishment of micro-aggregates - tiny clumps of minerals, organic residues, and living microbes.



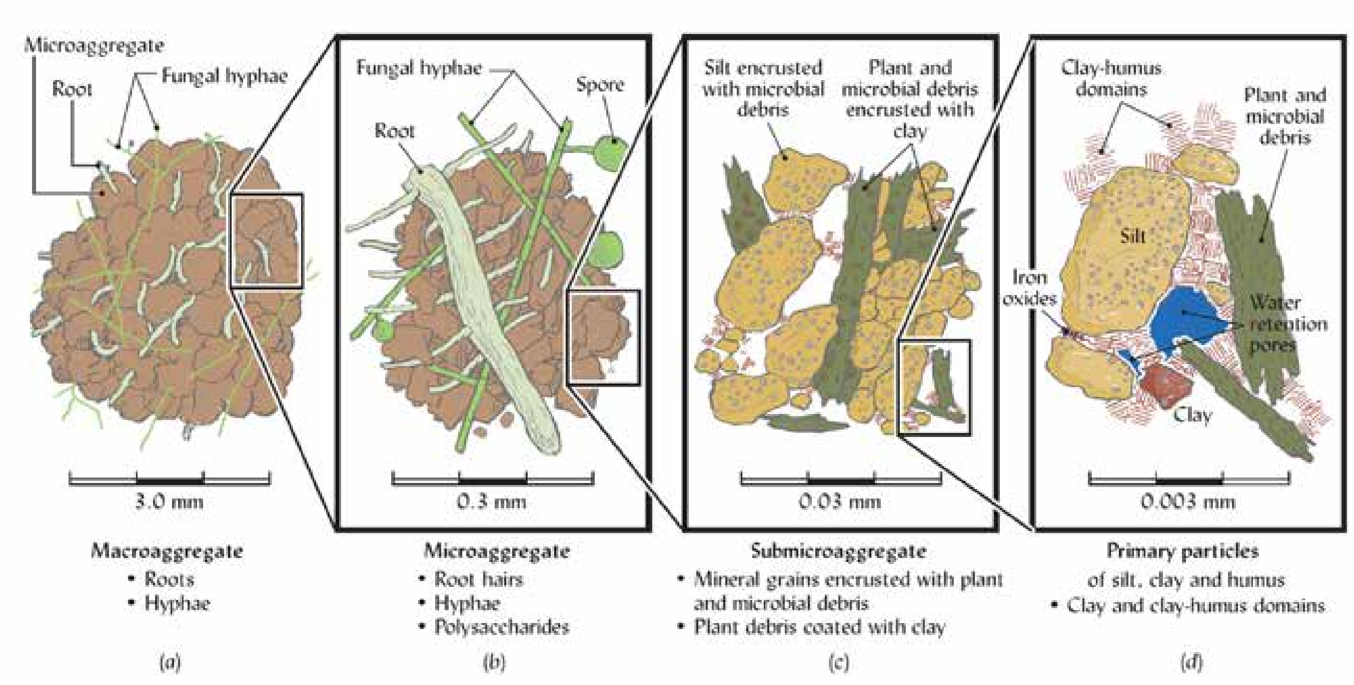
Bacteria under microscope
(Figure 21)
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society



Fungal hyphae & macroaggregates
(Figure 22)
Source: Eickhorst, Thilo & Tippkoetter, Rolf. Micropedology – The hidden world of soils. University of Bremen, Germany

Earthworms are also good at this job as they also secrete a sticky substance through their skins. As they travel their underground routes, they slough off mixtures of gluey slime, hitch-hiking microbes, and various soil particles, basically leaving aggregate components in their wake. Given these facts, it makes sense that the more bacteria and earthworms you have in your soil, the more potential your soil has for good texture or aggregation.

The *stable soil aggregate story*, however, does not end there; this is where fungi come in and really change the game. Fungal hyphae are always growing, moving through the soil in search of nutrients and water. Some of these hyphae twine themselves around groups of micro-aggregates, pulling them together into larger clumps (see **Figure 22**). In addition, hyphae of mycorrhizal fungi slough off a substance called glomalin, which is both sticky and resistant to degradation by other microbes. Fungal hyphae only live a few weeks, with new ones constantly growing to replace them. These aggregates are of different shapes and sizes, with their variability and relatively large size creating spaces between them (see **Figure 23**). These



Schematic of soil aggregate *(Figure 23)*
Source: Weil, R.R. and N.C. Brady, 2017. The nature and properties of soil. 15th ed. Pearson, Columbus 1086 pp.

are the pore spaces that allow for water storage and also promote aerobic conditions (air can enter a well aggregated soil more easily than a compacted one due to the pore spaces and the connections between them). In addition, the various glues involved are hydrophobic; that is, insoluble in water and resistant to breakdown in wet conditions. This is extremely important given their role in water storage.

This aggregate-forming process within soils is enhanced as organic matter is increased. This is mainly because soil organic matter supports soil life, with soil life creating the aggregates. Organic matter also absorbs and holds water, but it is the aggregation that is key to water management. Lately, scientists have determined that rates of aggregation increase directly with the increase in the amount of fungi present in the soil. These studies have shown a direct correlation between the amount of fungal biomass in soils and the levels of stable soil aggregates.

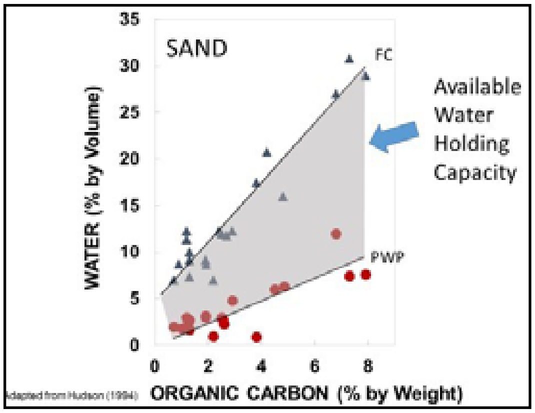
The Benefits of Good Soil Structure

Seasoned soil-health practitioners find that their soils allow for the complete infiltration of even very heavy rainfalls and that the water storage capacity of their soils increases greatly (see **Figure 24** – a rainfall simulator can demonstrate the infiltration rates of soils under different types of management). Droughts are much less of a problem for farmers with well aggregated soils. The increased pore space means that water is always available when the crop needs it.

Water-holding capacity, however important, is only one of the many benefits of well aggregated soil. Some of these benefits are mainly experienced by farmers; others are experienced by society at large, as environmental improvements. The following are some of the key benefits to farmers and to the environment:

Rainfall Simulator *(Figure 24)*
Source: Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA)

- **Better retention of valuable inputs**, such as fertilizer and pesticides. Water running off compacted soils takes a large percentage of these inputs with it.
- **Less standing water and flooding** (see **Figure 25**).
- **Better plant growth.** Good soil structure allows for better root growth and penetration, which in turn results in better nutrient uptake by plants.
- **More beneficial soil functions** (nutrient turnover, disease suppression, etc.). As we will see in later chapters, these functions depend on a large, diverse, and healthy soil food web. The community of organisms that make up this web depend on adequate water, oxygen and space to live - all of which require good soil structure.
- **Overall better profitability.** If farmers can reduce input costs (including labour and fuel) while maintaining or exceeding their yield, they will make more money. Successful soil-health practitioners always state that good soil structure is a key to their profitability.



Organic carbon and water-holding capacity *(Figure 25)*
Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society

Benefits to society at large include:

- **Food security.** As our climate changes, resiliency in the face of these changes becomes very important. A well structured soil is more resilient to extremes of temperature and precipitation, able to maintain productivity in cool, hot, dry, and wet seasons.
- **Less risk of flooding.** Always a concern in low-lying areas prone to extreme rainfall, flooding has become much more common almost everywhere as our climate has warmed. This is likely to get worse, rather than better, and soils that allow more infiltration and hold more water can have a big impact on flooding, significantly reducing its negative impacts.
- **Less pollution.** Nutrients that are valuable in the soil become a source of pollution in streams, rivers, lakes and even oceans (see **Figure 26**). Well-aggregated soils reduce pollution by eliminating run-off and through their greater capacity to hold on to both water and nutrients.
- **Enhanced biodiversity.** The organisms of the soil food web are at the base of the entire planet's food web. Fewer soil insects and earthworms mean less to eat for birds and small mammals. Less life in the soil translates into less diversity of life above ground.

Lake Erie Algal Bloom *(Figure 26)* *Source:* NASA

Summary

Soil consists of a mixture of minerals, air, water, organic matter, and living organisms. The mineral components (about 50 per cent by volume) are classified by size, with diameters ranging from relatively large sand particles (up to 2 mm) to microscopic clay particles (a few microns). Gravity and other physical forces, such as water movement and pressure from the tires of farm equipment, can cause these particles to settle in such a way as to fill in all the spaces between them, restricting the flow of air and water and reducing the living space available to soil organisms. This is known as compacted soil.

Fortunately, natural processes work to prevent this compaction through the development of soil structure. Clumps of soil particles (both mineral and organic) of different sizes and shapes are formed into aggregates. These clumps do not fit together evenly, resulting in spaces between them called pore spaces. It is in these spaces that water and air are held and where the living organisms of the soil food web reside. We now know that these aggregates are in fact largely created by soil microbes, which secrete water-resistant glues that hold the particles together. Fungi in particular play a very important role because of their ability to pull smaller aggregates together into larger ones, called macro-aggregates.

A well-aggregated soil (see **Figure 27**) provides both farmers and society at large with many benefits. Farmers find that their soils can infiltrate and hold much more water, resulting in less run-off of valuable inputs, greater drought resistance, higher yields, and increased profitability. Society benefits from a cleaner environment, greater food security, less risk of flooding, and the protection of biodiversity.

Comparison of well aggregated soil (left) to soil that is not (right) *(Figure 27)*
Source: Mel Luymes and Adam Ireland

Chapter Three

The Biology of Soil Fertility

How Plants Get Their Nutrients

What Nutrients do Plants Need?

Nutrients are substances that provide living organisms with the nourishment they need for growth and maintenance of life. Like people, plants need nutrients to survive and thrive. Unlike people, the list of essential nutrients required by plants is fairly limited. Some are needed in large amounts; these are called macronutrients. Others are only needed in small amounts and perhaps only at certain stages in the plant's life; these are called micronutrients. Each of them, to some degree or another, is essential for every plant's survival. These essential plant nutrients, as well as their sources and important functions in plants, are summarized in Table 1.[4]

Table 1: Essential Plant Nutrients

Macronutrients

Nutrient	Important Functions	As an Ion
Nitrogen (N)	Many essential functions; basis of amino acids, and thus proteins	NH_4^+, NO_3^-
Phosphorus (P)	Component of DNA/RNA; base for ATP (the energy molecule)	$H_2PO_4^-$
Potassium (K)	Regulator of water and CO_2 levels	K^+
Calcium (Ca)	Key component of cell walls; signaling; transport across cell membranes	Ca^{2+}
Magnesium (Mg)	Centre element in chlorophyll molecule – key to photosynthesis	Mg^{2+}
Sulfur (S)	A component of two important amino acids	SO_4^{2+}

Micronutrients

Nutrient	Important Functions	As an Ion
Boron (B)	Cell walls; formation of pollen tubes; moving starch and sugar	$B(OH)_3$ (neutral)
Chlorine (Cl)	Operation of stomata; breaks H_20 apart for photosynthesis	Cl^-
Copper (Cu)	Key element in important enzymes (e.g., for respiration)	Cu^{2+}
Iron (Fe)	Important to respiration, chlorophyll, N fixation processes	Fe^{2+}, Fe^{3+}
Manganese (Mn)	Frees O_2 during photosynthesis by accepting electrons from H_2O	Mn^{2+}
Molybdenum (Mo)	Synthesis of P compounds; necessary for N fixation by microbial symbiotes	MoO_4^{2-}
Nickel (Ni)	Prevents urea accumulation in leaves	Ni^{2+}
Zinc (Zn)	Oxidation/reduction; growth hormones; several key enzymes	Zn^{2+}

NOTE: Not included in Table 1 are the three non-mineral elements – carbon, hydrogen, and oxygen – that make plant life (and all life, for that matter) possible. While these elements comprise more than 95 per cent of a plant's weight, they are considered to be the basic constituents of plants rather than nutrients. In general, they are obtained from the air and water via photosynthesis rather than from the soil.

Nutrients in Soil – The Basic Chemistry

Each and every one of these nutrients is required by every plant if it is to grow and reproduce successfully. While some of the important functions of each nutrient are identified in Table 1, our focus is not on this but rather how the plant manages to get these nutrients from the soil. To understand this better, we must talk about how these nutrients get into the soil in the first place, how they are held there (or not), and how they become available (or unavailable) to plants.

All of the essential plant nutrients, with the exception of nitrogen, are originally derived from the mineral component of soils – in other words, the rocks. Zinc, for instance, is found in mineral compounds all over the planet, usually in very small amounts. On average, soils contain about 50 parts per million (ppm) zinc within their mineral components. This means that one tonne of soil minerals (1000 kilograms or one million grams) will contain, on average, 50 grams of zinc. This may seem like a very small amount, but it translates to about 150 kilograms (kg) of zinc per hectare (based on a depth of one half of a meter). This is not, however, all of the zinc potentially available in a hectare of soil. More zinc can be found in the soil organic matter because most of the zinc taken up by a plant is returned to the soil in the plant residues. This organics-based zinc is then recycled over and over. Finally, some nutrients arrive in the soil via atmospheric deposition (e.g., blown in from elsewhere on dust particles). The same processes apply to all of the other nutrients, except nitrogen, which is "fixed from the atmosphere" in biochemical form by soil microbes (see **Chapter One, Figure 7**).

It is very important to understand that nutrients in their mineral (rock) and organic-residue forms are not available to plants. Plants can only take up nutrients that are soluble in water. Fortunately, nature has many ways to free up nutrients, releasing them as ions (usually with an electrical charge) into the soil water (as shown in the right-hand column in Table 1). Nutrients are released from minerals by a number of mechanisms, some physical/chemical (e.g., weathering) and some biological/chemical (release of specific enzymes by microbes and plants). Nutrients are released from organic residues through the action of microbes (more on this below).

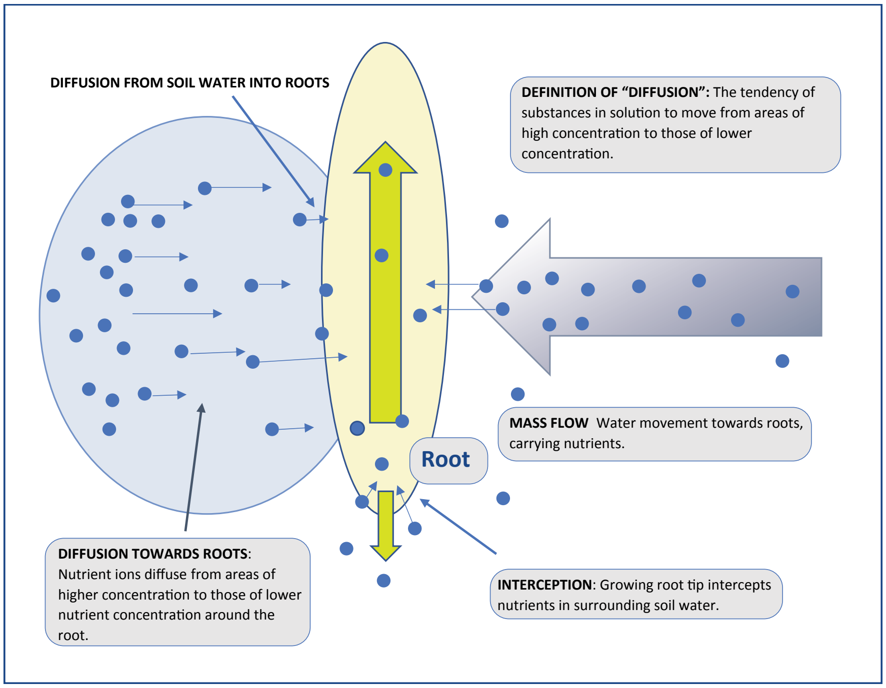
Ions are either positive or negative in charge (see **Table 1**). Some are cations (positive charged ions) and some are anions (negative charged ions). Cations are attracted to the negative charges on clay particles or on particles of organic matter. To go back to our zinc example, since it is a cation, it is often adsorbed on soil particles. Molybdenum, on the other hand, is an anion and tends to stay in solution in the soil water.

As a general rule, soils usually contain far more nutrients than a plant needs. In fact, most soils contain enough nutrients to supply crops for thousands of years, even with the loss of some nutrients to harvest each year. However, most of these nutrients are not plant-available, being tied up in minerals or, to a lesser extent, in soil organic matter. A small percentage of these nutrients is always available to plants, however, and these are either dissolved in soil water (this is called the "available pool") or loosely attached to soil particles (the "exchangeable pool").

Soil tests will tell us the amount and type of nutrients we have in the immediately-available and exchangeable categories. This then allows farmers to address any gaps in their current year's fertilizing requirements. But, for the long-term, building a strong and diverse microbial population -- the soil food web -- is the key to fertility. The stronger and more diverse the soil food web, the less need for external inputs. The rest of this Chapter explains why.

How Plants Access their Nutrients

First of all, we have the older version, found in all of the earlier soil text books. It goes as follows.
As plant roots and root hairs grow through the soil they access nutrients. This is essentially a random process, known as interception. However, they also count on two routine, on-going physical processes to bring nutrients to their roots: diffusion and mass flow (see **Figure 28**).



Interception, diffusion and mass flow *(Figure 28)*
Source: The Compost Council of Canada

Diffusion is the scientific term for the tendency of substances in solution to move from areas of high concentration to ones of lower concentration. For instance, nutrients in solution in soil water will generally, over time, move towards plant roots. This is because the roots are regularly absorbing nutrients, lowering the concentration in the immediate area around them and creating what we call a concentration gradient.

Mass flow is a somewhat similar process but instead involves a water gradient. Plants are always drawing water up from their roots via transpiration. As the water goes out into the atmosphere from its leaves, the lowered pressure above pulls water up from the roots through passageways in the body of the plant. This creates a lower water pressure in the roots which then are able to absorb water from the areas of higher pressure in the soil immediately around them. In turn, this soil becomes the low end of a water gradient moving away from the roots. As water moves from further afield along this gradient into the dry areas, it brings the nutrients it contains in solution with it. In essence, the plant is sucking water out of the soil, and the water is bringing dissolved nutrients with it.

But what about those cations (see p. 21) attached to soil particles via an electric charge? Plant roots and microbes take care of of this problem by releasing hydrogen ions into the soil water. These ions replace cations on soil particles, essentially kicking them off the particle and back into solution where interception, diffusion, and mass flow can deliver them to the plant.

Underground Carbon-Trading Systems

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

It's All About Carbon

The carbon atom (often written simply as C) is fundamental to life. It is the currency of all biochemical energy. Simply put, we couldn't lift a finger without it.

It all starts with the sun – by far the largest source of energy on our planet. The sun bathes us in energy every day. Plants use that energy to construct the building blocks of life. They combine carbon, taken from atmospheric carbon dioxide, with hydrogen and oxygen, taken from water. This is the amazing process we call photosynthesis. Combining these elements takes a lot of work, but it pays off in a big way. The resulting sugar molecules are embodied solar energy, which is now available to all living organisms, from bacteria to trees and whales.

The full story of how this sugar-based energy is transferred, used, and dissipated by life forms is long and complicated. All we need to say here, however, is that for living organisms, carbon is energy. We humans have money; Mother Nature has carbon. It is essential for all of life's processes, from basic respiration to the most complicated of human activities.

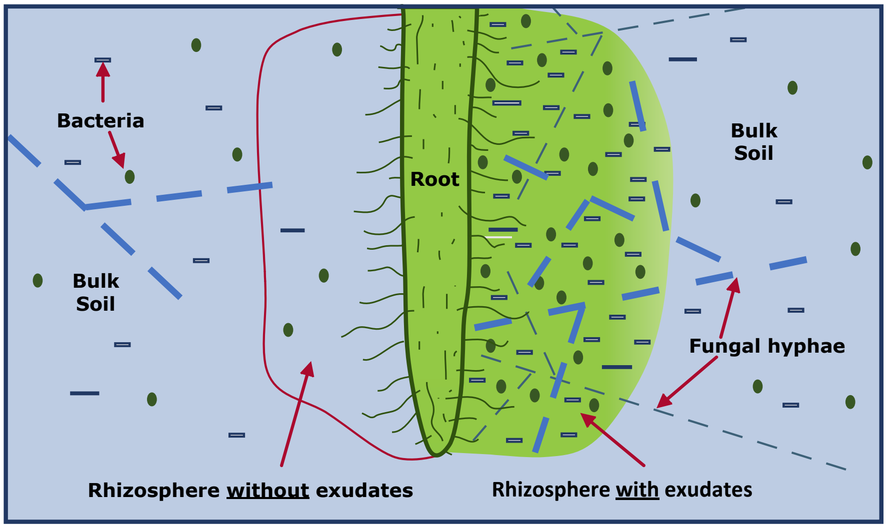
The biological processes that help plants get the nutrients they need, as described below, are all driven by the availability of carbon. Plants spend a substantial portion of their carbon currency to grow leaves, stems, and roots; they also spend a surprising amount of that currency to buy services from the microbes in the soil. The microbes provide these services to plants because they need the carbon for their own activities. Carbon is at a premium underground. This is the original carbon-trading system, and it has been going on for hundreds of millions of years.

The Rhizosphere Effect and the Microbial Loop

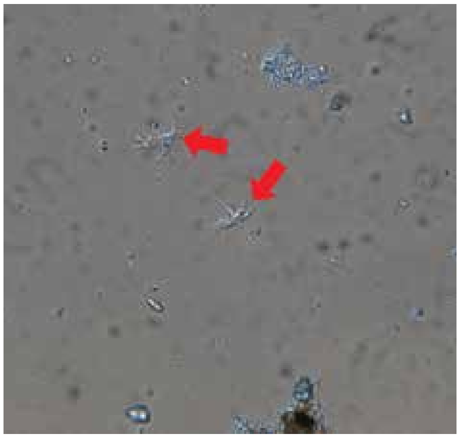
The first quick-delivery process is the result of something scientists call the *rhizosphere effect*. Terrestrial plants exude carbon-rich substances from their roots into the *rhizosphere* (this term simply refers to the soil close to the roots). These *exudates* include sugars, carbohydrates, organic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

Plants use root exudates to attract and grow microbes in the areas directly adjacent to their roots. Plants can devote more than 40 per cent of the chemical energy they fix through photosynthesis (materials collectively known as *photosynthate)* to this purpose – an incredibly high level of investment on their part. Why would they do this?

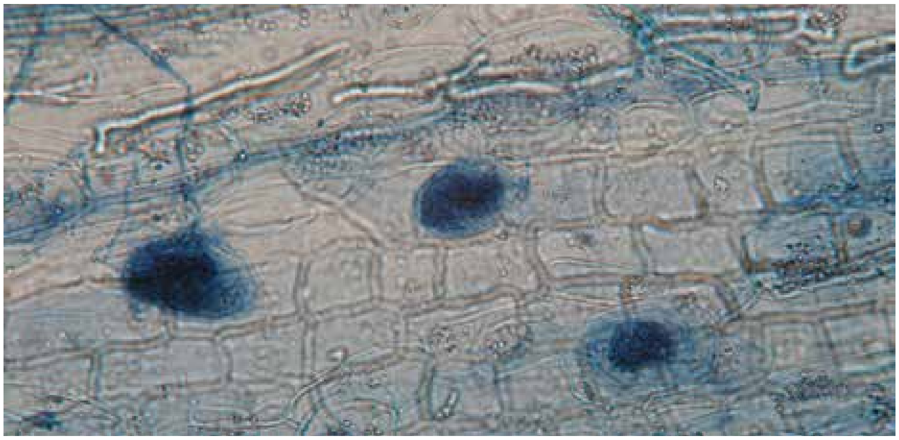
It turns out that they are essentially paying for a service – the fast, efficient delivery of nutrients to their root zones. How does this delivery system work? As watering holes in the desert attract thirsty animals, so the exudate-rich rhizosphere attract hungry bacteria and fungi. But they are not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



The rhizosphere effect *(Figure 29)*
Diagram by The Compost Council of Canada



Amoebae consuming bacteria
(Figure 30)
Source: Soil Foodweb Canada East



Mycorrhizal Fungi on Strawberry Roots
(Figure 31)
Source: Soil Foodweb Canada East

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

1 Bacteria and fungi break down soil organic matter and many minerals as well, and absorb the nutrients in their bodies.

2 These bacteria and fungi are attracted to plant roots because of the carbon-rich exudates available there.

3 Predators, mainly the various types of protozoa and nematodes, consume bacteria and fungi to obtain these nutrients, as well as carbon (see **Figure 30**).

4 Because bacteria and fungi are nutrient-rich relative to carbon, when compared to predators, excess nutrients are released by the predators in their wastes (i.e., microbial manures).

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

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

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

Mycorrhizal Fungi

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

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

One type of endo, known as *arbuscular mycorrhiza (AM)*, creates tree-like structures inside plant roots (see **Figure 31**). AM is the type of endomycorrhizal fungi found most commonly in agricultural fields.

The hyphal networks established by these fungi can be quite extensive. These networks explore and mine areas that plant roots cannot reach, greatly extending the feeding area of the plant. Most agricultural plants (e.g., corn, soy, wheat, most vegetables) establish mycorrhizal connections; the main crop exceptions are the brassicas.

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

- greater access to nutrients (particularly phosphorus) delivered directly to the plant;
- drought protection, as the fungi also deliver water to the plant when it is most needed;
- disease suppression (see Chapter Four);
- better soil aggregation and structure (see Chapter Two);
- increased carbon sequestration (see Chapter Five);
- weed suppression.

Many annual weeds are either non-mycorrhizal or have only a weak association with these fungi. This can be a great help to farmers in managing weeds. Plants that have mycorrhizal partners (the crop) have an advantage over the many weeds that do not. Weeds can actually be starved of phosphorus by the fungi who will deliver it all to their plant partners.

How to manage your soils to ensure good levels of mycorrhizal fungi is a topic covered in Chapter Seven.

Summary

Plants need certain essential nutrients in order to grow and reproduce. These include the six macronutrients – nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur – as well as the eight micronutrients – boron, chlorine, copper, iron, manganese, molybdenum, nickel and zinc. With the exception of nitrogen, which is fixed from the atmosphere by microbes, all of these come originally from the mineral component of soils. They are released over time by various mechanisms and can be found in ionic form in soil water or loosely attached to soil particles. Plants can only absorb nutrients that are dissolved in water. Nutrients are also recycled in the soil by microbes as they break down organic residues.

It used to be thought that plants had only three ways to access these nutrients: interception by roots; diffusion of nutrients along a concentration gradient; and mass flow. We now know that these processes are important but only part of the story. Microbes are not only involved as decomposers; they are also a fundamental part of two types of underground carbon-trading systems. Using these systems, plants are able to access more nutrients more quickly (and with more control over the process). The overall idea is that plants offer the products of photosynthesis (substances such as sugars rich in carbon) to the soil food web in return for access to nutrients.

There are two types of carbon trading systems underground. In the first, known as the microbial loop, plants put out their carbon-rich offerings through their root systems as plant-root exudates. These exudates attract very large numbers of bacteria and fungi which are themselves rich in nutrients due to their consumption of organic material and their ability to free up nutrients directly from minerals. As they congregate around the plant roots, predators (protozoa and nematodes) consume them in large numbers, releasing excess nutrients in the root zone in plant-available form. In the second system, plants form associations with a type of fungus known as mycorrhizal fungi. This is a more direct trading system - where plants provide the sugars to the fungus and the fungus provides nutrients and water to the plant. Both of these systems enhance the ability of plants to access the nutrients they need quickly and in sufficient quantities.

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

Chapter Four

The Biology of Disease and Pest Suppression

Diseases and Pests in Natural Systems

Natural Immunity

Plants have immune systems that evolved to protect them from diseases and pests. Ecosystems also have mechanisms to keep pests and diseases (and the ecosystem itself) in balance. Either or both of these systems, however, can get out of whack, allowing disease and pestilence to run amok. This happens in nature and it can and does happen in farm fields, which is of course why crop protection products have become so popular and their use so widespread. Plants need to be healthy for their immune systems to work, and that health depends on a lot of factors. What we are just beginning to learn, however, is how we can manage soils so that a plant's natural protection systems are optimized, rather than ignored (or worse, compromised). While this understanding is still fairly basic, there are many important ways to incorporate what has been learned so far into real-life farming applications.

The Importance of Diversity

First and foremost, microbial diversity is the key to keeping disease organisms in check. After all, it is in the interests of the beneficial soil food web entities to keep the plants in their region alive and healthy, for the plants provide them with their on-going supply of energy, via their exudates and residues.

Beneficial microbes fight plant disease by:

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

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

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

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

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

Root Exudates and Disease Suppression

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

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

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

Examples from Recent Research

Mycorrhizal Fungi and Inter-Plant Communication

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

Mycorrhizal fungi set up trading systems with plants, where they bring nutrients and water to the plant roots in return for the sugars and other carbon-rich materials plants produce via photosynthesis. In agriculture, mycorrhiza actually infect plant roots, creating within them tree-like structures called arbuscules. This is where the carbon-trading takes place. These fungi then grow their hyphae well out into the bulk soil, connecting with other plant roots as well as with other fungi. In essence, they create an underground network, referred to as *common mycelial networks*.

The following two studies clearly show that these underground networks are used for more than trading and nutrient delivery. In one study, the researchers looked at how tomato plants create a chemical that helps them fight off a specific disease that is common to tomatoes.

They found evidence that non-infected plants that are close to infected plants often get started on producing the anti-pathogen chemical even before they are infected, almost as if they had been warned. The researchers wondered if there was any way in which an infected tomato plant could send a message to other plants in its vicinity, warning them of the arrival of the pathogen. They set up an experiment where they isolated the various ways in which such communication could occur – one potential way being through the air (chemical messaging) and the other two ways being through the soil. The two soil-related possibilities they looked at were: messages sent via root exudates; and messages sent through the common mycelial networks.

By carefully managing the experiment to leave only one of the three options open at a time, they were able to show without any reasonable doubt that the messages were being sent through the mycorrhizal network. This makes sense from an evolutionary perspective. Scientists believe that terrestrial plants and mycorrhizal fungi evolved at around the same time in earth's history – around 450 million years ago. This means that they have had a long time to work out this system which benefits both the plant (better disease resistance) and the fungi (healthier trading partners).

A similar study was done with broad beans and aphids. The latter are a major pest on broad bean crops, both directly (by sucking sap from the plant) and indirectly, as a host for a number of plant viruses. Investigators found that, as part of their normal, day-to-day metabolism, non-infected bean

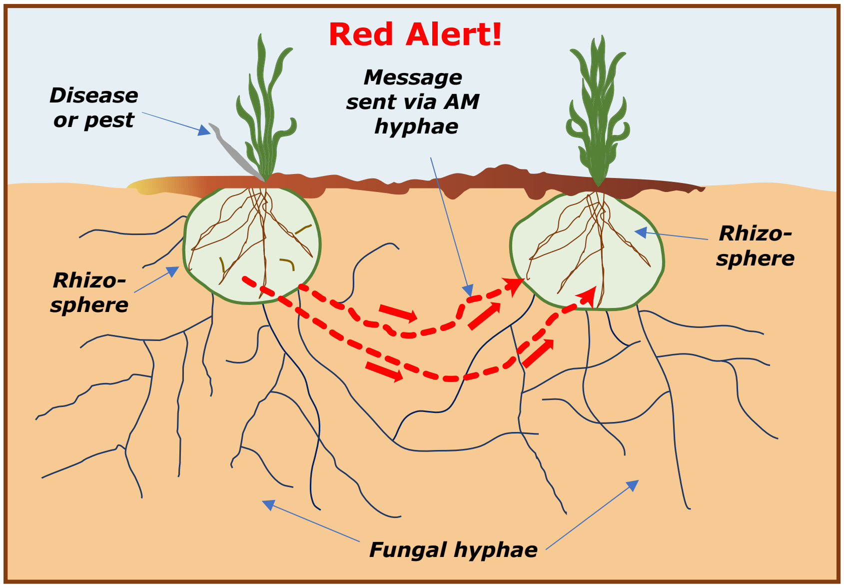


Diagram showing role of fungal networks in plant immunity
(Figure 33)
Diagram by The Compost Council of Canada

Aphid feeding on garden pea
(Figure 34)
Credits: Shipher Wu (photograph) and Gee-way Lin (aphid provision), National Taiwan University.

plants emit an air-borne chemical from their leaves that the aphids use to identify their next meal. However, once the beans are infected, they change their chemical signal to one that is attractive to a particular wasp species, one that preys on aphids. In other words, they send out a signal that will attract help in fighting off the aphids.

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

Bacterial Allies

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

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

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

PhyloChip *(Figure 35)*

Photo courtesy of Lawrence Berkeley National Laboratory © 2010 The Regents of the University of California, Lawrence Berkeley National Laboratory

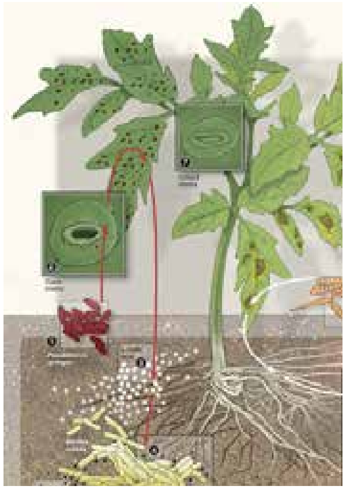
It Takes a Team

The studies above are examples of relationships between specific plants and their microbial partners. However, the use of molecular DNA-based technologies has opened up the possibility that some defense strategies are much more complicated than that. Research teams in California and the Netherlands, working cooperatively, used a technology known as the "PhyloChip" (see **Figure 35**) to look closely at the types of microbes found in soils that suppress an important disease of sugar beets. They determined that this disease, caused by a specific fungal pathogen, could be reliably controlled by a "consortium" of 17 beneficial bacteria. If all of these species were present in reasonable numbers, the pathogen was not a problem; if even one was missing, the soil did not suppress the pathogen, and the beets became diseased.

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

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

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



Plant Root Microbiome *(Figure 36)*

Credit: © Catherine Delphia

Summary

Plants have natural immune systems that can protect them from disease and pests. However, there are many factors that affect the ability of these protection mechanisms to function. Healthy soils are definitely one of the most important factors – they contain large, diverse numbers of beneficial soil organisms, usually bacteria and fungi, that can work to suppress disease and pests in a variety of ways including: physical protection, competition with pathogens, antibiotic production, direct predation of disease organisms, and supplying plants with substances necessary for their defences to work.

All of these microbial support systems for plants are dependent to some extent on diversity. Soils with a high level of microbial diversity are more likely to have the necessary partner available when the plant needs them. The plant is then able to signal, attract, even support the growth of the microbial partner that will help them to fight off a disease or pest.

Several scientific studies conducted over the past few years have revealed the details of some of these partnerships. They have shown that plants can communicate with each other through underground networks supplied by mycorrhizal fungi, allowing them to send warnings when diseases or pests attack. They have also shown that plants often produce root exudates that attract and grow populations of microbes that play a direct role in boosting their immunity or shutting out disease organisms attacking them above ground. In addition, advances in molecular technologies, based on DNA sequencing, have allowed researchers to actually identify teams of microbes that work together to prevent serious plant diseases. These studies point the way to a future where diseases and pests may be controlled by supporting the plant-microbe relationships that provide natural protection, as opposed to simply trying to destroy the "bad guys" with targeted chemical products.

Chapter Five
The Biology of Soil Carbon

The Fundamental Importance of Soil Carbon

Value of Carbon in Soil

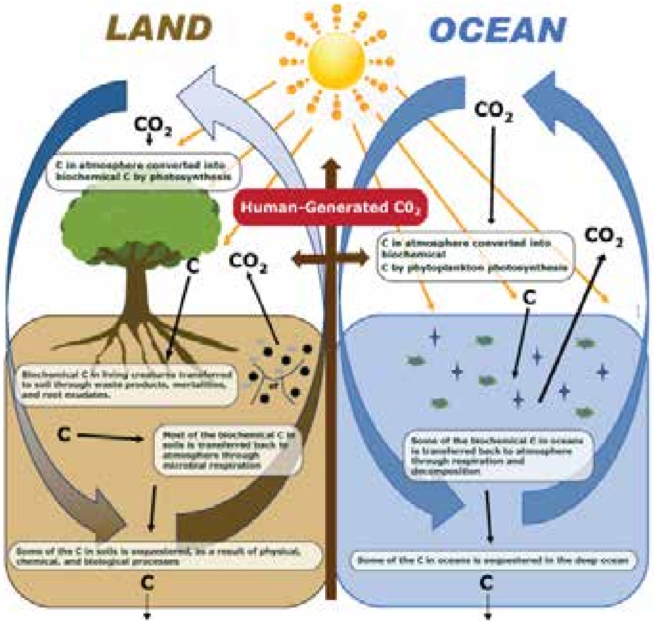
Soil organic matter, or SOM, is usually about 58 per cent carbon. As discussed in Chapter Three, it is the C in organic matter that provides the creatures of the soil food web with their energy; therefore, the higher the SOM level, the more energy for microbes. More energy for soil microbes should translate into stronger soil functions; that is, better soil structure (Chapter Two), better natural fertility (Chapter Three), and greater disease and pest suppression (Chapter Four). Better soil functions represent a large number of "free" benefits to farmers. In other words, the more soil carbon, the better.

In fact, many people think of soil carbon levels as being a good measurement of soil health. That is not completely true, however, as factors such as diversity (and even productivity) are not always directly related to soil carbon levels (more on this in Chapter Six). Nevertheless, SOM levels are probably as good a measure of the potential for healthy soil as we currently possess.

Figure 37 shows the basics of the Carbon Cycle – the system by which carbon moves between its various pools on the planet, including soils. Worldwide, our agricultural soils have been losing C for a long time. Some feel that the beginning of the loss of soil C goes back to the beginnings of agriculture, about 10-12,000 years ago, when the concept of stirring up or tilling the soil first developed. We do know that agriculture has had a very big negative impact on the amount of carbon stored in the planet's soils. Recently, researchers have estimated that about 8 per cent of total global soil carbon stocks may have been lost from the top two metres of the world's soil since agriculture was introduced – a total of 133 billion tonnes. This figure represents all soils (forests, prairies, farmland, etc.) -- the amount lost from agricultural soils worldwide is estimated to be much higher -- between 30 and 60 per cent. Moreover, the rate of loss has been increasing since the industrial revolution.

The Climate-Change Connection

The planet's climate is changing. This is no longer just a theory; we see it around us every day, in terms of things like the frequency of weather extremes, or the slow march northward of what we call "plant hardiness zones" (along with the pests, diseases, and invasive plants that come with warmer weather). It is also generally accepted (by almost all scientists, if not yet all politicians) that the changing climate is a result of more CO_2 (and other greenhouse gases, such as methane) in the atmosphere and that the increase in these gases is largely due to human activity. Of course, the main culprit is the burning of fossil fuels. Recent estimates put the contribution of agriculture to this atmospheric CO_2 excess at somewhere between 10 and 20 per cent.



Carbon Cycle *(Figure 37)*
Diagram by The Compost Council of Canada

While that may be bad news, it has a flip side that is nothing but good news. As the saying goes, this is where soil health can really punch above its weight. Soils already hold about three times as much C as the biosphere (all living creatures). In fact, the C deficit we have produced in agricultural soils over the past 10,000 years or so offers us a tremendous opportunity to help slow climate change by pulling C back out of the atmosphere and storing it in soils, where it does nothing but good things.

The remaining sections in this chapter are devoted to discussions of how we can put carbon back into our soils – a process known as *soil carbon sequestration* – and how the creatures of the soil food web are vital to this process.

Soil-Carbon Sequestration

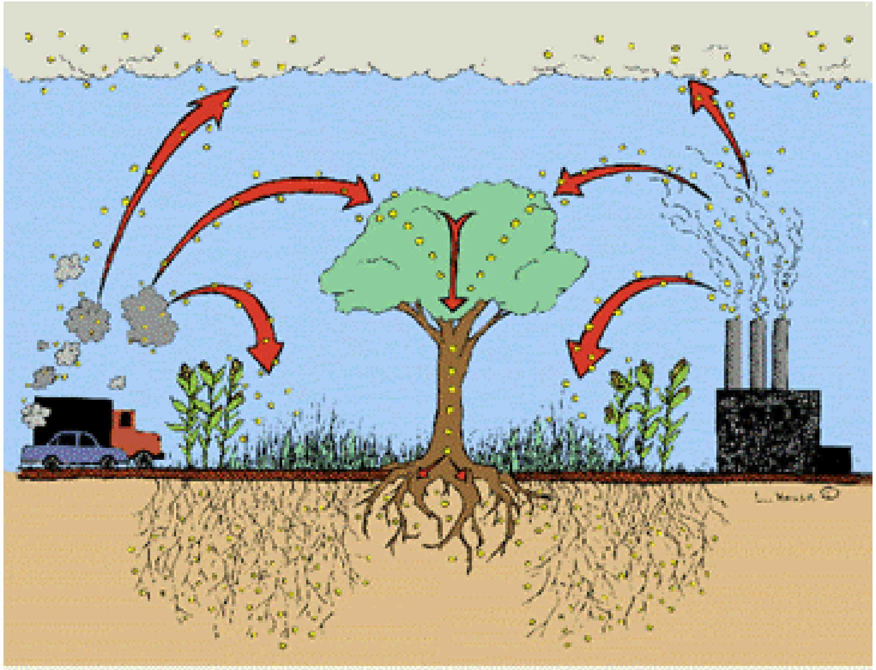
What is Soil-Carbon Sequestration?

Carbon sequestration in soils is really just a scientific way of saying that the soil is gaining more carbon over time than it is losing, thus building up its carbon levels. When organic matter, either residues or root exudates, first enter the soil, microbes immediately start using the new carbon for energy. As they do, they release CO_2 (just like we do) via respiration, thus returning the C to the atmosphere. This is the basic carbon cycle. Under certain (beneficial) circumstances, some of that carbon gets converted into substances that can resist the microbes' advances and thus stay in the soil for months, years or even centuries. Some carbon can also be protected from the microbes in other ways, such as incorporation inside stable soil aggregates.

The rate at which this conversion of carbon to a more stable or protected form occurs is very important. If it happens slowly, then other factors, such as microbial respiration, can pump carbon out of the soil more quickly than the plants can put it back in and the carbon levels drop. However, if significant amounts of carbon are stabilized fairly quickly, then the amount lost to respiration is reduced and soil carbon levels rise. When that happens, we say that the soil is sequestering carbon.

How Quickly Can Soils Sequester Carbon?

Nobody really questions whether or not soils can sequester carbon (see **Figure 38 – Soil Carbon Sequestration**); it is virtually a given among experts that they can, and that we should try to help them do so. What is being debated, quite vigorously around the world, is "how quickly can we build carbon levels in soils?".



Source: ERS/USDA

Soil-Carbon Sequestration *(Figure 38)*

The IPCC (see definition, following page) has estimated that agriculture as a whole could sequester 1.1 to 1.8 tonnes of CO_2 per hectare (ha) per year (see Box on "Carbon vs CO_2"). This is a fairly significant amount. For instance, the United States Environmental Protection Agency (US EPA) has stated that an automobile, driven by an average driver, generates 4.7 tonnes of CO_2 per year. Even if we assume the lowest end of the IPCC estimate (1.1 tonnes/ha/yr), a 500-hectare farm, practising proven methods for sequestering carbon, would offset the greenhouse gas (GHG) emissions of 117 cars annually. At the high end (1.8 tonnes/ha/yr), that same 500-ha farm would offset the GHGs of 192 cars annually.

The IPCC estimates are considered by many people to be very conservative. For instance, in a 2016 Report on soil health by the Environmental Commissioner of Ontario, soil-carbon data from an Ontario farm, collected over 20 years, was analyzed. The annual increase in carbon on that farm, where a number of soil-health practices have been employed for several years, and no tillage has occurred since the first soil carbon levels were measured, was calculated to be 4.75 tonnes of CO_2 per hectare per year (1.3 tonnes of soil C per ha per yr). This level of sequestration represents the removal of 505 cars from the roads each year. A look into the anecdotal literature on soil carbon sequestration available on the internet will show that similar, and sometimes even higher, figures are common among soil health practitioners.

The IPCC

The Intergovernmental Panel on Climate Change (IPCC) is the international body for assessing the science related to climate change. The IPCC was set up in 1988 by the World Meteorological Organization (WMO) and United Nations Environment Programme (UNEP) to provide policymakers with regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation.

How Does the Process Work?

So how specifically do soils capture and hold carbon? As with the story of natural soil fertility (Chapter Three), there is an older version and a newer version. Let's start with the older version. Until fairly recently, it used to be thought that soil carbon came mainly from organic residues, e.g., crop residues, animal manures, and dead insects, animals, etc. Therefore, by this logic, if you want to increase the level of carbon in your soil, leave as much of your residues on the soil as possible (or till them in), and add as much manure and/or compost as you can. Also, since carbon levels are a result of the balance of carbon coming in vs carbon going out, you would want to try to limit the latter if possible.

As discussed above, the C going out is largely a result of microbe metabolism -- they breathe oxygen and respire CO_2 (as we do) so they use up the C in the soil as they go about their own activities. This is why no-till has come to be encouraged by soil conservationists -- as a way to keep carbon in the soil. Tillage introduces more oxygen in to the system, allowing decomposer microbes to increase their populations. As they do so, they use up the available C and send CO_2 back into the atmosphere. Limiting tillage reduces the C going out and helps tilt the carbon in vs out equation back towards sequestration (provided you keep good amounts of C coming in).

Soil Carbon vs Carbon Dioxide

When in the soil, carbon is usually in a biochemical form, ranging from fresh plant residues to older, more stable forms of organic matter traditionally known as humus. Accordingly, it is measured as a weight, i.e., *tonnes of soil organic matter (SOM)*, or as a weight of pure carbon, i.e., *tonnes of C* (carbon is, on average, 58 per cent of SOM). However, in the atmosphere, C is in the form of CO_2 – a gas – and it is as a gas that carbon has its impact on climate. Therefore, C in the atmosphere is usually measured as tonnes of CO_2. When converting from soil C to atmospheric CO_2, we need to multiply the weight of C by 3.67 to get the equivalent weight of CO_2 (this is because the weight of two oxygen atoms has to be included with the weight of the C atom).

In addition, soil organic matter goes through a series of stages over time. As it is consumed by microbes, most C is gradually released as CO_2 but some smaller fraction is slowly converted to the more stable forms we call humus. These stable forms are more resistant to microbial degradation and thus stay longer in soils (years or even decades). Eventually, a very small fraction of the original SOM will become what is called *recalcitrant*, or extremely resistant to any kind of microbial degradation. Recalcitrant C can stay in soil for centuries.

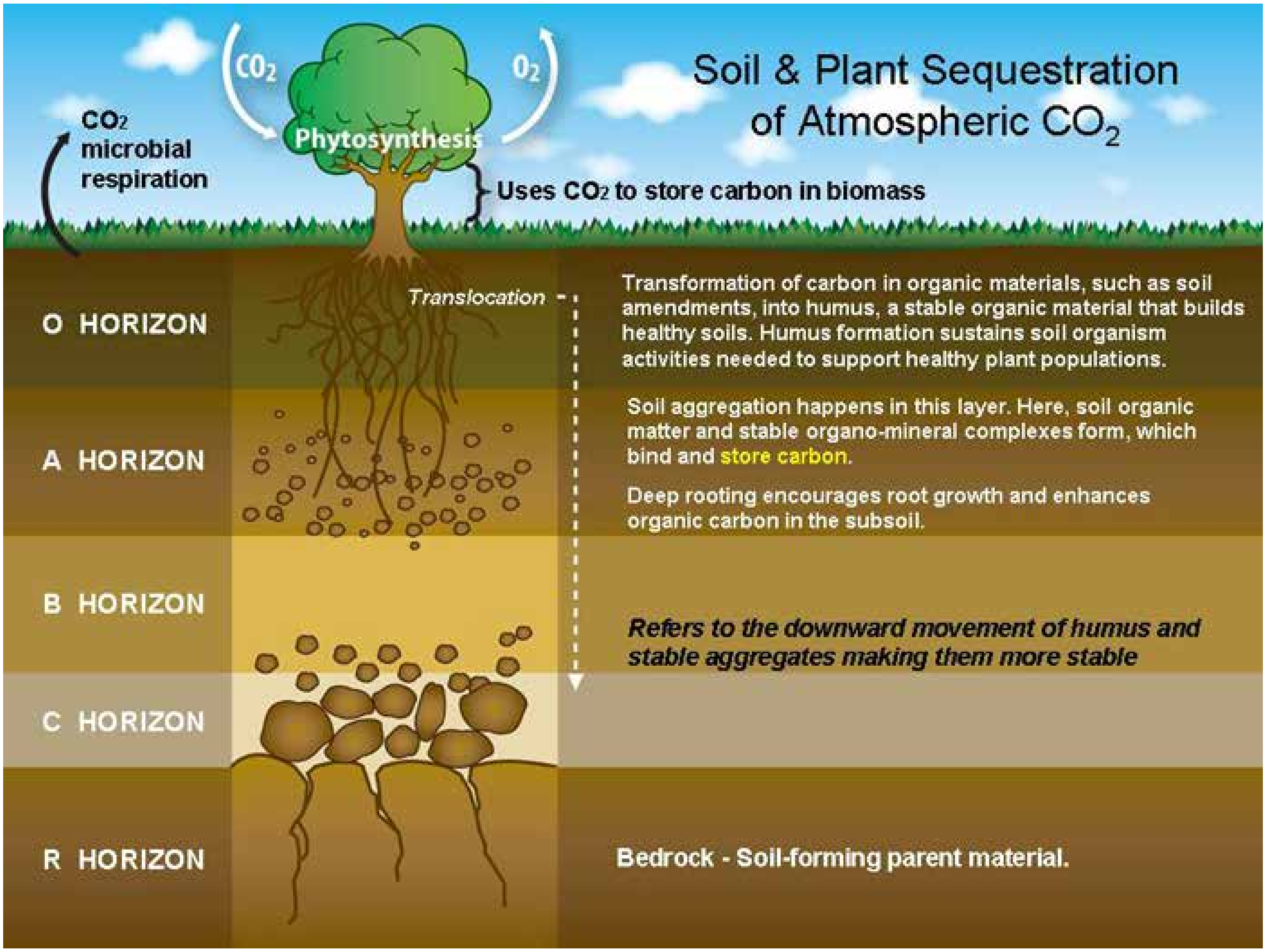
When we measure carbon in soils, we are measuring a mixture of fresh C (relatively new residues), labile C (organic matter in the process of being degraded by microbes), and stable C (carbon in various degrees of recalcitrance). The models used to predict soil carbon sequestration are generally based on the degradation rates of the types of residue involved (e.g., lignin is slow to degrade, sugars are quick), soil type, presumed moisture and temperature regimes, and so on. The resulting sequestration rate will depend on how much carbon is added each year compared to how much is lost each year, and the loss rate will depend on how long it takes to turn the carbon into more stable forms, given the environmental conditions.

The older version is completely true, and based on good science. However, as with the fertility issue, recent evidence is indicating that it may be incomplete. Here is why.

It is now understood that much of the C that ends up sequestered in soils comes through plant roots, and not from residues or amendments. Remember those carbon trading systems discussed in Chapter Three? And the soil aggregation processes discussed in Chapter Two? Both play a part here.

Root exudates are, almost by definition, rich in carbon. They are, after all, the direct products of photosynthesis, which converts the C in CO_2 into sugars. As mentioned in the earlier chapters, plants donate a lot of their photosynthate (more than 40 per cent in some cases) to the soil via exudates. They also trade a lot of their photosynthesized C to mycorrhiza, in return for water and nutrients. So, what happens to all that carbon?

Well, a lot of it does get burned up by the microbial community as part of their metabolic processes (living, eating, reproducing, etc.). But a lot of it also gets transformed into microbial biomass (the structural components of their bodies) and into the microbial glues (Chapter Two) that they use to hold on to soil particles. In the case of mycorrhizal fungi, the glue has a specific name – glomalin – and it appears that this substance, along with the bacterial glues, are not only very important to soil aggregation but also to carbon sequestration. As the soil aggregates are formed, a lot of the glues, as well as other organic materials, get trapped inside the aggregates. Inside these structures, the carbon is *protected* from attack by decomposing bacteria and fungi because the internal conditions (low oxygen, for one) are such that decomposition is greatly reduced (**See Figure 39**).



C Sequestration via humus and aggregate formation *(Figure 39)*
Source: United States Environmental Protection Agency (EPA)

Compost Application to Farmland *(Figure 40)*
Credit: Envirem Organics Inc.

Accordingly, soil C loss from these soils is reduced, tilting the balance towards sequestration. When these factors, previously not considered or under-weighted in the models, are taken into account, it may be that the higher sequestration rates being reported by soil health practitioners are not the result of faulty sampling methods but the result of sequestration processes not previously considered. The next section reports on a study that lends some support to this interpretation.

The Marin Carbon Project

Dr. Whendee Silver, a Professor of Ecosystem Ecology at the University of California, Berkeley, leads a research team that is trying to determine the potential for soil carbon sequestration on range, agricultural, and forest lands in California. Plans for the *Marin Carbon Project* go well into the future, but they have just recently completed their first major initiative -- a three-year project on soil-carbon sequestration on rangelands in West Marin County.

After performing "extensive baseline soil sampling and rangeland assessments", they applied 4000 cubic yards of food-waste compost to 100 acres of rangeland test sites situated on three separate farms. The compost was applied only once, at the beginning of the trials. The team then monitored several factors including: productivity, net carbon sequestration in the soil, and nitrous oxide and methane emissions.

The results of their work support the idea that carbon can be sequestered in soil at higher rates than previously thought. The one-time application of compost had a significant impact over each of the next three years including:

- A 50 per cent increase in forage production;
- An increase of one tonne of C (which translates to 3.7 t CO_2) per hectare per year.

Of particular note was the fact that much of the new carbon sequestered in the soil did not originate in the compost. The increased growth stimulated by the compost resulted in higher carbon input levels from both plant residuals and root exudates.

Summary

Carbon, often written simply as C, is the energy currency of life. Plants use photosynthesis to “fix” carbon, transforming it from a component of a gas, CO_2 - to the main component of sugar and the other organic molecules so important to all forms of life. A large proportion of this energy ends up in soils via residues (wastes, dead plants and other organisms, etc.) and via plant-root exudates. The creatures of the soil food web use this energy both to live and to create the beneficial soil functions as described in earlier chapters. Therefore, the more C we have in our soils, the better.

At the same time, we have too much C in our atmosphere, which is causing our climate to change. This is resulting in more extremes of temperature and moisture and less predictability, which is already impacting agriculture negatively. Most of this excess C is due to the burning of fossil fuels but some is due to our agricultural practices, particularly the use of the plough. Our agricultural lands have lost between 30 and 60 per cent of their original C since the beginnings of agriculture and this loss has been accelerating with the advent of modern agricultural techniques. This crisis also creates a great opportunity -- if we can put a lot of the excess atmospheric C back into the soil, we will help prevent climate change at the same time as we create healthier soil functions – a real win-win scenario.

Nobody denies that this opportunity exists – the question is one of rate – how fast can we sequester carbon? Experts differ on this important question but some recent science appears to be telling us that the use of soil-health-promoting methods can sequester C at a higher rate than had previously been thought. As an example, a research group in California demonstrated rates of sequestration that were double the maximum rates proposed by the IPCC, simply by applying municipal-waste compost to rangelands. This higher potential sequestration rate appears to be based on the concept that most carbon sequestered in soil is the result of activities of the soil food web. Carbon remains in soil longer than previously proposed because it is physically protected from degradation inside the aggregates.

The science on this topic is still evolving but it seems very likely that we can build soil carbon much faster than previously thought. This is good news for both farmers and the environment.

Chapter Six
The Ecology of Soil Health

What Soil Ecosystems Need from Us

Three Key Requirements

To this point, we have been talking about the processes going on in the soil, without much consideration of the influences on those processes from the world above-ground. In this chapter, we will pull back a bit and take a higher view. To begin this discussion, we will look at the science of ecology and see what it can bring to the big picture.

Ecology is the branch of the biological sciences that focuses on *the relationships of organisms to one another and to their physical surroundings*. Ecology is important because it tends to take a broader, more comprehensive view than other branches of biology. Ecology looks at whole systems rather than at the individual components of systems. We have all heard the expression that "the whole is greater than the sum of the parts" – well, in nature, this is almost always true. When we look at a system as a whole, we often find that it produces greater results than we would have been able to predict by simply studying each of the component pieces individually.

When we take an ecological view of soil health, we look at soil ecosystems and ask what do these entire ecosystems need, in practical terms, to be healthy. Of course, they will require the basic necessities of life, such as air and water, but the real important question is -- *what do they need from us? What can we do better as soil managers?* In other words, what can we do, as humans, to ensure that these below-ground ecosystems have what they need to be healthy?

In very general terms, healthy soil ecosystems require *three basic things* from us:

1. a regular supply of food and energy;
2. a stable home to live in;
3. a varied environment.

These are the fundamental requirements for a healthy, well-functioning soil ecosystem. Let's look at each one in more detail.

A Regular Supply of Food and Energy

All living things require food. Organisms use the energy obtained from food to both maintain their own metabolisms and to organize their environment. Every creature plays its part, not only by simply living, but also by organizing and maintaining a community. We all do it, every day of our lives; in our human communities, we call it "making a living".

We need energy (from food) in order to be able to make a living, and making a living usually results in us bringing in at least as much energy (in human terms, think dollars) as we expend to earn it. That energy buys more food as well as shelter, transportation, services of various kinds (medical, communications, entertainment, etc.). In addition, some percentage of our energy always goes to the common effort to sustain our community, via taxes or direct community service.

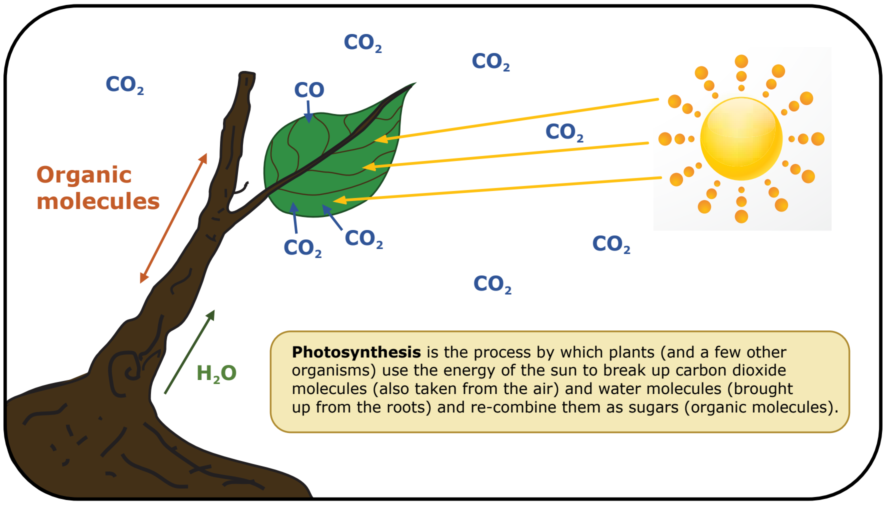
The world below-ground is no different. The organisms that make up that community need energy for basic metabolism but as we have seen in previous chapters, they use that energy to do things beyond searching for their next meal. Like us, they expend their energy to:

- create shelter for themselves
- extract resources from the physical environment
- recycle their wastes
- travel
- communicate
- grow more food for themselves and their offspring
- contribute to a number of common efforts to sustain their community.

One big difference between the world above ground and the one below is where the food (and thus energy) comes from. Almost all the energy that organisms on our planet consume and utilize comes from the sun, either directly or indirectly. The creatures above ground derive their energy directly, either from photosynthesis, as in the case of plants, or by consuming the products of photosynthesis as food, in the case of animals. The creatures below ground, on the other hand, obtain most of their energy from the creatures above ground.

Figures 1 and 2, back in Chapter One, provide a summary in graphical form of these two separate but inter-connected worlds – the *above-ground food web* and the *soil food web*. As shown in the illustration, the above-ground food web (the one we are most familiar with) gets most of its energy from the sun. Plants perform this vital job, which we know as photosynthesis, every day, whenever the sun is shining (see **Figure 41**). That energy (whose currency is carbon) drives the above-ground food web, as each level of organism, from the tiniest insect to the largest mammal, extracts its share of the bounty.

Organic molecules created through photosynthesis are used to build stems, leaves, and roots. Some portion is also released to the soil as root exudates.



Photosynthesis is the process by which plants (and a few other organisms) use the energy of the sun to break up carbon dioxide molecules (also taken from the air) and water molecules (brought up from the roots) and re-combine them as sugars (organic molecules).

Photosynthesis *(Figure 41)*
Credit: The Compost Council of Canada

The below-ground community, the living world of soil, is completely dependent on energy delivered from the world above, in the form of these basic types of foods:

- *organic residues* (dead organisms, wastes of living organisms)
- voluntary contributions, in the form of secretions by plant roots *(plant-root exudates - see p.23)*
- *non-voluntary contributions by above-ground organisms* (in the case of root parasites and pathogens).

Like any community of organisms, the health and prosperity of this world below ground depends on the availability of *reasonably priced* energy; that is, energy available at a price lower than that which the organisms obtain from it, so that there is energy left over for other needs, such as shelter, transportation, waste management, etc.

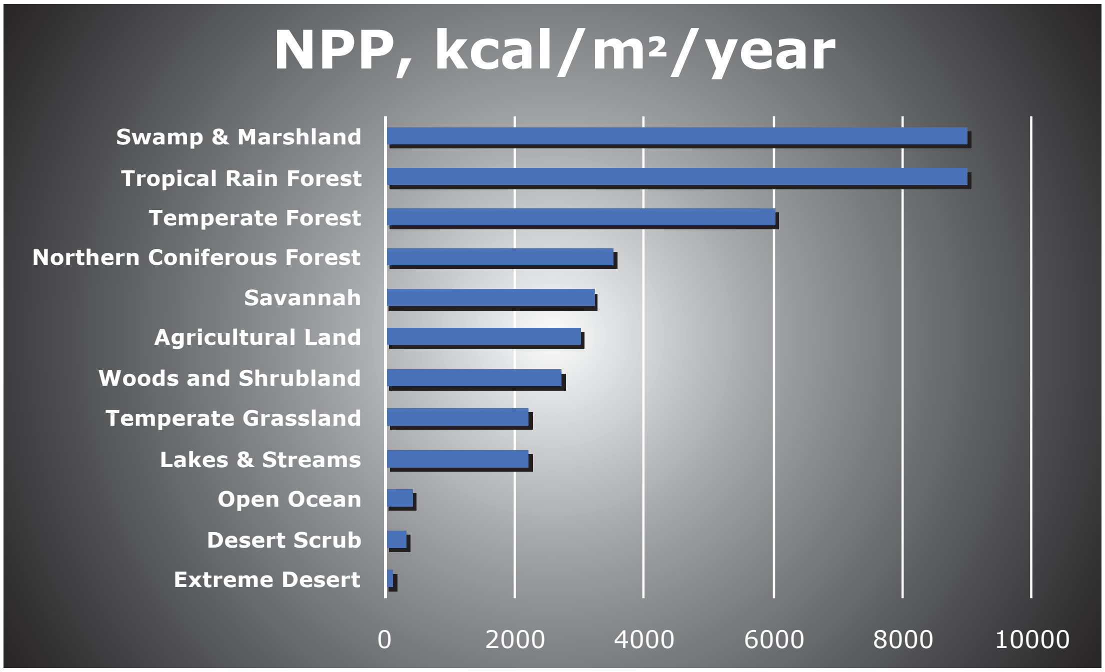
This is the concept of "energy return on energy invested", i.e., the efficiency of the process by which energy is obtained by the community. If the return is good, and all other factors are adequate, the community prospers; if it is poor, the community struggles and can even die out.

Humans have a lot to say about how efficiently energy is captured and transferred to the soil community in agricultural settings. The potential is huge.

Energy Flows in Ecosystems

All our energy comes from the sun, either directly or indirectly. The sun is the engine of life. Photosynthesis captures a portion of the sun's energy for use by plants. Scientists refer to the energy captured by plants as *Gross Primary Productivity*. If we subtract the energy plants use for their own metabolism, we get what is called *Net Primary Productivity (NPP)*. This is the energy that is available to the rest of the ecosystem for all other biological purposes.

Averaged over the entire planet, annual NPP is 4,950,000 calories per square meter. To put this in perspective, a liter of gasoline contains about 7,750 calories of energy. This means that the average square meter on the earth's surface produces the energy equivalent of 639 liters of gasoline each year. The type of land use will factor heavily on the amount of NPP produced. In general, farmland is not nearly as productive as the global average, coming in at about 3,000,000 calories (387 litres of gas) per m2/year (see **Figure 42**).



Net Primary Productivity (NPP) ***(Figure 42)***
Credit: The Compost Council of Canada

It all adds up, however, and a 100-hectare farm produces the energy equivalent of 8,750,000 litres of gas per day. More than half of that energy is consumed by organisms that live above ground, such as insects, birds, and up through small mammals to humans. But a significant amount ends up being used by the organisms in the below-ground community via residues and plant-root exudates.

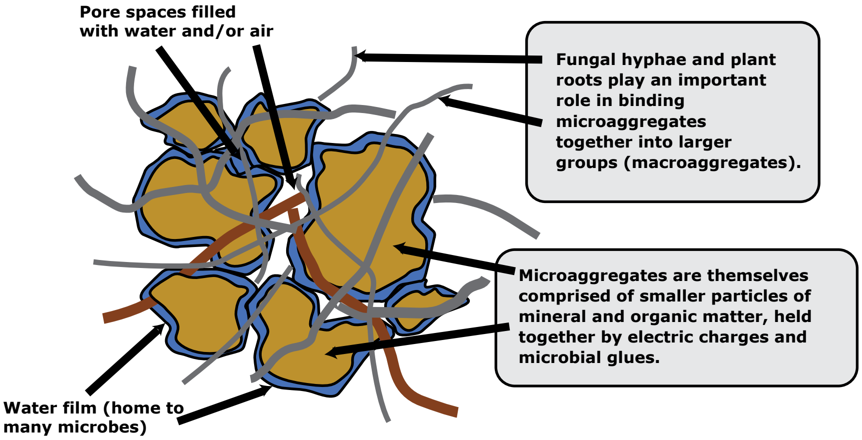
Organic residues are highly visible and it is easy to understand their value to soil. Root exudates, on the other hand, are invisible and their importance is often unknown or under-appreciated. A healthy plant may contribute almost half of its photosynthesized organic product to the soil. This is a high energy cost to the plant and indicates quite clearly, at an individual level, how much plants value the activities of the world below.

A Stable Home

Every community, above or below the ground, requires a suitable home or habitat. Just as we need access to water, food, air, natural resources, shelter, etc., so do the creatures beneath our feet. And just as we spend a lot of our energy creating better habitats for ourselves, so do they.

Soil habitats need to be structured in such a way that the organisms that live there are able to easily access the food, water, air, and natural resources that they need to live, procreate, and build and maintain their community. These organisms also need the soil habitat to provide shelter from extreme conditions, protection from predators, access to transportation routes, and storage capacity for water and nutrients.

Pore space is fundamental to all of the above. As discussed in Chapter Two, the amount and quality of pore space is the result of good soil aggregation. Good aggregation opens up the soil and allows air and water to infiltrate and be stored in the resulting spaces between the aggregates (the pores) (see **Figure 43**).



Pore Spaces in Aggregated Soil
(Figure 43)
Credit: The Compost Council of Canada

We also saw in Chapter Two that many different soil organisms play a crucial role in aggregate formation, and therefore the creation and maintenance of pore space. In effect, they build their own underground equivalent to our cities, complete with housing, storage capacity for water and nutrients, transportation routes, and communications infrastructure. As above-ground land managers, it will serve farmers well to take into account how their actions might support or damage the structure engineered by soil organisms.

A Diverse Environment

What do we mean by diversity? We mean a wide variety of:

- above-ground plant life -- such as diverse crop rotations, multi-species cover crops, inter-cropping, etc.
- above-ground animal life, such as insects and mammals
- the types of organisms in the soil itself.

A diverse set of above-ground plants results in a diversity of inputs to the life below-ground. A diverse variety of above-ground animals (e.g., insects, birds, etc.) results in a more well-balanced ecosystem and greater total productivity (biomass production per unit area) which in turn provides more food for the creatures of the soil. Lastly, diversity among the soil organisms themselves is very important as it ensures the capacity of the soil to adapt to changing conditions, a characteristic that scientists refer to as *resilience*.

Soil Health and Ecological Succession

Ecological Succession

In nature, ecosystems change inexorably and predictably, as if they have a plan, and in fact, you could say that they do. Scientists have painstakingly documented nature’s “succession plans” over the past century. These consist of an orderly succession of different types of plant life over time, which gradually change both the physical environment and the biological composition of the community. This process continues until an equilibrium or *climax* state is reached. Once that climax state is in place, changes in the plant community composition become slower, more cyclical and balanced, as we can see in an old growth forest or a mature prairie. Of course, things eventually happen to upset this balance, such as major fires, floods, changes in climate, disease outbreaks, and especially human activity. These occurrences typically push the ecosystem back to an earlier successional state. When this occurs, natural succession again kicks in, working diligently to reclaim the lost balance.

The term *primary succession* is used to refer to the entire process, from (for example) bare rock to mature forest. Early successional plants tend to be *fast-growing, short-lived herbaceous species*. They are able to take advantage of the conditions of low competition and high nutrient availability by growing quickly and covering the soil. As they live and die, however, they increase soil organic matter, altering the soil food web and creating conditions better suited for their successors. Over time, these *pioneer species* are replaced by *slower growing but more efficient* plants that can thrive in conditions where competition is greater and nutrients harder to come by.

Early-successional herbaceous plants are gradually replaced by annual grasses, which are typical mid-successional species. Perennial grasses come later and are themselves followed by woody shrubs. Similarly, as longer-lived trees take over, the fast-growing (for trees, that is), sun-loving poplars and birch arrive first, to be eventually replaced by shade-tolerant, slower-growing trees such as oaks and maples. The point at which the succession stops (the climax state) depends on the region's long-term environment, with precipitation levels being a major factor (as in prairies vs forests, with the latter requiring more annual rainfall).

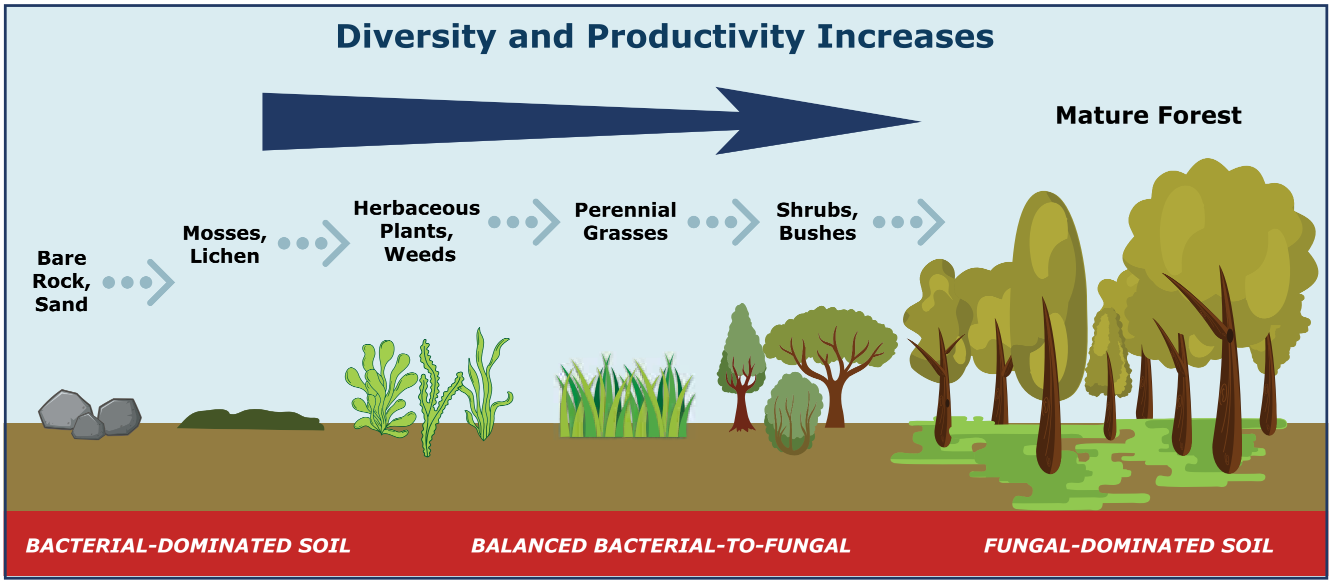
The term *secondary succession* is used to refer to those situations where the successional process is knocked back along the successional path by a catastrophic event or series of event(s) and has to start again at an earlier stage. It is a force to be reckoned with in agricultural fields, particularly when the fields are left bare, both between rows of field crops and between crops. The combination of high nutrient levels from fertilization and bare soil (no competition) is ideal for early successional plants, many of which are the annuals or biennials we know as weeds.

What do the principles of ecological succession mean for agriculture? First of all, modern agriculture usually tries to stop natural succession in its tracks – to hold it steady, so to speak. This might be easier if a monoculture field represented a natural climax state, but it definitely does not. These attempts to thwart nature take a lot of energy. Weeds play an important role in succession. They are opportunists who are adapted to taking advantage of disturbed habitats where competition for nutrients, sunlight, moisture, etc, has been reduced. They grow quickly and are able to make use of easily available nutrients (usually the case after a major disturbance). Over time, they are able to increase soil carbon with their exudates and residues. Ignoring these facts makes weed control more difficult and costly.

In addition, succession also happens below-ground. Early successional soils are different from later successional soils in terms of the types of organisms that dominate. What this means is that a healthy soil looks different at different stages of succession. These differences can affect what happens above ground, and what a farmer has to do to get good and efficient productivity.

How Soil Health Evolves with Ecological Succession

As the food web above ground evolves from early successional plants to later successional grasses or trees, the soil food web also changes. The proportion of various types of organisms changes. One particular change is particularly relevant – *the relative biomass of bacteria vs fungi*. In early successional systems, bacteria dominate; in mid-successional systems, bacteria and fungi are relatively equal in total biomass; finally, in later successional situations, fungi dominate. See **Figure 44**.



Ecological Succession *(Figure 44)*
Credit: The Compost Council of Canada

As soils become more fungal, they also become more productive and have the potential to sequester more carbon. Increased organic matter and number of soil aggregates are both highly correlated with increased fungal dominance. It is important to remember that a bacterial-dominated soil can still be considered a healthy soil given the successional state above ground.

All of the above suggests that there may be an advantage in managing farm ecosystems with the concept of ecological succession in mind. Many farms are currently managed to be early successional ecosystems (constant disturbance, little cover, etc.). The soil health approach, on the other hand, encourages farm management that mimics mid-successional systems (constant cover, low disturbance, greater diversity). As in **Figure 44**, this type of management appears to shift the farm ecosystem to the right, from early successional (bacterial-dominated) to mid-successional (balanced). Given that movement along this gradient is associated in nature with higher productivity as well as improved soil functions, it would seem to offer significant benefits to farmers.

Summary

The term *healthy soils* really means *healthy soil ecosystems*.

Healthy soil ecosystems need good, efficient access to food and energy if their living members are to thrive. Secondly, these creatures need a home that is protected from constant disruption, so that they can maintain the complex infrastructures that they are always building below ground. Thirdly, they need lots of variety in both the above-ground and below-ground environments, so that they can develop and maintain resilience in the face of environmental change and occasional high-impact events.

Also, soil ecosystems always change and they do so in a directional and predictable way, known as ecological succession. This means that ecosystems can be healthy in different ways, depending on the stage of succession. This is an important and under-recognized aspect of soil health in agriculture. Finally, there is a growing body of science that is indicating that the role of beneficial fungi in farm soils is very important. Even though much of this science is relatively new and not yet well established, there is certainly good reason to suggest that building larger, more stable populations of soil fungi may be one of the keys to sustainable productivity in agriculture.

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5 Of course, other factors enter into the issue of community health, such as the consistent availability of water (e.g., deserts, savannah, tropical forests), frequency of catastrophic events (e.g., fires, flooding, mudslides), and the temperature regime (e.g., tropical, temperate, arctic). However, the availability to soil organisms of a good share of energy from the sun is crucial in all environments and can greatly influence the ability of both above- and below-ground communities to thrive in otherwise difficult environments.

6 Diversity drops off slightly as the system reaches a "climax" state (e.g., mature forest); however, for agricultural discussion purposes, diversity increases over time as secondary succession proceeds.

Chapter Seven

Soil Health Principles and Practices

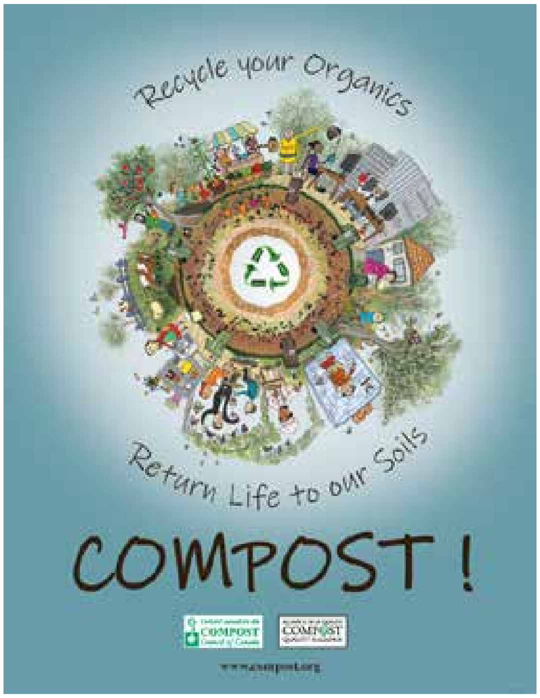
The Five Principles of Soil Health

When it comes to the health of a soil, it is all about the biology, not the chemistry or the physics. It is the living component of soils – the soil food web – that determines whether or not a soil is healthy. The planet Mars is covered in weathered minerals that look like soil but they lack any living organisms. You can't call them healthy. To a lesser extent, we have many soils here on Earth that, for whatever reason, have had their soil food webs diminished in number or diversity. These soils are not healthy either. There is no health without life.

As soil managers, we have many methods that we can employ to improve and sustain healthy soils. We call these best management practices (BMPs). It is important to realize, however, that all of these BMPs have certain principles in common. Fortunately, soil-health professionals generally agree on the basic soil-health principles that underlie these BMPs.

The five basic principles of soil health are:

1. **Cover the Soil.** Whether you grow cover crops, or use residues or mulches, you should never leave bare soil exposed. As the Practical Farmers of Iowa say: "Don't Farm Naked".
2. **Keep Live Roots in the Soil.** Roots feed the soil food web. Always have something growing, even over the winter.
3. **Add Compost and/or Other Organic Amendments.** This can be done by integrating grazing animals into your crop rotation, where they naturally and routinely deposit their manure, or by adding organic amendments separately. The latter can include manures, digestates, biosolids, or any other organic waste products, although all are improved in a number of positive ways by prior composting (see Chapter Eight).
4. **Support Plant and Soil Diversity.** Diversity above-ground is linked to diversity below-ground. Both are extremely important for healthy soils and crops.
5. **Minimize soil disturbance.** Reduce or eliminate tillage or any other mechanical disturbance of the soil ecosystem habitat.



What is the Basis for Soil Health Principles?

The soil is alive, the source of that life are the organisms in the soil ecosystem (the soil food web), and living organisms have certain basic needs. Those needs are energy, habitat, and diversity. When these needs are met, the life in the soil organizes stable, productive communities that are enormously beneficial to both the underground and above ground communities.

The soil health principles discussed in this chapter all derive from those basic needs, and from the overall intent of protecting and enhancing the life in soils. They also take into account the reality of ecological succession and its on-going impact on soils and crops.

Minimize Soil Disturbance

This refers primarily to the practice of tillage. Once we begin to see the soil ecosystem as an intricately structured community, the destructiveness of tillage becomes very apparent. Imagine how difficult life would be for you if every year somebody came around with a wrecking ball and destroyed your house. Most of your energy and money would be going into rebuilding each year and you would have little left for anything else.

Tillage is like that in its effects on soil, but of course it is a bit more than that, too. Farmers till for a reason – it has a powerful short-term effect. Tillage releases nutrients by introducing a big burst of oxygen into the soil which stimulates the decomposer microbes. As these microbes explode in number, the predator microbes also increase, resulting in a flush of nutrients as the predator-prey action described in Chapter Three increases enormously in the rhizosphere. The soil is also loosened by tillage, allowing for easier planting, and weeds are uprooted and destroyed. All of these short-term benefits, however, come at a huge cost to the community below ground, and that eventually translates into greater costs to the farmer and to the environment.

Soybeans grown into corn stalks in a no-till field in Union County, Iowa *(Figure 45)*
Source: USDA

Eliminating tillage has a number of challenges, dealing with which are beyond the scope of this primer. Nevertheless, we can say here that any practice that minimizes disturbance of the soil is good for the health of the soil (see **Figure 45**). Both science and practical experience tell us that when the soil community is protected from violent and/or frequent disturbance, beneficial soil functions of all kinds gradually increase, so that the short-term fertility benefits of tillage are replaced by long-term, sustainable levels of fertility that at least match, and can often exceed, those of tillage. Of course, best results are obtained if all of the other soil-health principles are followed as well. Reducing tillage, all by itself, may not protect, feed, and diversify the soil food web enough to compensate for the loss of tillage's short-term benefits.

Finally, we should note that minimizing soil disturbance allows ecological succession to proceed below ground. As discussed in Chapter Six, below-ground communities change with succession, just as above ground communities do.

Tillage is a catastrophic event that knocks succession backwards, causing it to re-set. Not only does this encourage weeds, which are by definition pioneer species, but it also damages fungal hyphae, forcing these organisms to spend too much energy trying to rebuild their networks. This scenario frustrates the development of more established fungal communities, resulting in permanently bacterial-dominated fields. The long-term, sustainable benefits of a thriving, well-balanced soil food web require a more balanced ratio of fungus-to-bacteria, something that soils simply can't develop under a heavy tillage regime.

Multi-species Cover Crop *(Figure 46)*
Source: Stefan Zehetner, Huron County, ON

Keep the Soil Covered

There are two basic ways for farmers to keep the soil covered: with crop residues and with cover crops. The basic benefit of covered soil is protection of the soil food web habitat. Both residues and living plant material protect the soil from temperature extremes, reduce the impacts of heavy rains and wind, and conserve moisture. All of these things directly benefit the members of the soil community. Covered soil is also more compatible with conditions found in ecosystems that are more advanced in ecological succession, as opposed to the more disturbed habitats of early succession, where soil is often bare and conditions are more extreme. The less harsh conditions under covered soil allow more advanced and productive soil ecosystems to form and sustain themselves.

Keep Live Roots in the Ground

Allowing soil to lie bare of living plant life *starves the organisms of the soil food web*. As discussed in Chapter Six, living soils require a consistent source of energy. Some of that energy comes from plant residues (another reason for the previous principle of keeping soils covered), but much of the energy in living ecosystems comes from plant root exudates, which of course requires that there be plants growing in the soil.

Starving the food web organisms has some very important negative consequences. Deprived of food, the microbes will either die or become dormant, depriving the communities (both below- and above-ground) of their valuable services. But that, unfortunately, is not the whole story. Before the microbes go dormant or die, they will try to find energy in other places. The glues that hold soil aggregates together are not the preferred food of soil microbes (that really would not make any sense ecologically), but they will consume these glues if they have no other option. Of course, that is not good for your soil structure, and starving your microbes in this way on a consistent basis is a good way to ensure that your soil is structure-less and compacted.

Even worse, soils without living roots deplete mycorrhiza. As we discussed in Chapters Two to Four, Mycorrhizal fungi are fundamental to soil structure, natural fertility, disease suppression, and a number of other important soil functions. They are also what is called *obligate symbiotes*. What this means is that they don't have a choice with respect to their symbiotic relationship with plant roots; they need roots as hosts or they die. Accordingly, a bare field for months on end will mean low mycorrhizal numbers in your fields, with all that entails. Mycorrhizal spores will survive, of course, but instead of starting the new growing season with a full mycorrhizal network in place, you will be counting on those spores to repopulate the field, a slow and very energy intensive process from the fungal perspective. This is not efficient and over time a field can become a mycorrhizal desert, to the detriment of the soil ecosystem, plant yield and health, and the farmer's bottom line.

Maximize Soil Diversity

Farmers can maximize diversity in any number of ways including (but not limited to): more complex crop rotations; multi-species cover crop mixes (see **Figure 46**); a variety of inputs, such as various types of fertilizers, manures, composts, digestates, etc.; above-ground areas of pollinator habitat; and the use of different seed varieties. All of these tools help to ensure that the soil food web experiences a variety of inputs. For instance, using a mix of cover crops can provide a range of different plant root exudates, with different plants secreting different organic substances. It can also ensure that these exudates occur at different depths as the various cover crops should have different root forms and lengths. Crop rotations can also provide these benefits and both rotations and covers can be used to simulate some degree of ecological succession, allowing the soil ecosystem to further develop its complexity, resilience, and productivity.

The above-ground diversity of plants also helps to ensure an above-ground diversity of organisms, particularly beneficial insects. The vast majority of insects are either beneficial to farmers or neutral. Therefore, the larger the numbers of diverse species, the less chance that a pest will find an empty niche in the farm field ecology, where it can take over and cause harm to the crop.

When diversity rules, resilience is not far behind. When we look at how much redundancy exists in terms of functions in a good soil, it can be amazing. For instance, there may be hundreds or even thousands of species that perform the same task, such as secreting glues that bind mineral particles to make micro-aggregates, when it would seem that simply a high number of one or two varieties would suffice. However, when environmental conditions change, as they do all the time, it is good to have another set of organisms ready to take over when the first set can no longer manage the task. The soil dries out, for instance; this is no problem if you have a set of drought resistant microbes ready to step in and take over! The temperature climbs and your disease suppressors can't take the heat and go dormant? Again, no problem if the soil contains another set, perhaps sleeping up until now, who really like the heat and can't wait to swing into action.

Promoting diversity in all its forms builds and supports resilient soil ecosystems. Resilience is important in any environment but even more so when the climate is changing, becoming less consistent and predictable and prone to extreme events.

Some Other Important Soil Health Practices

Manage Nutrients Carefully

A farmer will not get a good crop without adequate nutrients. However, the ways in which nutrients are applied, in terms of amounts, timing, placement, etc., are also important. Too much nutrient, broadly applied, in combination with other factors, such as tillage and uncovered soil, can mimic an early successional ecosystem. It is similar to the results of a catastrophic event, such as flooding, fire or a major disease outbreak. Weeds are pioneer species, adapted to just such scenarios. It is not surprising, therefore, that bare soils, high in available nutrient, can experience very high weed pressure. In addition, some studies have shown that high levels of available P, and sometimes N as well (or in combination) suppress mycorrhizal fungi, diminishing this important source of natural fertility. Finally, excess nutrient levels often lead to run-off and pollution, costly both to the farmer and the environment.

The goal of a soil-health-inspired nutrient management plan should be to get the most out of natural fertility and, as much as possible, use synthetic fertility to complement and enhance, rather than replace, the natural system. Of course, finding the right balance is easier said than done, and we still have a lot to learn in order to be able to do this optimally. However, following the *4Rs program for nutrient use* (right source, right rate, right time, right place) is a very good place to start.

Ontario no-till farmer, Dean Glenney, fertilized for 150 bushels of corn, and got 300. Careful nutrient management combined with good soil-health practices did the trick. *(Figure 47)*
Photo Credit: Glenn Munroe

Manage Crop Protection Products Carefully

As with nutrients, pesticides can be a double-edged sword. If not used carefully, or if over-used, they can negatively impact soil health in a variety of ways. Most of them do not discriminate between the “good guys” and the “bad guys” in terms of organisms; everything takes a hit. As with over-use of nutrients, ecosystems may experience this as a type of disruption event, triggering secondary succession. For instance, when a field is chemically “burned down”, this process destroys the competition and releases nutrients, mimicking a natural successional setback. Similarly, when fungicides are used too often, the beneficial fungi are constantly knocked back and the field tends to become bacterial. Both of these examples result in a more simplified ecology similar to early successional scenarios, with all of the resulting issues for farmers.

This is not to say that farmers should never use any pesticides; rather, it is to point out that they should be used carefully and, in most cases, as a later line of defense, only after damage thresholds have been reached, as in the *Integrated Pest Management (IPM)* approach (see **Figure 48**). Pesticides in general can often be precluded through the use of other management techniques but where they are used, it would only make sense to ensure that their impact on soil health is minimal by making them part of a broader management plan that includes a wide variety of practices based in all of the soil health principles described above. This will give the soil organisms the best chance to handle the chemical inputs without reducing the level of their functions.

Recent research by A & L Canada Laboratories has shown that the soil microbial communities are in general very resilient and can handle most pesticides (that is, break them down into harmless components) when the latter are used carefully and properly. This is good news but should be taken in context. There is always a cost when chemicals are used: that cost can be light and easily manageable by the soil food web; or it can be heavy, as when mycorrhiza have to expend energy that could be helping plants to regrow hyphal networks destroyed as collateral damage of fungicide use. Awareness of the costs and benefits by the farmer would seem to be the key.

ONTARIO CropIPM
Integrated Pest Management Training
February 2009

LA LUTTE INTÉGRÉE DANS
LES CULTURES DE L'ONTARIO
Formation en lutte intégrée
Février 2009

Ministry of Agriculture,
Food and Rural Affairs

Ministère de l'Agriculture, de
l'Alimentation et des Affaires rurales

Ontario

OMAFRA IPM Training Manual *(Figure 48)*
Source: OMAFRA

Apply Organic Amendments such as Manure and Compost

Adding organic materials to soils is always good, for these substances both feed the soil food web and provide good habitat for its members. Compost, in particular, has another advantage – as an inoculant. Traditionally perceived as a disadvantage for their relatively low nutrient levels relative to synthetic fertilizers, when looked at from a soil-health perspective, organic material inputs are a tremendous complement to synthetic fertilization. This is because organic inputs can support the soil food web in ways that synthetic inputs cannot. Of course, these attributes often do not carry the economic weight that the provision of nutrients do, but as we have seen in the previous chapters, this may not be an accurate assessment.

The research and resulting tools required to make a better economic analysis of the value of inputs such as compost are not yet complete and available for farmers to use. Added to this, the overarching need to mitigate and adapt to climate change may soon offer, through government policies and support, additional revenues for these materials to be used on-farm. However, even now, and just from a soil health perspective, it is hard to argue against the benefits associated with manure and compost application to farm fields.

Chapter Eight

The Unique Role of Compost in Soil Health and Climate Change

> *"Compost returns organic matter to the soil and helps retain nutrients, improves water-holding capacity, improves soil structure, and reduces soil compaction caused by farm equipment."*
>
> \- ***Agriculture and Agri-Food Canada***

Introduction: The Acknowledged Benefits of Compost

Adding compost to soil produces many benefits including (but not limited to):

- increased levels of soil organic matter (SOM);
- higher levels of natural fertility in soils;
- a stronger, healthier plant (see **Figure 49**);
- improved soil structure, which in turn leads to –
    - better water-holding capacity,
    - greater infiltration of rainfall,
    - reduced soil erosion,
    - less run-off of nutrients and other inputs, and
    - disease suppression.

Figure 49: Impact of Compost Application on a Carrot Crop
Photo Credit: Glenn Munroe

Controlled field trials with compost have shown generally positive results, with farmers finding slight to moderate yield increases, improved soil structure, and some disease suppression. The issue, however, has never been whether or not the compost provides benefits; rather, it has been whether or not the sometimes-inconsistent benefits were worth the additional cost.

This practical cost-benefit assessment, however, may require an update. A number of factors may be changing the assumptions underlying this issue, and we will look at each of them in some detail in this Chapter. In overview, they are:

- the rise in awareness of the importance of soil health;
- the increasing need to do something significant with respect to climate change;
- an evolving understanding of the co-benefits of compost use, and in particular, its potential ability to protect our fresh water supplies;
- the emergence of the concept of compost as an inoculant, whereby the cost-efficiency of compost use is given a substantial boost.

Scientific research has been the main driver in all of the above factors. In particular, the huge advances in genomic (DNA-based) analysis in the last decade are helping us to better understand what is going on in the soil. In turn, this better understanding is providing us with some powerful tools. Going forward, we should increasingly be able to:

- make our agricultural soils produce more, with fewer inputs;
- tackle climate change effectively and affordably;
- better protect our overall environment without sacrificing the economy; and,
- create the business opportunities and well-paying jobs of the future.

Compost can and should be a big part of all this. Let's take a close look at some of this new knowledge and the potential compost-related opportunities arising from it.

Compost and Soil Health

> *"Many organic materials serve both as fertilizers and soil conditioners: they feed the soil and the plants…..Soluble chemical fertilizers contain mineral salts that plant roots can absorb quickly. However, they do not provide a food source for soil microorganisms and earthworms. Over time, soils treated only with synthetic chemical fertilizers lose organic matter and the living organisms that help to build a quality soil."*
>
> - ***Food and Agriculture Association of the United Nations***

Compost's Versatility

Compost can be seen as the "swiss army knife" of soil health tools and practices. Why? Primarily because of its versatility.

Compost can be used to:

- enhance the benefits provided by other practices, such as cover crops;
- ameliorate the effects of less-than-ideal practices, such as tillage;
- build healthy soils; and
- help maintain that health.

And here is the key point: compost has a particular benefit that the other practices just don't have -- it can rapidly increase both the number and the diversity of a soil's food web. Well made, mature compost usually contains a greater concentration and variety of soil organisms than the soil that receives it. Of course, this depends on factors such as the source materials, where it was made, the composting methods used, etc., but good, mature compost is loaded with a wide variety of beneficial soil microbes. In fact, you could say that diversity is compost's forte.

We discussed earlier in this document how soil health influences fertility (Chapter Two), soil structure (Chapter Three), and disease and pest suppression (Chapter Four). Below are a few more details with respect to compost's potential role in each of these areas of concern to farmers.

Compost makes a very good partner with synthetic fertilizer, for at least two important reasons:

First, soil organisms are stimulated by the addition of nutrients, and they look to carbon for energy. Without plentiful carbon to feed these hungry microbes, SOM levels may decline. Compost supplies SOM.

Second, adding compost with fertilizer can increase the latter's efficiency. Compost increases the size of the soil food web. Any excess nutrients will be taken up by these organisms, preventing their loss via leaching.

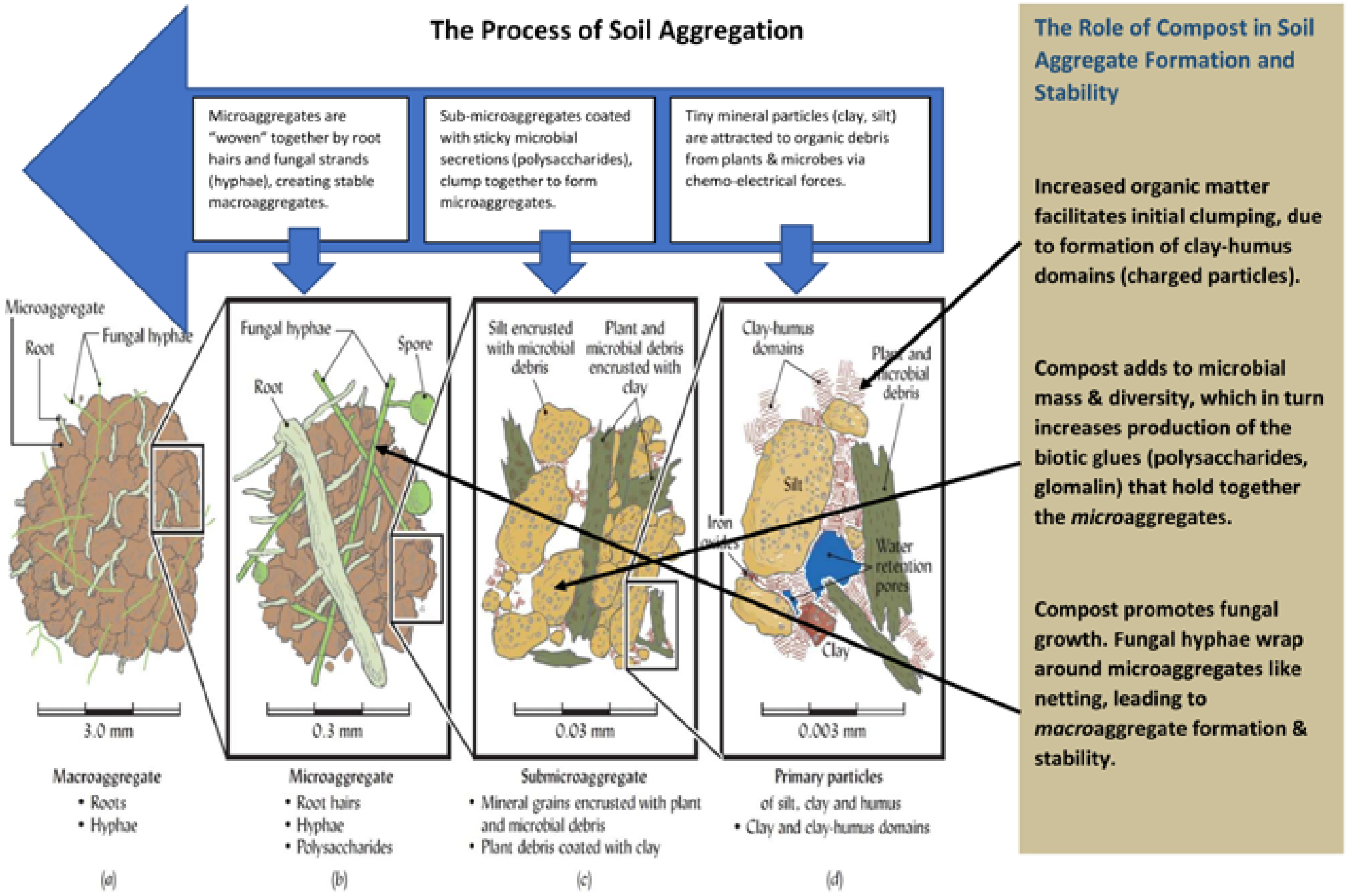
Soil Fertility

Compost hides its potency behind low NPK numbers. To understand what compost can really do, we have to look more closely at natural systems. As described in Chapter Two, natural soil fertility is not based solely on the amount of nutrient available to plants at any given time; rather, it is an ongoing product of a well-functioning soil food web. Plants depend on carbon-trading system elements such as the activities of microbes in the root zone (see discussion of the microbial loop, pp. 23-24) as well as mycorrhizal associations (pp. 24-25) to ensure that they get the nutrients they need, when they need them. Compost not only supports the creatures of the soil food web with food energy, nutrients, and habitat, but also adds diversity, making the systems referenced above more robust and reliable.

Soil Structure

The only real long-term solution to compacted soils is to build good soil structure. To do this, you must nurture and protect the soil organisms that create and sustain soil aggregates. This was discussed in detail in Chapter Three. **Figure 50** summarizes that discussion and adds some information on the potential role of compost in this process. In essence, compost supports the organisms that do the aggregating, and in particular the fungi.

Figure 50: Compost's Role in Soil Aggregation



The Process of Soil Aggregation

Microaggregates are "woven" together by root hairs and fungal strands (hyphae), creating stable macroaggregates.

Sub-microaggregates coated with sticky microbial secretions (polysaccharides), clump together to form microaggregates.

Tiny mineral particles (clay, silt) are attracted to organic debris from plants & microbes via chemo-electrical forces.

The Role of Compost in Soil Aggregate Formation and Stability

Increased organic matter facilitates initial clumping, due to formation of clay-humus domains (charged particles).

Compost adds to microbial mass & diversity, which in turn increases production of the biotic glues (polysaccharides, glomalin) that hold together the *micro*aggregates.

Compost promotes fungal growth. Fungal hyphae wrap around microaggregates like netting, leading to *macro*aggregate formation & stability.

[**Image Credit:** Original Diagram from *Weil, R.R., and N.C. Brady. 2017. The nature and properties of soils. 15th ed. Pearson, Columbus. 1086 p.*; further explanation of process (blue arrow) and notes on role of compost (sidebar) added by Compost Council of Canada.]

Why is this so important? Well, the latest science indicates that it is difficult, if not impossible, to have good, stable soil aggregates without having a good, stable population of beneficial soil fungi. The fungal filaments provide the necessary glues and "netting" to build the larger aggregates and to hold them together.

Mature compost both supplies and feeds soil fungi. Testing has revealed that compost piles, when left to mature, gradually become more fungal; that is, the biomass ratio of fungi to bacteria rises. This is due to the fact that fungi are better able than bacteria to break down the more complex, recalcitrant molecules that are left after the first flush of bacterial decomposition takes out all the "easy" stuff. Accordingly, the application of mature compost inoculates soil with various types of saprophytic fungi and then supports the growth of both saprophytic and mycorrhizal species, increasing the number and degree of the ecosystem benefits for which these organisms are largely responsible.

Disease Suppression

As mentioned above, quite a few studies have documented the disease-suppressive nature of compost. The exact mechanisms that are responsible for the suppression, however, are not well known. What we do know is that compost boosts the soil food web, both in terms of food supply and diversity. Therefore, in terms of disease suppression, it is likely that the soil organisms do the real work.

What kind of work? In Chapter Four, we set out the basic mechanisms in general terms:

- competition (beneficial microbes out-compete harmful ones);
- physical protection (microbes provide a physical barrier around plant);
- antagonism (e.g., production of antibiotics);
- direct consumption of pathogens by beneficial microbe predators;
- partnerships (microbes provide some type of chemical assistance to plant immune system);
- and, communications (plants receive advance warnings via the soil food web).

The potency of compost as a disease suppressant will depend to a large extent on the number and variety of its microbial populations. Some types of organisms in the compost might excel at surrounding roots and protecting them through sheer numbers; others (and we know these types exist) might produce antibiotics to fight off pathogens; while still others, such as the B. subtillis in Chapter Four, might specialize in helping plants activate their own defense mechanisms. A diverse, mature compost will likely include all of these groups.

Compost and Climate Change

You may already be aware that the composting process itself helps to reduce climate change. This is because composting diverts organic wastes from landfills. In landfills, organic residuals degrade anaerobically (in the absence of oxygen), resulting in the production of methane gas (see box on right, below).

It is certainly true that the composting process itself releases some greenhouse gases (GHGs). The main one is carbon dioxide (CO_2). But this gas would have been released as part of the normal carbon cycle; therefore, its release in the composting process adds no new GHGs to the atmosphere. However, some methane and nitrous oxide (N_2O) are also produced and these gasses are considered to be GHGs. Fortunately, in a well-managed composting system, very few of these gasses are emitted. In fact, the overall carbon footprint of composting is so good that some compost facilities are able to earn carbon offsets, just by doing their day-to-day business.

Reducing emissions of GHGs is crucial in fighting climate change but it is not the only way to go about it. Actually pulling carbon out of the atmosphere is also very important. In Chapter Five, we looked at how carbon gets sequestered in soils. The Marin Carbon Project shows that one application of compost to rangelands set up a feedback loop in the soil that resulted in a gain of about **one tonne of carbon per hectare per year for the full three years of the study** (and is projected to keep adding C for at least 10 years!!).

The Hidden Danger of Methane

Methane (CH_4) is generally stated to be about 20-30 times more potent than CO_2 as a greenhouse gas (GHG). However, that number provides only part of the story. GHG potency is generally measured over a 100-year timeframe. Unlike CO_2, methane doesn't last that long in the atmosphere, so measuring its impact over 100 years dilutes its potency. It is much more dangerous over the 20 years that it does hang around -- **84 times more potent than CO_2.** Why is this important? Well, to start with, most climate scientists believe that we have less than 20 years to get our GHG emissions under control if we want to avoid runaway climate change. Given that very short window, reducing methane emissions can be seen to be particularly important.

One of the main reasons that a single compost application was able to sequester so much carbon, for such a long time, is that it was applied to rangelands, rather than croplands. It is important to understand that on these particular lands:

- no tillage was happening;
- the ground was covered year-round;
- the ground cover included a wide diversity of plants; and,
- these plants also ensured that live roots were in the ground all year long.

Note that the above points are exactly the same as the basic soil-health principles described in Chapter Seven!

Does this mean that the added compost is not responsible for that large increase in soil carbon? No - as the increases occurred only on the soil where the compost was added.

The added compost was able to sequester so much carbon because there were no management practices working against it. The addition of compost to soils can result in high levels of carbon sequestration, given that the other main tenets of soil health are followed. This is an important point for farmers to keep in mind. It is almost certainly true that compost can build soil carbon much faster when used in conjunction with the other soil-health BMPs.

Does this mean that farmers who are not employing other soil-health BMPs should not bother to use compost? The answer is no – because compost can help your soil under any circumstances. It simply means that to experience compost's full value, you will need to make it part of a full soil-health based system (see Box on right).

Why not try this on a few acres?

See for yourself if the combination of compost with the other four soil-health BMPs (see Chapter Seven) can transform the health of your soils and boost their productivity. For more information on this approach, which people are calling "regenerative agriculture", visit the website of California State University, Chico, at

https://www.csuchico.edu/regenerativeagriculture/index.shtml

Compost and Fresh Water

General Benefits

Mature compost protects fresh water in a number of ways. As described above, when applied to agricultural land or turf, compost:

- improves soil structure, resisting compaction and allowing better infiltration of rainfall and increased water-holding capacity;
- reduces surface run-off of rain or irrigation water, protecting surface waters from many sources of pollution and reducing flooding;
- increases the number and variety of beneficial soil microbes, which break down toxic residues and clean water passing through the soil on its way to recharging local aquifers.

Compost can also be used in on-farm infrastructure projects, such as filter strips and grassed water ways. Filter systems work well around drain inlets, around storm drainage systems, surrounding receiving channels, and for sediment containment. Living filter systems, based on compost, trap sediment, bind and absorb pollutants, and degrade various toxic compounds with bacteria and fungi. Studies have shown that compost-based living filters can remove up to 99 per cent of coliform bacteria, 73 per cent of heavy metals, 92 per cent of nutrients, and 99 per cent of hydrocarbons.

Phosphorus

Compost applications can also help with the ever-growing, country-wide phosphorus problem.

As a general rule, phosphorus is tricky to manage. It binds very easily to other substances in the soil, making much of it unavailable to plants. As a result, growers may add phosphorus fertilizer, even when the soil already has high overall levels, in order to ensure that their crops have enough available P to ensure a good yield. If the soil becomes saturated (that is, all the P-binding sites are occupied), this can result in run-off of phosphorus into surface waters.

Since P is an important limiting nutrient for all plant growth, the result of this pollution is usually algae blooms in lakes, such as Lake Erie (see **Figure 26** in Chapter Two) and Lake Winnipeg. These have become serious issues in many parts of the country. However, there are solutions to this problem that don't require a sacrifice in yield.

Increasing evidence suggests that the P problem can be addressed biologically. The key is a large and diverse population of soil organisms.

Farmers who have developed very healthy soils report that tests indicate little or no P leaving their land. This is probably the result of a couple of factors: first, soil-health practicing farmers use cover crops, and having living roots in the soil all the time makes it more likely that any available P will be taken up by a plant, preventing immediate run-off; and secondly, when the main crop is growing in a healthy soil, the numerous and diverse organisms of the soil food web can take up P from the organic matter left behind by the covers (as well as any newly applied synthetic P) and thus prevent any major nutrient loss.

Moreover, these organisms then deliver the P to the plants in their root zones via the microbial loop (for more detail on how this works, see the section on carbon trading systems in Chapter 3, page 22). While these factors are likely the main reason for the reductions in P run-off from healthy soils, more applied research is needed, so that ever greater practical information is available on things like application rates, timing, and synergy between practices. In this way, farmers can feel confident that the soil-health approach will reduce their environmental impact.

Compost has a potentially important role to play here as it helps to support a large and diverse soil food web. However, it is important to use a mature compost product. Immature compost is similar to raw manure and digestates, in that it contains higher amounts of soluble nutrients than does mature compost. Accordingly, as with synthetic fertilizer, it is possible to create a phosphorus pollution problem with manures, digestates and immature compost. Alternatively, the P in stable, mature compost is mostly tied up and is made available by microbes in a slow-release process largely controlled by the crop, minimizing losses.

In summary, there is growing evidence that one of the ways in which P pollution can be averted, without sacrificing yield, is by combining the 4Rs approach to fertilizer use (see Chapter Seven), the use of cover crops to support soil health and mop up excess nutrients, and the application of mature compost to build the numbers and diversity of the soil food web.

Compost as Inoculant: Emerging Opportunities for Compost-Use Efficiency

Compost seed coatings

The concept of microbial seed coatings has been around for a long time. For instance, seeds treated with rhizobia (nitrogen fixing bacteria that form partnerships with leguminous plants) have been widely and successfully used for many decades. Until recently, however, the number of such applications has been relatively small in comparison to chemical seed treatments. However, this appears to be changing, with many agricultural input companies working to develop biological treatments (including seed coatings) for factors such as disease suppression, pest control, environmental adaptability, and growth promotion.

Results to-date have been mixed however as there are a number of barriers that need to be addressed if these new "technologies" are to be consistently effective. Issues include (but are not limited to):

- identifying the right microbes, or microbial "consortia" (see p. 26), to put on the seed as a coating, depending on the function(s) desired and the type of crop;
- finding the best method for attaching the microbes to the seed, without killing the microbes;
- keeping the microbial populations alive during seed storage and application;
- identifying the range of environmental conditions (e.g., soil type, moisture content, pH, etc.) within which the particular microbes will be active and deliver results.

One possible general solution to these issues is getting some attention lately. This approach is to coat the seeds with a slurry derived from local, or indigenous, compost. The thinking is that such a compost might have among its populations all of the microbial partners that a local crop would need and that they would be already adapted to local environmental conditions. This approach would address the first and last of the above issues. It would also help with the other two issues (i.e., microbe survival) because compost is a natural habitat for microbes and could sustain them during the interval between seed coating and seed planting.

Compost Pellets

Compost has been made into pellets many times by many different compost producers. However, in most, if not all cases, the purpose was simply to facilitate the application of the compost to land (pellets are easier to apply using conventional farm machinery than is unprocessed compost). This purpose for pelletizing, while useful, is rather limited. It does not take advantage of compost's unique ability to act as an inoculant, simply because the pelletizing process is usually not designed to ensure that the beneficial microbes survive.

Recently, however, pelletizing options that are more microbe friendly are emerging. Some companies are refining their pelletizing processes to allow high microbe survival rates inside the pellets. The theory behind this approach is that most agricultural land has been depleted in the variety of its soil life to some degree, resulting in reductions in fertility, disease suppression, and overall crop health. These compost pellets are made in such a way as to both preserve and enhance indigenous soil organisms. The goal is to address any deficiencies in the local soil food web and thus rehabilitate the natural system.

Compost Tea

The concept behind compost tea is that the beneficial organisms in compost can be extracted and then "brewed" in water by adding microbe foods while keeping the oxygen levels high enough to prevent the mix from becoming anaerobic. This increases microbe populations and produces a microbe-rich liquid that can be applied to soils and/or leaf surfaces. It is generally used as a way to suppress disease but many growers also feel that it is like a probiotic for their soil.

Perhaps the best way to think about compost tea is that it may offer a way to extend many of compost's benefits over much larger areas and at a lower cost. Although it will not provide much organic matter or nutrients, it may give the soil food web in any given soil a boost, with some scientific studies indicating that it can confer some of compost's disease suppression capacity to certain crops. This could be a valuable way to obtain some of the good things that compost has to offer when lack of availability or the cost of applying compost itself to a larger farm operation is prohibitive.

The Importance of Compost Quality

If compost's benefits primarily arise from its ability to nurture and support soil microbes, it is obviously very important that the compost be made properly so that it contains stabilized organic matter, a good balance of nutrients, and the right kind of microbial populations. As it turns out, all Canadian jurisdictions have rules in place to ensure that the compost from licensed facilities is properly manufactured – that it is, in fact, good compost.

Each province and territory has its own guidelines for compost quality or has adopted those produced by the Canadian Council of Ministers of the Environment (CCME). These guidelines protect the environment by ensuring that concentrations of trace metals, such as cadmium and mercury, as well as foreign matter and sharps, are within maximum limits. They also protect human health by ensuring that pathogen levels are within required limits. Maturity must also be measured as well as total organic matter and moisture. What all of this means is that users of compost from licensed facilities in Canada can be assured that the product they are buying is properly manufactured, mature, and safe for humans and the environment.

While these guidelines meet the requirements from the perspective of government regulators, the members of the Compost Council of Canada recognized a few years ago that something more was required. Different end uses of compost require different agronomic properties. For instance, the amount of soluble salt in a compost must be very low when it is used as a media for small plants and seedlings but can be higher when used as a top dressing or as a soil amendment. Similarly, the ratio of carbon-to-nitrogen in the compost (known as the C:N ratio) must be within a certain range (12-22) for most landscaping, turf topdressing, and planting media purposes, but can be considerably higher when the compost is used as a soil amendment (12-30) or for remediation (10-40).

About the CQA laboratory accreditation program:

Participating CQA-laboratories across Canada and the United States are involved in the CAP (Compost Analysis Proficiency) program, a laboratory quality assurance program to calibrate procedures and evaluate inter-lab method performance. The Test Methods for Examination of Composting and Compost (TMECC) forms the basis of the analytical test methods. CAP is administered by Dr. Robert Miller of Colorado State University.

ALLIANCE DE LA QUALITÉ COMPOST QUALITY ALLIANCE

The Council recognized that knowledge of agronomic parameters such as the above would help ensure that the right compost was used for the right purpose. This is the concept behind the **Compost Quality Alliance (CQA)** – to not only reflect government regulations but to go above and beyond to also test for the agronomic properties of compost and direct its usage appropriately.

The CQA is a voluntary initiative, open to all compost producers across Canada. Upfront operational audits as well as testing procedures are required of all CQA-members along with an ongoing sampling regime and product attribute focus and market sale. If you buy your compost from a CQA-certified producer, you will not only be able to get the results of the testing done to satisfy government requirements but also the testing done to meet CQA requirements – and the end-use recommendations that arise from that testing.

BE A SOIL BUILDER

Although some nematodes are pests (root feeders), most are beneficial nutrient cyclers.

Amoebae (protozoa) use pseudopods for traveling, eat many bacteria, and cycle nutrients.

Bacteria are tiny (billions/cup of soil) decomposers, consuming organic wastes.

Cover the soil

Keep roots in the ground

Add Compost & other organic amendments

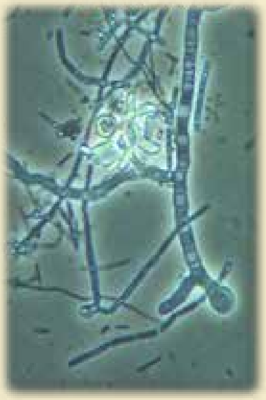
Support plant & soil diversity

Minimize soil disturbance

Field: Adam Ireland, Teeswater. Photo: Ontario Soil Network.

Flagellates (smallest protozoa) use little tails to move, eat bacteria and cycle nutrients.

Cilates (largest protozoa) use little hairs like oars to move, eat bacteria & cycle nutrients.



Some fungi are decomposers, consuming organic wastes. Others are symbiotic with plant roots.

Conseil canadien du
COMPOST
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