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, from a management perspective?* In other words, what can we do, as humans, to ensure that these below-ground ecosystems have what they need to be healthy?

What we have found to date, in very general terms, is that 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.

One way to look at this is that the above requirements form the foundation of soil health. 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 simple 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, but also 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.

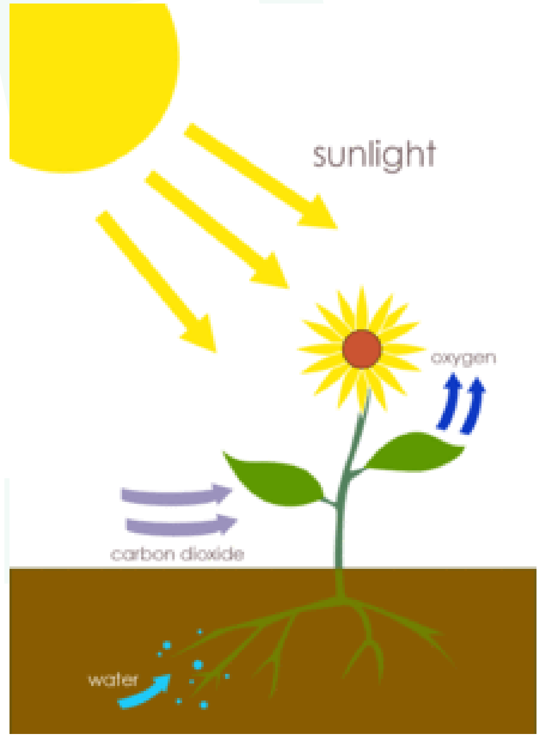
The world below ground is no different. The organisms that make up that community need energy for basic metabolism, but as we have seen in previous chapters, they use that energy to do things beyond searching for their next meal. Like us, they expend their energy to:

- 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.



Photosynthesis *(Figure 41)*

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 (the *plant-root exudates* referred to in Figure 1)
- *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 (See below: Energy Flows in Ecosystems), but unfortunately not always well realized in modern farming, and this is a big factor in soil health.

Energy Flows in Ecosystems

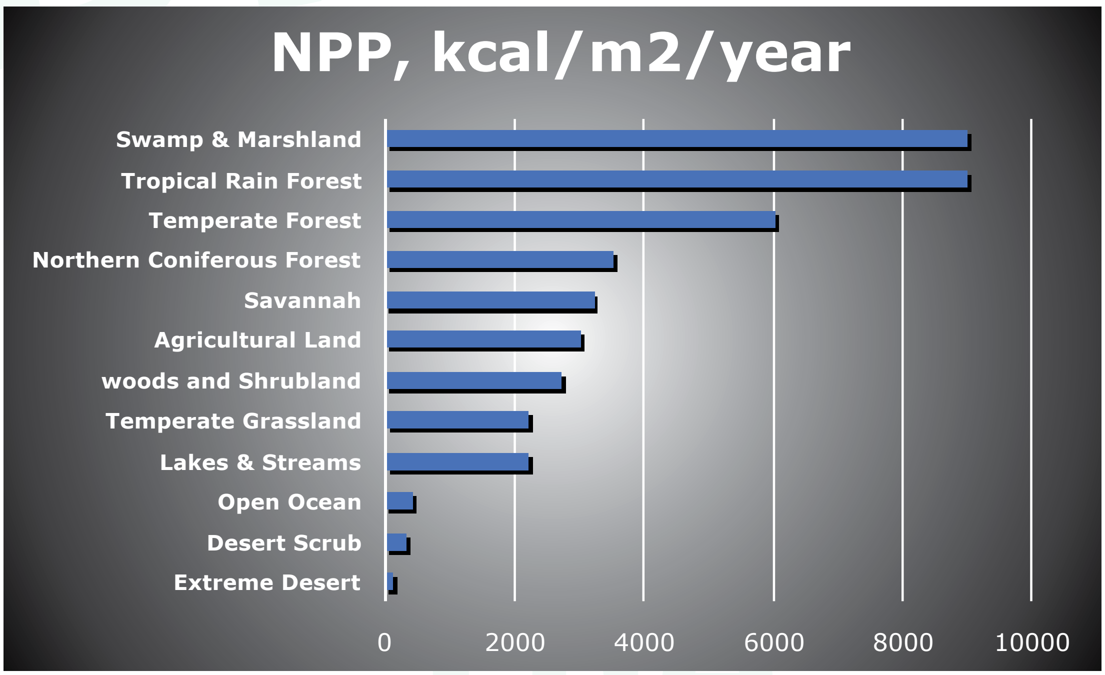
As described in Chapter Six, all of the energy that drives biological life comes from the sun, either directly or indirectly. The sun is the engine of life. Some portion of the sun's energy is captured for biological use by plants, via photosynthesis. Scientists refer to the energy captured by plants 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.

However, farmland in general is not nearly as productive as the global average, coming in at about 3,000,000 calories (387 liters of gas) per m2/year (see **Figure 42**).

It all adds up, however, and a 500-hectare farm produces the energy equivalent of 8,750,000 liters 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.

The energy route most well understood by most people is by means of organic residues, such as wastes from living plants and animals, as well as their dead bodies. However, as we have discussed in previous chapters, plants also exude freshly photosynthesized substances into the soil through their roots (plant root exudates). These non-residual contributions are extremely important to the community below ground. 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.

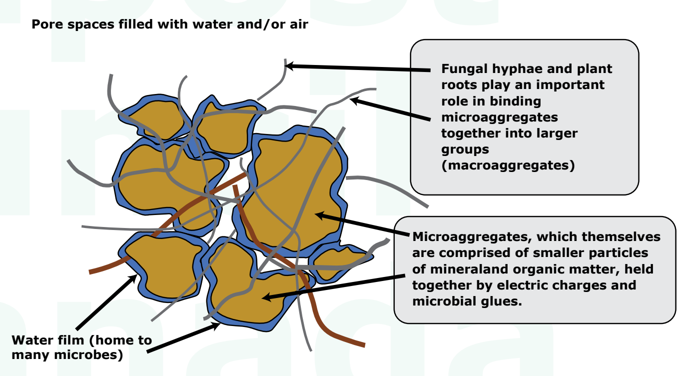


Net Primary Productivity (NPP) ***(Figure 42)***

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 Spaces in Aggregated Soil
(Figure 43)

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**).

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. More on that later in this chapter.

A Diverse Environment

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

- above-ground plant life -- the opposite of monoculture, which is one crop only, rotated with a bare field
- 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. Again, this is an area where modern agriculture has often been lacking, given the propensity for simplified rotations, few if any cover crops, little habitat for wildlife, etc.

Soil Health and Ecological Succession

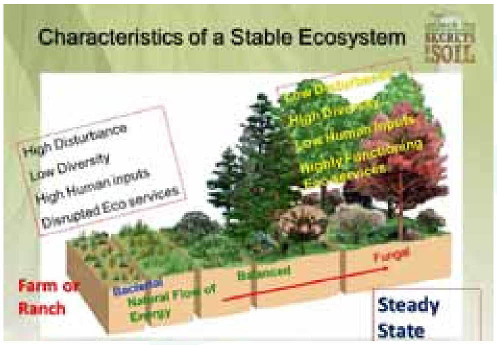
Ecological Succession

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.



Ecological Succession *(Figure 44)*
Source: NRCS

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 is 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 in terms of the types of organisms that dominate. What this means is that a healthy soil looks different at different stages of succession, and 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**.

This is important for a variety of reasons. For one thing, it demonstrates clearly that healthy soils can have different types of soil food webs – they are not always the same. Secondly, there are some other changes that come as soils move through succession, and these can be quite significant.

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, for a variety of reasons. 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 again as the system reaches a "climax" state (e.g., mature forest); however, for agricultural discussion purposes, diversity increases over time as secondary succession proceeds.