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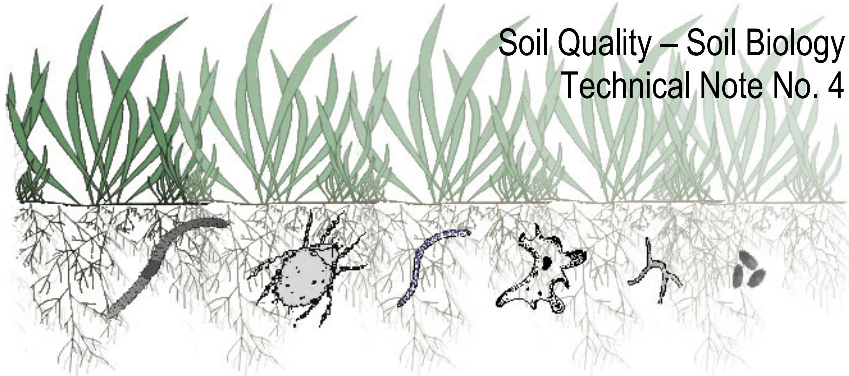

Soil Biology and Land Management

Table of contents

Soil Quality – Soil Biology
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Other titles in this series:
#1 Soil Biology Primer
#2 Introduction to Microbiotic Crusts
#3 Soil Biology Slide Set

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Introduction

The purpose of this technical note is to provide information about the effects of land management decisions on the belowground component of the food web. It points out changes in soil biological function that land managers should look for when changing management practices. This information is not a set of prescriptive guidelines, but is designed to increase awareness and prompt field trials.

The goal of soil biology management

The goal of managing the soil biological community is to improve biological functions, including forming and stabilizing soil structure, cycling nutrients, controlling pests and disease, and degrading or detoxifying contaminants.

Research shows that management practices and disturbances impact soil biological functions because they can 1) enhance or degrade the microbial habitat, 2) add to or remove food resources, or 3) directly add or kill soil organisms. Although management practices are known to impact soil biology, there is limited knowledge to support the development of detailed management strategies. A particular practice may have the desired result in one situation but have little effect in another because biological communities respond to the interaction of multiple factors including food sources, physical habitat, moisture, and impacts of historical land use. Therefore, before a new product or practice is applied to a large parcel of land, it should be tested on a limited area and results should be monitored in comparison to an untreated plot.

Why should land managers understand soil biology?

Energy and the food web

Through agriculture, the sun's energy is converted into food, feed, and fiber. However, most of the solar energy captured by plants is not directly harvested when crops are gathered; instead, it feeds the belowground food web. Feeding the "underground livestock" is essential to productive forests, rangeland, and farmland. Figure 1 shows how energy is recycled repeatedly through belowground soil organisms. The soil food web is part of energy, nutrient, and water cycles. The energy cycle begins when the sun's energy is captured by the plant-based (aboveground) food web. Nutrient availability is governed by the detritus-based (belowground) food web. The water cycle is also influenced by the interaction of plants, soils, and soil organisms.

Functions of the soil food web

Nutrient cycling

In a healthy soil ecosystem, soil biota regulates the flow and storage of nutrients in many ways. For example, they decompose plant and animal residue, fix atmospheric nitrogen, transform nitrogen and other nutrients among various organic and inorganic forms, release plant available forms of nutrients, mobilize phosphorus, and form mycorrhizal (fungus-root) associations for nutrient exchange. Even applied fertilizers may pass through soil organisms before being utilized by crops.

Soil stability and erosion

Soil organisms play an important role in forming and stabilizing soil structure. In a healthy soil ecosystem, fungal filaments and exudates from microbes and earthworms help bind soil particles together into stable aggregates that improve water infiltration, and protect soil from erosion, crusting, and compaction. Macropores formed by earthworms and other burrowing creatures facilitate the movement of water into and through soil. Good soil structure enhances root development, which further improves the soil.

Water quality and quantity

By improving or stabilizing soil structure, soil organism dynamics help reduce runoff and improve the infiltration and filtering capacity of soil. In a healthy soil ecosystem, soil organisms reduce the impacts of pollution by buffering, detoxifying, and decomposing potential pollutants. Bacteria and other microbes are increasingly used for remediation of contaminated water and soil.

Plant health

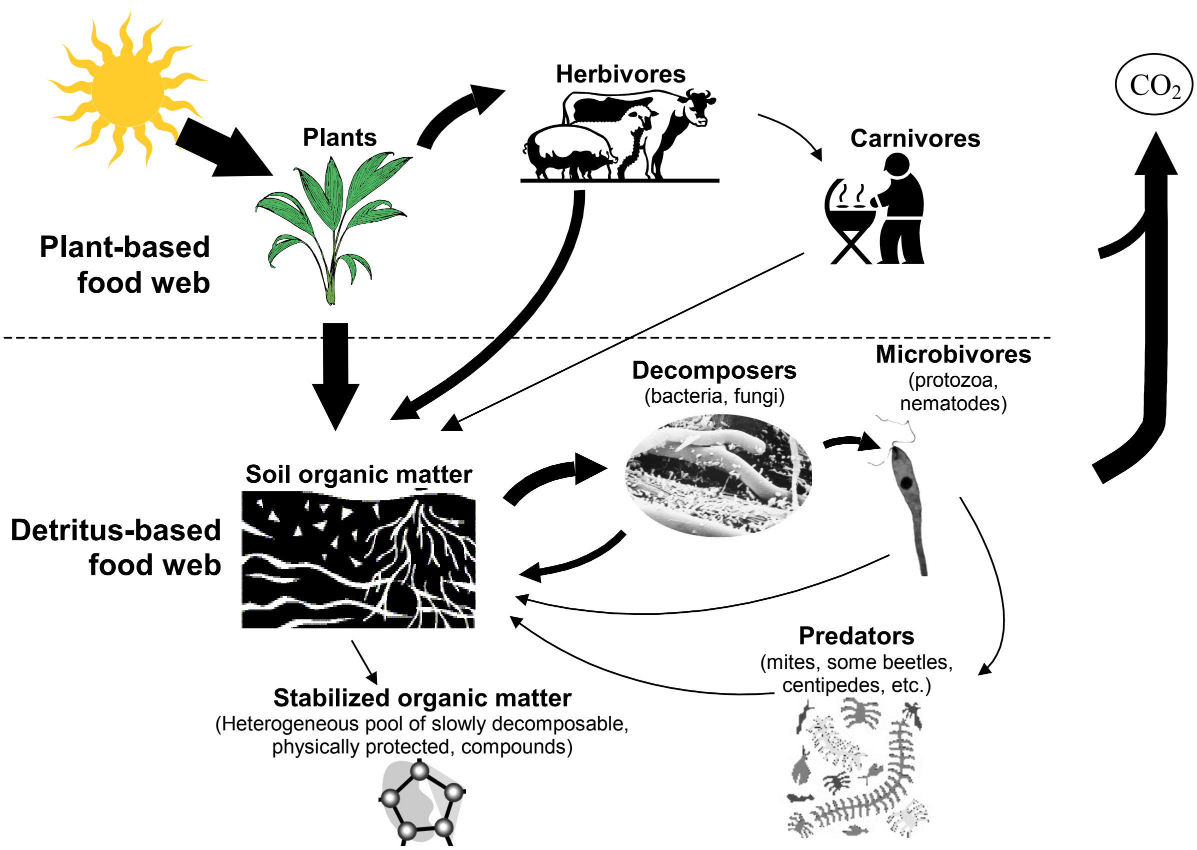
A relatively small number of soil organisms cause plant disease. A healthy soil ecosystem has a diverse soil food web that keeps pest organisms in check through competition and predation. Some soil organisms release compounds that enhance plant growth or reduce disease susceptibility. Plants may exude specific substances that attract beneficial organisms or repel harmful ones, especially when they are under stress, such as grazing.

For more information about what lives in the soil and how they function, see the "Soil Biology Primer" (Tugel and Lewandowski, 1999), and the soil biology glossary on the NRCS Soil Quality web site.

Complexity and function

Many soil biological functions emerge from the complex interactions of soil organisms and are not predictable by adding up the activity of individual soil organisms. How well the soil community performs each of these functions depends in part on the complexity of the biological community. Complexity is a factor of both the number of species and the different kinds or functions of species. Greater complexity may imply more diversity of functions and more redundancy of functions, and therefore more stability. For example, when multiple populations of microbes convert ammonium to nitrate, even if one population dies out, the function (nitrification) will continue to be performed. Functional redundancy is the underlying idea behind the "insurance hypothesis," which states that biodiversity insures ecosystems against declines in function.

Figure 1. The plant-based (aboveground) and detritus-based (belowground) food webs. Arrows represent energy flow (commonly measured in carbon units). Of the aboveground organic matter entering the pool of soil organic matter, 60%-80% of the carbon is eventually lost as CO_2. (Based on Chapin et al., 2002, Fig. 11.12.)



The underground community

Soil organisms can be grouped by size as shown in figure 2, or by functions as described below (Wardle, 2002; Coleman & Crossley, 1996).

Decomposers

Bacteria, actinomycetes (filamentous bacteria), and saprophytic fungi degrade plant and animal residue, organic compounds, and some pesticides. Bacteria generally, but not exclusively, degrade the more readily decomposed (lower C:N ratio) materials, compared to fungi, which can use more chemically complex materials. (See boxes on pages 7 and 8.) Bacteria often degrade what they can of a particular material; then fungi decompose the remainder.

Grazers and predators

Protozoa, mites, nematodes, and other organisms "graze" on bacteria or fungi; prey on other species of protozoa and nematodes; or both graze and prey. Grazers and predators release plant-available nutrients as they consume microbes. Often organisms specialize in one type of prey, such as either bacteria or fungi. Certain collembolans (springtails) even specialize on specific species of fungi. Other organisms are generalists and will feed on any microbial species they encounter.

Litter transformers

Arthropods are invertebrates with jointed legs, including insects, spiders, mites, springtails, centipedes, and millipedes. Many soil arthropods shred and consume plant litter and other organic matter, increasing the surface area accessible to decomposers. The organic matter in their fecal pellets is frequently more physically and chemically accessible to microbes than was the original litter. Some litter transformers, especially ants, termites, scarab beetles, and earthworms, are "ecosystem engineers" that physically change the soil habitat for other organisms by chewing and burrowing through the soil. Microbes (decomposers) living within their guts break down the plant residue, dung, and fecal pellets consumed along with the soil.

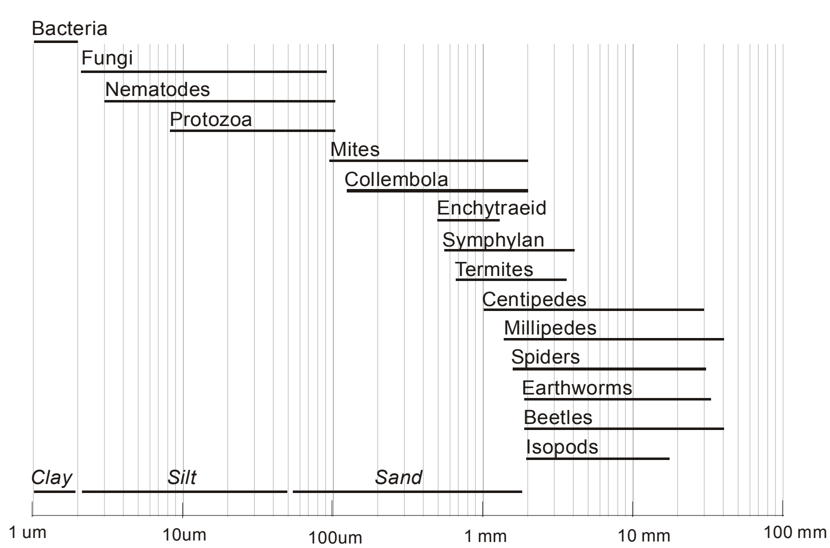
Mutualists

Mycorrhizal fungi, nitrogen-fixing bacteria, and some free-living microbes have co-evolved together with plants to form mutually beneficial associations with plants. Mycorrhizae are associations between fungi and plant roots in which the fungus supplies nutrients and perhaps water to the plant, and the plant supplies food to the fungi. These fungi can exist inside (endomycorrhizae) or outside (ectomycorrhizae) the plant root cell wall. The common arbuscular mycorrhizae (AM or VAM fungi) are endomycorrhizae.

Pathogens, parasites, and root feeders

Organisms that cause disease make up a tiny fraction of the organisms in the soil, but have been most studied by researchers. Disease-causing organisms include certain species of bacteria, fungi, protozoa, nematodes, insects, and mites.

Figure 2. Body width of soil organisms (Swift et al., 1979).



What controls soil biology?

People can adapt management strategies to affect the factors that control soil biological communities. Soil biological activity is determined by factors at three different levels. 1) At the scale of *individual organisms*, biological activity is determined by conditions such as temperature and moisture in the microbial habitats. 2) At the scale of *populations*, biological activity is determined by the amount of habitat diversity, the types of habitat disturbances, and the diversity and interactions among various soil populations.
3) At the scale of *biological processes*, functions such as nutrient cycling or pest control are affected by the interaction of biological populations with physical and chemical soil properties.

For example, consider the effect of tillage on earthworms at each of these scales. At the scale of individual organisms, a single tillage event may kill as many as 25 percent of individual earthworms. At the scale of populations, a single tillage pass may have little effect after a few months as the earthworms reproduce and rebuild their population. At the scale of soil processes, tillage will weaken soil structure over time and reduce the amount of surface residue available to fungi and earthworms. As fungal and earthworm activity declines, soil stability declines and alters the microhabitats for other organisms.

Microscale factors

The following environmental factors affect the types and activity levels of soil organisms. These factors may vary over short distances in the soil. Consider how each factor is impacted by climate, soil texture, time of day or season, and management practices including tillage, crop rotation, and irrigation.

Food (nutrients and energy)

All organisms require a source of food that supplies nutrients and energy. “Primary producers” are organisms that use photosynthesis to make their own food from sunlight and CO_2. “Consumers” are organisms that use organic compounds from other organisms as their source of both carbon and energy. A small group of bacteria get their energy from inorganic nitrogen, sulfur, or iron compounds, rather than from sunlight or organic compounds. These bacteria are important in cycling some nutrients required by plants. Soil organisms also require varying amounts of macronutrients (N, S, and P) and micronutrients (e.g. Fe, Cu, Zn). The amount of all these nutrients and the quality of nutrient sources will favor some organisms over others, depending on each species’ requirements and preferences.

Oxygen

Animals and most soil organisms are obligate aerobes, meaning they require oxygen. Some bacteria are obligate anaerobes, meaning they require oxygen-free conditions to function. Many organisms are facultative anaerobes, meaning they can switch metabolic pathways and function as either aerobes or anaerobes depending on environmental conditions. Anaerobes use nitrate, sulfate, or iron instead of oxygen as an electron acceptor. Aerobic respiration is the most common form of metabolism and typically produces ten times more energy per unit of organic matter than that generated through anaerobic metabolism. Anaerobic conditions and anaerobic microbes dominate in marshes and other saturated soils. However, even well-drained soils can have anaerobic and aerobic microsites within millimeters of each other. See box (next page) for a list of processes performed by aerobic and anaerobic organisms.

Anaerobic soil biological processes

Fermentation – Conversion of sugar to alcohol.
Denitrification – Reduction of nitrate to gaseous nitrogen.
Methane production – Reduction of CO_2 to methane (CH_4) in marshes and rumens.
Sulfur reduction – Reduction of sulfate to hydrogen sulfide or sulfur.
Iron reduction

Aerobic soil biological processes

Respiration – The conversion of oxygen eventually to carbon dioxide and water.
Ammonification – The creation of ammonia from organic compounds. May also occur anaerobically slowly.
Nitrification – The oxidation of ammonium to nitrite and then nitrate.

Other physical factors

Moisture, temperature, light, pH, and electrical conductivity (salinity) are other critical factors determining the level of biological activity within an ecosystem. Each species has different optimal conditions, but overall bacterial activity is highest at temperatures between 20°C and 40°C, at pH levels between 6 and 8, and when pore spaces are about 60% water-filled. Soil texture and porosity determine the amount of space available for soil organisms and for the movement of air and water through the soil. Thus, porosity, aeration, and moisture levels are linked. Relatively larger organisms, such as nematodes and small mites (figure 2), require large pore spaces to move. Many organisms, including protozoa and nematodes, are essentially aquatic and require water films.

Community-scale factors

The microscale factors listed above directly affect soil organisms. However, to understand soil biological function we also have to consider large-scale factors such as heterogeneity of habitat, disturbances, and biological interactions.

Heterogeneity of resources

Heterogeneity can refer to variation in food sources or any of the other microscale conditions listed above. Heterogeneity of soil habitats creates diversity and complexity in the structure of the soil food web. Plant diversity is an important means for creating heterogeneity because plants affect the food sources, the physical habitat (e.g. root structures and soil structure), and the chemical attractants and deterrents for soil organisms.

Disturbance

All human land uses, especially agriculture, are subject to natural and human disturbances including fire, harvest, tillage, compaction, overgrazing, disease, or pesticide applications. The frequency, severity, and timing of disturbances determine their effect on soil biological activity. According to the intermediate disturbance hypothesis, the greatest level of biological diversity and stability occurs with a "Goldilocks" amount of disturbance – not so much that processes are continually disrupted, and not so little that just a few species gain dominance. Conventional cropping systems are highly disturbed systems. Low-input, conservation tillage systems with crop rotations may be an example of an intermediately disturbed ecosystem.

Interactions with other organisms

Soil populations are affected by interactions with other soil organisms. One type of biotic interaction is *competition* for limited food and habitat. A second type is *predation* by larger organisms, such as nematodes and mites. A third type is *mutualism* – interactions beneficial to both parties, such as those involving mycorrhizae, symbiotic nitrogen fixers, many rhizosphere microbes, and microbes living in earthworm guts. When land management practices disproportionately affect one group of organisms over another, they impact the interactions among soil organisms.

General management strategies

Four broad management strategies are presented below. The diversity and functioning of a soil biological community are likely to improve when these strategies are used. Management plans should consider both the timing of management practices and disturbances, and the duration and degree of their effects on soil biology. The effects of management and disturbances vary by season, and the capacity of the soil community to recover from a particular practice or disturbance ranges widely.

1) Manage organic matter.

Regular inputs of organic matter are essential for supplying the energy that drives the soil food web. Each source of organic matter favors a different mix of organisms. (See boxes, this page and next.) Thus, a variety of sources may support a variety of organisms. The location of the organic matter—whether at the surface, mixed into the soil, or as roots—also affects the type of organisms that dominate in the food web.

Under any land use, organic matter inputs to the soil can be increased by improving plant productivity and increasing annual biomass production. In particular, good root growth is important for building soil organic matter. High biomass production should be combined with other organic matter management practices including minimizing residue removal and tillage, growing cover crops, and adding manure, mulch, or other amendments.

Components of organic matter

Organic matter is composed of a heterogeneous mix of compounds with various chemical bonding and branching characteristics. Each organism has the necessary enzymes for decomposing some compounds but not others. For example, lignin is a recalcitrant organic compound that can only be broken down by white and brown rot fungi.

The composition of organic matter from plants varies considerably, but generally comprises 60-70% carbohydrates (polysaccharides),
15-20% lignin, and 15% other compounds including proteins, nucleic acids, lipids, waxes, and pigments.

2) Manage for diversity.

The diversity of plant assemblages across the landscape and over time promotes a variety of microbial habitats and soil organisms. Up to a point, soil biological function generally improves when the complexity or diversity of the soil biological community increases.

Many types of diversity should be considered, such as diversity of land uses (buffers, forest, row crops, grazing land), plant types (perennial, annual, woody, grassy, broadleaf, legume, etc.), root structures (tap, fibrous, etc.), and soil pore sizes. Diversity is desirable over time as well as across the landscape. Land managers can increase diversity with appropriate grazing management, patchy or selective tree harvest (in contrast to broad clear-cutting), vegetated fencerows, buffer strips, strip cropping, and small fields. These landscape features provide refuges for beneficial arthropods. Diversity over time can be achieved with crop rotations. Rotated crops put a different food source into the soil each year, encouraging a wide variety of organisms and preventing the build-up of a single pest species.

3) Keep the ground covered.

Ground cover at or near the surface moderates soil temperature and moisture; provides food and habitat for fungi, bacteria, and arthropods; and prevents the destruction of microbial habitat by erosion. Minimize the length of time each year that soil is bare by maintaining a cover of living plants, biological crusts, or plant residue at the surface.

Living plants are especially important as cover because they create the rhizosphere—that area within one or two millimeters of living roots where soil biological activity is concentrated.

Microbes around roots take advantage of plant exudates and sloughed-off root cells. Maintaining a rhizosphere environment is one of the important benefits of using cover crops. In addition to preserving microbial habitat, cover crops help build and maintain populations and diversity of arthropods by preserving their habitat for an extended portion of the growing season.

4) Manage disturbances.

Some soil perturbations are a normal part of soil processes, or are a necessary part of agriculture and other land uses. However, some disturbances significantly impact soil biology and can be minimized to reduce their negative effects. These disturbances include compaction, erosion, soil displacement, tillage, catastrophic fires, certain pesticide applications, and excessive pesticide usage.

Carbon-to-nitrogen ratio

The carbon-to-nitrogen ratio (C:N) of organic matter can vary from about 4:1 (low carbon, high nitrogen) for bacteria to more than 200:1 to 600:1 for woody materials. Ratios for wheat straw are about 80:1, and young legumes may be 15:1. The C:N ratio of soil organic matter in agricultural soils averages 10:1. Fungi have a fairly constant C content of 45%, but N levels vary, resulting in C:N ratios of 15:1 to 4.5:1.

Low N materials have a low nutritional quality for microbes. When organic materials are added to soil, the carbon triggers microbial growth. If the amount of N in the added material is inadequate to support the increased growth, the microbes will absorb nitrogen from the soil and immobilize it in their tissues, thus depriving plants of nitrogen, at least temporarily. As a rule-of-thumb, materials with C:N ratios less than 25 or 30:1 will not trigger this N deficiency in plants. Materials with lower C:N ratios tend to decompose quickly. Materials with higher C:N ratios are slow to decompose and can lead to carbon storage or sequestration in the soil when accompanied by additional nitrogen inputs in reduced tillage systems.

C:N ratios of soil organic matter provide clues about the microbial community. For example, higher ratios tend to support more fungi compared to bacteria. A labile pool of soil organic matter with a low C:N ratio implies that the SOM consists of a high proportion of microbes.

Compaction

Ideally, soils are approximately 50 to 60% pore space comprising a variety of pore sizes and lengths. The size and continuity of pores controls whether larger microbes, such as protozoa, can prey upon bacteria and fungi. Compaction reduces the diversity of pore sizes and the amount of space and pathways available for larger organisms (figure 2) to move through the soil. This favors bacteria and small predators over fungi and the larger predators. Arthropods are severely affected by compaction. Among nematodes, the predatory species are most sensitive to compaction, followed by fungal-feeders, then bacterial-feeders. Root-feeding nematodes are least sensitive to compaction—perhaps because they do not need to move through soil in search of food. Compaction changes the movement of air and water through soil, can cause a shift from aerobic to more anaerobic organisms, and may increase losses of nitrogen to the atmosphere (denitrification). Rooting depth may be limited in highly compacted soils. This restricts the depth of the rhizosphere environment that supports microbes.

Erosion and sedimentation

Most soil organisms – especially larger ones – live in the top few inches of soil. Erosion disrupts and removes that habitat. Sedimentation buries the surface habitat and deprives organisms of space and air.

Soil displacement and tillage

Displacement and mixing of the soil occur during many activites including tillage, land leveling, grading, intense grazing, and site preparation and harvesting on forestlands. Some soil displacement can be useful such as tillage for seedbed preparation in cropland, limited disturbances in highly productive grassland systems, and soil scarification to ensure success of some types of reforestation. However, soil disturbances significantly change the biological habitat of the soil. If the extent of the disturbance is limited to small areas, the overall impact will also be limited. Broadly applied practices such as tillage, grazing, or clear-cutting can impact large areas. Even a single tillage or compaction event can significantly affect the location and quantity of the food supply and the physical habitat of soil organisms. If enough nitrogen is present, tillage and other practices that mix the soil usually lead to a flush of microbial activity and nutrient release, and loss of soil organic matter via CO_2 respiration. Where there is a loss of soil organic matter, microbial activity will eventually drop to a rate that is lower than the initial rate. Over time, tillage shifts the food web from being dominated by fungi to being dominated by bacteria.

Pesticides and herbicides

All pesticides impact some non-target organisms. Heavy pesticide use tends to reduce soil biological complexity. Total microbial activity often increases temporarily as bacteria and fungi degrade a pesticide. However, effects vary with the type of pesticide and species of soil organism. Labels generally do not list the non-target organisms affected by a product. In fact, few pesticides have been studied for their effect on a wide range of soil organisms. Pesticides that kill aboveground insects can also kill beneficial soil insects. Foliar insecticides applied at recommended rates have a smaller impact on soil organisms than fumigants or fungicides. Herbicides probably affect few organisms directly, but they affect the food and habitat of soil organisms by killing vegetation. A pulse of dead vegetation may trigger a flush of biological activity and decomposition. Crop rotations are useful for breaking pest cycles, reducing pesticide application rates, and for varying the families of pesticides used.

Considerations for specific land uses

The effects of management practices, operations, and natural disturbances often are specific to particular land uses, such as those discussed in this section. Each of the considerations below relates to the general management strategies described in the previous section.

Cropland

The highly disturbed soils of cropland may have as many bacteria and protozoa as other ecosystems, but tend to have far fewer fungi, nematodes, and arthropods. Reduced tillage and perennial cropping systems will support more of these larger soil organisms.

Crop biomass additions

Roots and surface residue from crops are convenient and valuable sources of soil organic matter and food for soil organisms. Corn harvested for grain will generate 3 to 4 tons of surface residue per acre and 1 to 2 tons of root biomass. Dense, sod-type crops produce generous amounts of root biomass. Recent research suggests that root contributions are more significant for building soil organic matter than are contributions from aboveground plant residue.

Surface residue encourages the decomposers—especially fungi—and generally increases food web complexity. Residue provides food and habitat for surface-feeding organisms, such as some earthworms, and for surface-dwellers, such as some arthropods. It also changes the moisture and temperature of the soil surface, and protects soil organic matter from erosion. The residue will increase some pathogens and reduce others. Soybeans, peanuts, and many vegetables leave little surface residue and should be rotated with high residue crops or cover crops.

Animal manure

Dung pats provide food and habitat for a variety of larger soil organisms. Manure in any form is a significant source of nutrients. Manure application substantially changes the mix of organisms in the soil compared to plant sources of organic matter. The implications of these differences are not clear, but they probably affect disease levels and nutrient cycling. Over-application of N or P (whether from organic amendments or synthetic fertilizer) can suppress certain soil organisms, especially mycorrhizal fungi, as well as lead to degradation of air and water quality.

Compost

Compost can be used to inoculate the soil with a wide variety of organisms and to provide a high quality food source for them. Composts have also been credited with reducing the incidence of plant disease (Ceuster and Hoitink, 1999). Some species thrive in both compost and soil, but many prefer one or the other. For example, the redworms (*Eisenia fetida*) commonly used to make vermicompost do not survive well in soil. The quality of compost varies substantially depending on the material used, peak temperature during the composting process, and the level of aeration. Organic materials decomposed with little oxygen (e.g. liquid manure) will contain a very different set of organisms and compounds than well-aerated compost. (For information about how to make compost, see NRCS conservation practice standard #317, Composting Facilities.)

Sewage sludge

Like manure, sludge can be an excellent food source for organisms. However, high levels of metals or salts in some sludge kill or reduce the activity of some organisms.

Cover crops

Cover crops have several positive effects on soil communities. Most soil organisms live in the rhizosphere – the area directly around living roots. By planting cover crops (also called green manure) the rhizosphere environment is available to soil organisms for a longer portion of the year. Cover crops typically increase the amount and diversity of roots and aboveground growth that become part of soil. Because of each crop's unique physiology, populations of specific soil organisms will increase or decline depending on the crop. For example, some cover crops exude compounds that inhibit disease-causing organisms.

Inorganic fertilizers

Fertilizer provides some of the nutrients needed by soil organisms and will favor those species that can best utilize the forms of nutrients found in fertilizers. The effect of acidity, alkalinity, or salt of some fertilizers (e.g. ammonium nitrate, ammonium sulfate, and urea formaldehyde) tends to reduce populations of fungi, nematodes, and probably protozoa. It is not clear how persistent these population reductions are in various situations.

Judicious fertilizer use can be positive for overall biological activity because it increases plant growth and organic matter inputs to the soil.

Genetically modified (GMO) crops

Each type of GMO is likely to have a different effect on soil biology. For example, Bt crops seem to have little direct effect on the composition of the soil biological community, yet decomposition rates of the crop residue differ from that of other corn varieties – perhaps because of changes in plant lignin composition, which may indirectly affect soil organisms via changes in food resources. (Lignin is a plant compound that is highly resistant to microbial attack.) However, soil type and crop variety seem to be more important than the presence of the Bt gene in determining decomposition rates (Saxena and Stotzky, 2001a, b).

Drainage

Improved water drainage tends to improve microbial activity by increasing oxygen availability. Poorly drained soils have a high level of anaerobic microsites and therefore a higher rate of denitrification (conversion of nitrate to gaseous nitrogen) compared to well-drained soils.

Irrigation and salt build-up

Where irrigation increases plant yield, it increases biomass production and soil organic matter, and therefore tends to increase biological activity and to alter the biological community structure. However, irrigation water can contain salts. To prevent salt accumulation that can reduce biological activity and crop yield, additional water must be applied to leach these salts from the root zone. Some irrigation techniques, such as furrow irrigation, require extreme soil disturbance that is detrimental to biological habitat. When the disturbance is a one-time event (i.e., intense but infrequent), as with installation of subterranean irrigation pipes, the disturbance is less likely to do lasting damage.

Soil inoculants and compost tea

Some commercially available inocula are intended to increase populations of specific soil organisms. Some products have a long track record of effectiveness, including nitrogen-fixing bacteria and some pest predators, such as bacteria, nematodes, or insects. Some products are unproven or unpredictable.

Inoculants will have little effect or only a temporary effect if the organisms cannot compete in their new environment. Because they must have supplies of organic matter as a food source, soils low in organic matter will not see long-lasting results unless a recurring supply of organic matter is added to the system. Furthermore, many functions performed by soil organisms result from the interactions of organisms, not from a few individual species.

When considering using inoculants, ask the following questions:

- Do you have assurances that the organisms claimed to be in the product are viable?
- Will the organisms survive in your soil environment long enough to have the desired effect?
- If you achieve positive results, was the change caused by the inoculated organisms or by associated management

practices, such as changes in tillage or added organic matter?

Before committing a whole farm to a new product, test it on a small area and compare results to a control strip managed identically but without application of the product. Monitor both short- and long-term effects.

Land leveling

Land leveling may have effects similar to erosion and sedimentation because biologically active surface soil is removed from some areas and deposited in other parts of the field. It may also expose subsoil with a less desirable texture or lower organic matter levels. This effect can be reduced by intense soil building practices after land leveling or by removing and stockpiling the topsoil just prior to land leveling and then spreading it over the newly leveled surface.

Terraces and grassed waterways

Permanent vegetative structures add diversity to a landscape and thus can enhance the biodiversity of the area. They serve as a refuge for larger soil organisms such as arthropods and pest predators. However, like land leveling, the soil movement involved during construction of terraces can significantly disrupt soil biological habitat.

Tillage and no-till

Tillage enhances bacterial growth in the short-term by aerating the soil and by breaking apart soil aggregates to expose organic matter that had been protected from microbial decay. The bacterial activity increases the loss of carbon respired as CO_2, and triggers population explosions of bacterial predators such as protozoa. Ultimately, recurrent tillage reduces the amount of soil organic matter that fuels the soil food web.

The mechanical action of tillage tends to temporarily reduce populations of fungi, earthworms, nematodes, and arthropods. Over the long term with repeated tillage, these populations are likely to decline because of the lack of surface residue rather than because of the mechanical action of tillage.

The environment for soil organisms can differ significantly in no-till compared to conventionally tilled soils. For example, because the surface soil structure is not regularly disrupted, no-till soils are more likely to have:

- Anaerobic micro-environments,
- Cooler spring soil temperatures because of greater surface cover,
- More macropores to facilitate infiltration,
- Greater soil moisture and carbon near the surface, and
- Uneven distribution of organic matter throughout the topsoil.
- In addition, surface compaction may be a problem if compaction was present before the conversion to no-till, and if biomass inputs are low or traffic patterns are not controlled.

Organic matter decomposition rates are lower in no-till vs. conventionally tilled soils because of the lower level of soil disturbance. The lack of disturbance and the presence of surface residue encourage fungi and large organisms such as arthropods and earthworms. No-till soils generally have a higher ratio of fungi to bacteria.

Fallow periods

Because microbes concentrate around living roots, fallow periods of even a few weeks at the beginning or end of a growing season reduce an important microbial habitat. During long fallow periods, most arthropods will emigrate or die of starvation. Some organisms can form cysts, allowing them to lie dormant until conditions become more favorable. Mycorrhizal fungi also "starve" during a fallow period and take time to recover after the fallow period ends. Growing non-mycorrhizal plants is equivalent to a fallow year from the perspective of mycorrhizal fungi. Plants that do not support mycorrhizae include brassicas (mustard, broccoli, canola) and chenopods (beets, lamb's-quarters, chard, spinach). (See section on mutualists, page 4, for more information about mycorrhizae.)

Forestland

Forest soils have high ratios of fungi relative to bacteria, especially under coniferous forests. The fungi are predominately ectomycorrhizae that infect tree roots and then extend their hyphae into the soil. This greatly increases the tree's effective root zone, allowing access to a greater area of soil from which to extract water and nutrients. The mantle created by mycorrhizae around the root also prevents pathogenic fungi and bacteria from attacking the root system.

Arthropods can be quite numerous in forests because the soil is rarely disturbed. Earthworms are common in deciduous forests, but rare among conifers. Where non-native earthworms (e.g., fishing bait) have been introduced into deciduous forests, significant changes in understory vegetation have been observed (Minnesota DNR, 2004).

Tree harvesting

Tree harvesting removes nutrients from the area, reduces the total uptake of nutrients by plants, and can accelerate biological activity and decomposition. Tree harvest can change the activity, amount, and diversity of the microbial community. The degree of site disturbance during harvesting and the amount of slash remaining after harvest determines the effects on soil organisms. Techniques that minimize soil disturbance and compaction will have the least detrimental effect on soil organisms. Tractors, wheeled skidders, and mechanized harvesting equipment disturb the soil surface and can cause compaction that restricts biological activity. Cable, helicopter, and horse logging produce the least disturbance. Soil surface displacement and mixing of soil, duff, and slash temporarily increase microbial activity and may interfere with arthropod activity.

Clear-cutting generally has a negative effect on soil biological activity. The large number of roads, skid trails, and landings compact soil and are particularly susceptible to erosion. When erosion and loss of mycorrhizal host plants is severe mycorrhizal fungi may be lost from the ecosystem. Compared to soil under trees, bacteria and actinomycetes, such as streptomyces, are more prominent in clear-cut areas, between trees in thinned areas, and between intact forest patches. When reclaiming clear-cut forests it is beneficial to inoculate new tree seedlings with mycorrhizal fungi, forest soils, or litter containing these fungi. Retaining patches of intact forests among clear-cut areas provides a source of soil organisms to re-inoculate the harvested areas.

Thinning and fuel management

Thinning of forests has a positive effect on soil biological diversity, especially in single-age stands. Thinning increases the diversity of understory vegetation and thus creates more diversity of habitats and food sources for soil organisms. (This is an example of the intermediate disturbance hypothesis described on page 6.) However, excessive compaction and soil displacement can have negative effects.

Roads, trails, and landings

Compaction created under roads, skid trails, and landings compresses soil particles together and reduces pore sizes. This restricts the habitat for soil organisms, especially the nematodes and larger arthropods. The use of designated skid trails and restoration of landings after harvest minimizes the amount of forestland affected.

Slash piling and woody debris

Machine or hand piling of slash concentrates nutrient-rich branches, foliage, and sometimes topsoil. This increases soil organism populations and activity locally. Excessive nutrient leaching can occur in areas where microbial activity increases. Windrowing of slash has severe detrimental effects on areas between windrows because topsoil rich in soil organisms is scarified and placed in the windrows. Runoff may also erode nutrient-rich surface soil and organic matter from slash areas, potentially degrading water quality of nearby streams and lakes.

Wind damage increases the amount of dead wood available for soil organisms. Woody debris can enhance biological function because dead wood mitigates environmental extremes, such as heat and cold, in the microclimate of a disturbed area. In forests, downed logs serve as centers for biological activity including mycorrhizal hyphae, nitrogen-fixing bacteria, other microbes, arthropods, and even small mammals. In some systems, fungi extract water from large rotting logs and supply the water to growing trees during times of moisture stress. Downed logs also serve as natural dams to help reduce erosion and increase infiltration and thus improve recolonization by desirable species in highly disturbed areas.

Fire

Stand replacement fires – Stand replacement fires are common in single age stands of fire-adapted tree species such as lodgepole pine, jack pine, longleaf pine and black spruce. Fire is an integral part of the ecology of these forests. The microbial community tends to drop back to its previous level of activity after an initial flush of activity after a fire.

Cool or patchy fires – Frequent ground fires are an integral part of some forest ecosystems, such as ponderosa pine stands. These fires are not hot enough to burn the overstory trees, but the understory trees and brush are killed. A short, cool fire rarely eliminates any group of organisms. If the fire is cool, nitrogen will not be volatilized, and the nitrogen in ash may stimulate plant growth and diversity of species. Arthropods will repopulate readily after a patchy fire.

Catastrophic wildfire – Hot, long-duration fires will kill most organisms, including microbes at or near the soil surface. The ignition of litter and duff as well as erosion after the fire reduces food available to soil organisms. The mineralization and subsequent leaching of nitrogen can significantly decrease soil fertility. Hydrophobic layers formed during hot fires can restrict the penetration of water into the soil for several years. This restricts plant and root growth thus reducing the food supply for soil organisms.

Insects and disease

The reduction of fire in some forests, such as Ponderosa pine forests, has led to an increase in insect infestations and disease. Diseased or dead trees increase the amount of woody debris that serves as fuel for hotter-burning, potentially catastrophic fires.

An invasion or increase of less disease-resistant tree species will make a forest stand more susceptible to insect infestation and disease.

Rangeland

Soil biological activity in rangelands may vary greatly over short distances. Activity may be high under shrubs and grasses and almost none in the bare spaces between plants.

Some seemingly bare spots are actually encrusted with soil organisms, such as cyanobacteria. Biological soil crusts are important for nutrient and water cycling, particularly in arid and semi-arid environments.

When plant assemblages change dramatically over time, for example, from grass- to shrub-dominated, the character of the soil biology may change to the extent that it may be difficult to convert the system back to the original plant assemblage with its associated soil community.

Grazing and vegetation management

Grazing and vegetation management are the most important tools for maintaining the benefits of the soil food web. Timely grazing, the proper frequency of grazing, and control of the amount of vegetation removed will maintain or enhance plant production and the supply of organic matter. Both overgrazing and non-grazing reduces root growth and thus the amount of organic matter inputs to the soil. Grazing stimulates root growth and production of root exudates, but overgrazing reduces the amount of leaf surface for photosynthesizing. (This is another example of the intermediate disturbance hypothesis. See page 6.) With reduced food supplies, biological activity decreases along with important soil functions, including nutrient cycling, water infiltration, and water storage. As these functions decline, the ability of the plant and soil biological communities to replenish soil organic matter also declines. Heavy grazing can reduce the abundance of nitrogen-fixing plants, causing a decrease in the nitrogen supply for the entire plant community. Where biological crusts provide important functions such as protection from erosion, the timing and intensity of grazing should be managed to minimize damage to crusts. Ensuring even manure distribution is another mechanism by which good grazing management enhances soil biological activity.

Fire

Prescribed burning in grassland communities generally produces cool temperature fires that have little or no direct effect on soil organisms. There can be short-term losses of habitat or food sources, but patchy fires leave refuges for larger soil organisms in adjacent unburned litter and grass.

Absence of fire or an increased length of time between fires commonly promotes vegetation shifts from grass-dominated to shrub- or tree-dominated plant communities. Such vegetation shifts affect the soil organisms through the change in residue composition and the depth of root zones that contribute food sources. Woody residue and roots will increase fungal populations. Bare soil between shrubs provides little food and will result in a decline in soil organism populations.

Catastrophic fire is likely to occur in dense shrub- or tree-dominated plant communities. The resinous wood and longer burn times promote hot fires that can effectively scorch the upper few inches of the soil. This will kill some soil organisms and reduce their food supply while also increasing the availability of some nutrients.

Invasive weeds

Invasive weeds can cause a shift in the types of soil organisms present because the quantity and quality of plant residue and root exudates will change. Weeds that cause increased litter buildup tend to promote more fungal dominance in soil. The encroachment of annuals into perennial plant systems will cause changes in organism community composition because soil biological activity corresponds with plant growth stages and periods of litter fall and root die-off.

Shrub removal

Removing shrubs by chaining, thinning, or applying herbicides promotes a shift to a different plant community and affects food sources for soil organisms. Less woody material and more herbaceous material will promote bacterial increases compared to fungi. Arthropod species will also change to those supported by the new plant community. As with tillage, the soil displacement and mixing that occurs during chaining will enhance bacterial decomposition of soil organic matter and residues. Compaction and herbicide effects, as described in "General Management Principles" above, may also be an issue during shrub removal.

Plowing and seeding

Plowing and seeding disturbances are related to the degree of soil mixing. Tillage that completely mixes or inverts the topsoil will result in a sudden, drastic change in habitat, increased organic matter decomposition rates, and thus reduced food sources for soil organisms. It also destroys larger pores and some macrohabitats. Use of a seed drill minimizes soil mixing and is much less of a disturbance to soil biology. Changes in the amount of residue either from plowing or the establishment of the seeded species will alter the food sources for soil organisms. Loss of residue can reduce or eliminate habitats for larger organisms in the food web, such as insects and arthropods.

Compaction from traffic

Grazing animals and vehicles may cause compaction, especially when traffic is concentrated in small areas or soil is too wet. See "General management strategies" for a description of the implications of compaction on soil biology.

Erosion

Off-road vehicle traffic or heavily used trails can create ruts that compact soil and channel water. The resulting accelerated erosion, rills, and gullies can strip or bury topsoil and have a negative effect on soil organisms. Erosion associated with vegetation shifts often results in the redistribution of topsoil, organic matter, resources, and habitat across short distances. At the shrub-intershrub scale, bare areas between shrubs provide the least habitat and resources for soil organisms. Areas of grass, shrubs, or trees have more diversity of soil organisms.

Assessment and monitoring

In contrast to soil physical and chemical parameters, there are few specific guidelines for managing soil biological properties. Thus, it is especially important that land managers track changes in soil biological functions over time to monitor the effects of management choices.

Monitoring is the identification of trends by systematically collecting quantitative data over time from permanently marked locations. Objectives for monitoring soil biological function include:

- Evaluation and documentation of the progress toward management goals,
- Detection of changes that may be an early warning of future degradation, and
- Determination of the trend for areas in desired condition, at risk, or with potential for recovery.

Assessment is the estimation of the current functional status of soil biological processes. It requires a standard for comparison. Objectives of assessments can be:

- Selection of sites for monitoring,
- Gathering of inventory data,
- Identification of areas at risk of degradation, and
- Targeting management inputs.

Techniques for measuring soil biological properties range from informal, qualitative observations to quantitative laboratory techniques. These techniques can be useful for learning about organisms' resource requirements and functions. However, soil biological tests can be difficult to interpret, and thus provide limited support for making specific management decisions. More information may be gleaned by assessing and monitoring properties affected by soil biological activity including soil surface stability (aggregate stability and slake tests), water infiltration rates (ring infiltrometer and rainfall simulation tests), decomposition rates, pest activity, and soil nitrate and carbon levels (microbial biomass and total organic carbon tests). These measures of soil properties assess the soil functions of interest to a land manager. However, they are likely to change more slowly than biological measures and thus are more delayed indicators. When deciding what to assess or monitor, keep in mind the objectives and the time and resources available.

For more about planning appropriate soil quality assessments see "Guidelines for Soil Quality Assessment in Conservation Planning" (NRCS, 2001c).

Types of tests

As discussed in the Soil Biology Primer, a variety of approaches can be used to describe the soil community, including 1) counting soil organisms or measuring biomass, 2) measuring their activity, or 3) measuring diversity, such as diversity of functions (e.g., biolog plates) or diversity of chemical structure (e.g. cell components or DNA). Each approach provides different information.

Methods for measuring biomass identify either the total number of organisms or only those that are active. A pitfall trap or Berlese funnel (NRCS, 2001b) can be used to collect larger organisms living in litter from a forest floor, pasture, or cropland.

Activity measurements provide a better understanding of soil biological function than do biomass measurements. One measure of biological activity is testing for various microbial enzymes (Dick, 1997). By choosing the appropriate enzyme, an enzyme assay can be used to assess the rate of carbon, nitrogen, or phosphorus cycling, or overall microbial activity. Enzyme assays have potential as a useful indicator and can be done with the equipment found in typical soil analysis labs, but most labs do not yet offer these tests.

Respiration, or the amount of CO_2 produced from the soil, is another measure of biological activity. The test can be done in the field (NRCS, 1998), but results are difficult to interpret. Respiration rates are extremely variable hourly, seasonally, and by region and soil type, so baseline or reference data are nearly meaningless. Furthermore, high respiration may indicate a healthy and active biological community, or it may indicate recent disturbance, such as tillage, that has triggered a flush of activity. High respiration represents a loss of soil carbon to the atmosphere, which is counter to the goal of carbon sequestration. Yet there are no guidelines for determining how much is too much. For these reasons, soil respiration tests can be useful in side-by-side demonstrations, but are of limited value as a soil biological indicator.

Cotton strip tests (NRCS, 1998 and 2001b) and a few other techniques measure decomposition rates over days or weeks, and therefore are not confounded by short term variation as much as are respiration tests. However, results are still difficult to interpret and require a standard or control for comparison.

With any of these measures of the soil biological community, refer to a specialist for help interpreting test results.

Get to know your community

To gain a general awareness of soil organisms and their effects, try these simple methods. Choose a few places to take a close look at what lives in your soil. Look under a shrub, in the woods, along a fence line, in a meadow, in a field, etc. Take time to examine the litter on the surface and look for organisms that move. Look for biotic crusts, burrows, fungal hyphae, and other evidence of soil organisms. Over the seasons, look for birds picking out earthworms behind a tillage implement. Observe the rate that dung pats decompose. Notice the amount of runoff or ponding after a rain.

Collecting samples for laboratory analyses

A small number of commercial labs will test soil biological properties. Typical measures are microbial biomass and direct counts of soil microbes. When choosing a lab and soil biology tests, consider the following.

- What quality control measures does the lab use to ensure reliable results?
- What is the significance of each test in terms of soil function?
- How will the test assist in your management decisions?
- Do interpretations of results consider your specific soil type and cropping systems?

The biomass (total amount of organisms) changes seasonally, but does not change drastically from day to day. However, activity levels (e.g., respiration) can change quickly, so note the time of year and the temperature and moisture conditions when sampling, and sample under similar conditions for future observations.

Samples should be placed in sealed bags and chilled (but not frozen) immediately.

Summary

Soil organisms are integral to soil processes, including nutrient cycling, energy cycling, water cycling, processing of potential pollutants, and plant pest dynamics. These processes are essential to agriculture and forestry, and for protecting the quality of water, air, and habitat. Therefore, land managers should consider the effects of their actions on the health and function of the soil biological community.

Despite the well-known importance of soil biological processes, the development of monitoring and management guidelines is in its infancy. However, land managers can learn the general principles of how their choices affect biological processes and can monitor changes in soil function.

Soil biological health generally improves when the following management practices are applied:

- Regularly adding adequate organic matter,
- Diversifying the type of plants across the landscape (in all land uses) and though time (in cropping systems),
- Keeping the ground covered with living plants and residue,
- Avoiding excessive levels of disturbances including soil mixing or tillage, compaction, pesticides, heavy grazing, and catastrophic wildfires.

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