Soil Health and Organic Farming

Understanding and Optimizing the Community of Soil Life

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SOIL HEALTH AND ORGANIC FARMING

UNDERSTANDING AND OPTIMIZING THE COMMUNITY OF SOIL LIFE

An Analysis of USDA Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) Funded Research from 2002-2016

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Table of Contents

Introduction

The life in the soil provides the foundation for successful farming, and for all terrestrial plant, animal, and human life on Earth. A diverse community of soil bacteria, fungi, protozoa, worms, arthropods, and other organisms, commonly known as the soil food web, converts fresh residues into soil organic matter (SOM), and plays a central role in each of the soil functions considered essential for agricultural production (Figure 1, Table 1).

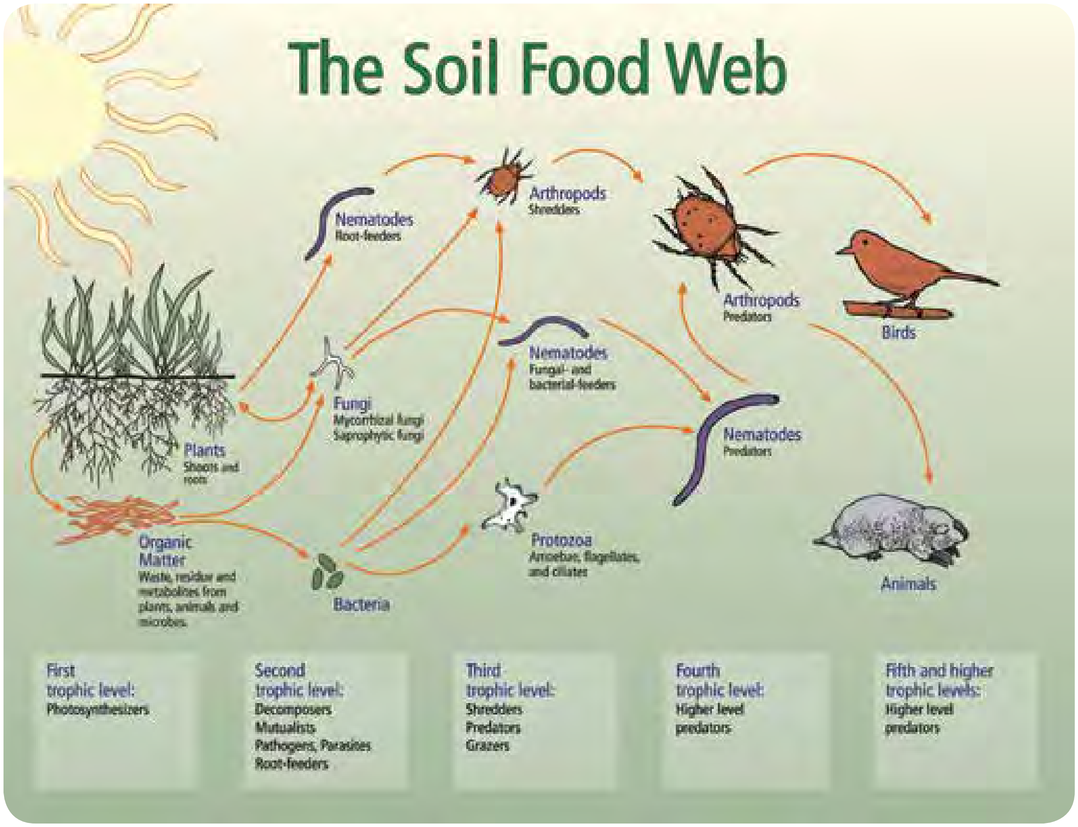

Figure 1. The soil biotic community, or soil food web, conceptualized as a series of trophic levels, each feeding on the preceding one. Ingham, E. R., A. R. Moldenke, and C. A. Edwards. 2000. Soil Biology Primer. Soil and Water Conservation Society (SWCS). Rev. ed. Ankeny, IA.

Ever since the dawn of organic agriculture in the early 20th Century, ecologically-minded farmers and ranchers have understood that "if you feed the soil, the soil will feed the plant." While early leaders such as Sir Albert Howard (1947) and Ehrenfried Pfeiffer (1943) intuited that soil organisms nourish plants, there were no research methods that could elucidate precisely how this occurs. As a result, mainstream agricultural scientists of their time discounted soil life and organic matter as key factors in soil fertility and plant nutrition (Montgomery, 2017).

Historically, producers and agricultural professionals have described the soil's capacity to meet the requisites for successful production—nutrients, moisture, aeration, workability, and stability—as *soil quality*. With growing understanding that only a living, biodiverse soil with sufficient soil organic matter (SOM) can sustain crop and livestock production over the long run, farmers and professionals have adopted the term *soil health*.

Over the past 30 years, extensive research has begun to elucidate the many trophic levels and functional groups of the soil food web, and how an optimally functioning soil biota feeds and protects crops, reduces risks, and strengthens farm economic viability (Ingham et al., 2000; Figure 1). For example, 20th century service providers cited the fact that soil microbes initially immobilize (tie-up) plant nutrients in organic residues as the reason organic farming "won't work." It is now widely understood that these nutrients are not lost but conserved, and that diverse soil organisms work together to recycle nutrients, protect water quality, provide for plant nutrition, and enhance crop resilience to stresses. Table 1 summarizes the roles of different soil organisms in key soil functions and ecosystem services.

Table 1. Soil Life and Soil Functions

	Soil Functions	**Some Key Organisms**
CROP PRODUCTION NEEDS		
Plant nutrition	Retains and recycles nutrients from organic residues	Decomposer bacteria and fungi, earthworms, arthropods*
	Delivers nutrients to plants.	Protozoa, nematodes, N fixing bacteria, mycorrhizal fungi
Plant-available moisture Drainage and aeration	Maintains SOM, aggregation (tilth), network of small and large pores, deep channels.	Bacteria (glues), fungi (mycelia), earthworms, arthropods, plant roots, (pores, channels, exudates)
Crop protection	Deters plant pathogens, nematode and other pests.	Pathogen antagonists, predators and parasites of pests
	Enhances plant disease and pest resilience.	Microbial symbionts that induce systemic resistance (ISR)
ECOSYSTEM SERVICES		
Water quality	Minimizes leaching and runoff. Retains nutrients.	Plant roots and cover, microbes that immobilize nutrients
Detoxification	Attenuates plant, animal, and human pathogens. Binds or destroys toxins.	Dung beetles, microbes that degrade organic wastes and pesticides, or bind heavy metals
Carbon sequestration	Builds stable soil organic matter (SOM).	Plant roots, fungi, bacteria, deep-burrowing earthworms
SOIL SELF-MAINTENANCE		
Stability against erosion	Protects soil surface, maintains soil aggregation.	Plant cover and roots, fungi (hyphae), bacteria (glues)
Resilience and tilth	Restores structure after tillage, grazing, traffic, or downpour.	Plant roots, earthworms, arthropods, fungi
Active and stable SOM	Digests manure and plant residues into SOM.	Decomposer bacteria and fungi, earthworms, arthropods
Food and habitat for soil life	Builds active SOM, maintains large and small pore spaces.	Plant roots (exudates), fungi, bacteria, earthworms, arthropods

* *Mites, springtails, ants, termites, ground beetles, dung beetles, centipedes, millipedes, etc.*

Since organic systems rely to a great degree on the soil food web for crop nutrition and crop protection, practitioners protect soil organisms by avoiding the use of synthetic chemicals. Organic farmers build soil life by adding compost and other organic materials, diversifying the crop rotation, growing cover crops, utilizing legumes to provide nitrogen (N), and integrating crops and livestock. They conserve soil life by limiting tillage, pesticide sprays, and concentrated fertilizers inputs (Baker et al., 2016; Schonbeck et al., 2017). In a meta-analysis of 56 studies conducted around the world, organically managed soils maintained 32 – 84% greater microbial biomass and enzyme activity than the same soils managed conventionally (Lori et al., 2017).

The explosion of information on soil life presents farmers at once with exciting possibilities and mind-boggling complexity. For example, vendors of organic amendments offer dozens of microbial inoculants and biostimulant products, which they claim will prevent disease, enhance nutrient uptake and plant growth, or improve soil food web function. The efficacy of specific products (e.g., mycorrhizal inoculant) or practices (e.g., cover crop) in optimizing soil biology or suppressing disease varies with climate, soil type, crop rotation, and production system. Thus, identifying the best inputs and practices for a particular site can be challenging.

The goal of this guidebook is to help organic farmers navigate the wilderness of soil life and soil health management by providing up-to-date, science-based information on:

- The soil food web, its key components, and functions.
- Assessing and monitoring soil life and soil biological condition.
- Managing soil life for long term soil health and productivity in organic systems.
- Biological management of plant diseases.
- Microbial inoculants and biostimulants: whether, when, and how to use them.

Soil Biology 101

The community of soil life or soil food web consists of:

- Soil organisms, including:
    - *Microbiota* or *microbiome* – bacteria, archaea (a separate group of bacteria-like microbes), fungi, protozoa, and small nematodes.
    - *Mesofauna* – mites, springtails, larger nematodes, and other organisms 0.1 – 2 mm (1/250 – 1/12 inch) in length.
    - *Macrofauna* – larger insects, earthworms, mollusks, burrowing vertebrates, etc.
- Their food, water, and air supply.
- Their habitat or living space.
- Plant roots.
- The web of trophic (food chain), cooperative (symbiotic), and antagonistic (competitive, parasitic, or antibiotic) relationships among soil organisms and plant roots.

With a total live weight of 1,700 – 27,000 lb/ac, the soil biota accounts for just 1 – 5% of total SOM (Weil and Brady, 2017), yet they regulate essentially the entire stock of SOM. Recent research indicates that nearly all stable SOM ("humus") is derived from microbial processing of plant residues, and consists largely of microbial remains and metabolites tightly adsorbed to soil minerals (Kallenbach et al., 2016). As soil organisms digest fresh residues and active SOM for their own nutrition and growth, they provide both crop nutrition and long term SOM stabilization and carbon (C) sequestration (Figure 2).

Many farmers consider the soil life their "underground livestock," which they must keep fed, watered, and sheltered as they do their herds and flocks.

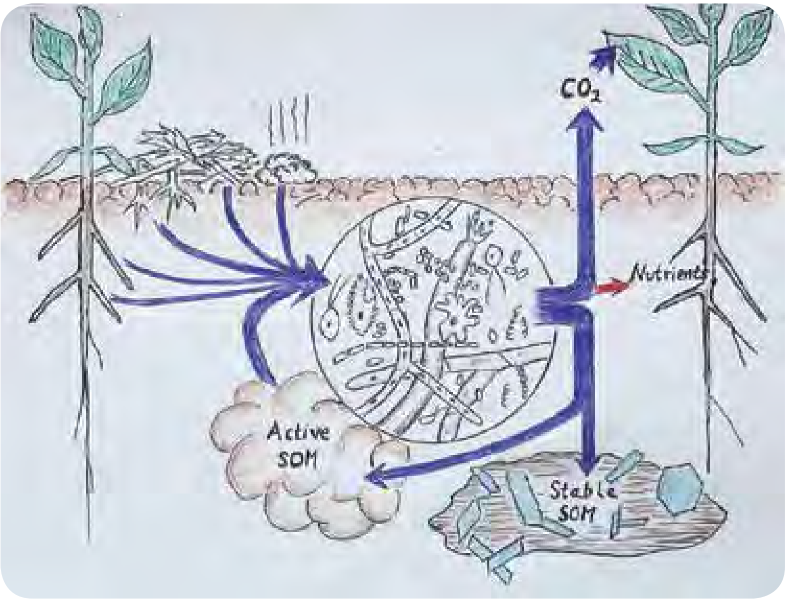

Figure 2. Soil life plays a central role in plant nutrition, soil health, and the global carbon (C) cycle. Soil organisms process all organic inputs from plants, animals, and their remains, releasing some as respiratory carbon dioxide (CO2) and plant nutrients, and converting the rest into new biomass and ultimately soil organic matter (SOM). The active fraction of SOM undergoes further processing, while stable SOM remains sequestered for decades to millennia.

Soil biodiversity, habitats, and functional groups

Most soils show incredible biodiversity, with thousands of microbial genotypes and hundreds of meso- and macro-fauna species present in a single handful of topsoil (Weil and Brady, 2017). This diversity allows the soil life to adapt in response to seasonal shifts in temperature, moisture, and plant community; and to disturbances such as fire or grazing. Agricultural soil food webs change dynamically over time in response to crop rotation phase, tillage and other field operations, and weather conditions. In addition, soil microbial communities evolve continually by sharing genetic material in a process known as “horizontal gene transfer,” that renders the very concept of “species” difficult to define (Weil and Brady, 2017). Thus, in lieu of attempting to catalogue the soil biota by species, soil scientists focus on functional groups of soil organisms and their roles in agricultural production (Table 2).

Table 2. Some key functional groups of soil organisms

Functional group	Energy and carbon source	Organisms
Photosynthesizers	Sunlight + atmospheric CO_2.	Plants, algae, cyanobacteria
Chemo-autotrophs*	Inorganic compounds + CO_2	Specialized archaea and bacteria
Decomposers	Organic residues	Bacteria, fungi
Grazers	Bacteria, archaea, fungi	Protozoa, nematodes
Predators	Various soil organisms	Nematodes, arthropods
Shredders	Organic residues + microbes	Micro-arthropods
Ecosystem engineers	Organic residues + organisms	Earthworms, termites, ants, dung beetles
Plant symbionts	Living plant roots	Rhizobia, other N_2 fixers, mycorrhizal fungi, other beneficial endophytes
Plant pathogens and herbivores	Living plant tissue	Pathogenic fungi and bacteria, root-feeding nematodes, grubs, rodents, etc.

** These include microbes that oxidize ammonium-N (nitrifying bacteria), sulfur, iron, and other micronutrients; they can play important roles in plant nutrition.*

Decomposer bacteria and fungi begin the process of recycling organic residues (dung, plant litter, etc.), initially immobilizing (binding) N and other nutrients that might otherwise be lost from the soil-plant ecosystem. Protozoa and small nematodes, collectively known as grazers, release plant-available nutrients as they feed on bacteria and fungi. Higher trophic levels of predators release additional nutrients and regulate populations of grazers and some plant pests.

Larger organisms, including mites, springtails, insects, and earthworms, facilitate microbial processes by shredding and incorporating organic residues into the soil. The soil's ecosystem engineers, including earthworms and dung beetles, play key roles in soil structure, drainage, SOM, and nutrient cycling. Earthworms ingest organic residues and mineral soil, excreting the latter as aggregated castings enriched in nutrients, SOM, and beneficial microbes.

Nitrogen-fixing microorganisms and mycorrhizal fungi play central roles in agricultural production, and in

“The diversity of substrates and environmental conditions found in every handful of soil spawns a diversity of adapted organisms that staggers the imagination. The collective vitality, diversity, and balance among these organisms make possible the functions of a healthy soil.” (Weil and Brady, 2017, The Nature and Properties of Soils, p 464).

all life on Earth. Without microbes equipped with nitrogenase enzyme to convert elemental nitrogen (N_2) into plant-available N, our crops, livestock, and humanity itself would be unable to access the atmosphere’s huge reserve of this essential element. N_2 fixers include nodule-forming plant-symbiotic *Rhizobium* and *Bradyrhizobium* bacteria in legumes, *Frankia* actinomycetes in several plant families of trees and shrubs, free-living N-fixing bacteria such as *Azotobacter,* which utilize organic residues or root exudates as carbon sources, and some of the photosynthetic cyanobacteria.

Mycorrhizal fungi associate with about 80% of plant species, including 70% of agricultural crops, growing into root tissues and extending into the soil, thereby vastly enhancing effective volume, and moisture and nutrient absorptive capacity of roots. Fossil evidence indicates that mycorrhizal fungi co-evolved with the earliest land plants more than 400 million years ago.

While mutualists like N_2-fixing microbes and mycorrhizal fungi repay their hosts’ investment of photosynthetic product, other plant-feeding soil organisms are “freeloaders” that can damage the plant. These include various fungal and bacterial pathogens, root-feeding nematodes, and soil macrofauna such as grubs, rootworms, and voles that eat plant tissues wholesale. In addition, *deleterious rhizobacteria* do not attack plants directly, but release substances that slow plant growth or otherwise cause subtle degrees of injury. An abundant and diverse soil microbial community generally reduces damage from plant pathogens.

Soil habitat diversity underpins soil biodiversity. Soil organisms inhabit the surfaces of soil mineral particles, surface and interior of organic materials and soil aggregates, and a network of pores and channels varying in diameter from less than 1 μm (a millionth of a meter, or

1/25,000th inch) to one inch or more. While soil biological activity is greatest in the topsoil, soil organisms extend at least as deep into the soil profile as plant roots. This mosaic of habitats offers a wide range of moisture and oxygen levels, temperature regimes, pH, and organic and mineral nutrient levels, and thereby supports soil microbial diversity that may be 1,000-fold greater than in aboveground or aquatic ecosystems (Williamson et al., 2017).

Microbial habitats also include plant root tissues and the digestive tracts of larger organisms such as mites and earthworms, where the microbes play vital roles in their hosts' nutrition and health. In turn, the daily activities of roots, earthworms, and other soil organisms continually re-create and maintain soil structure and habitat, including both air- and water-filled pore space.

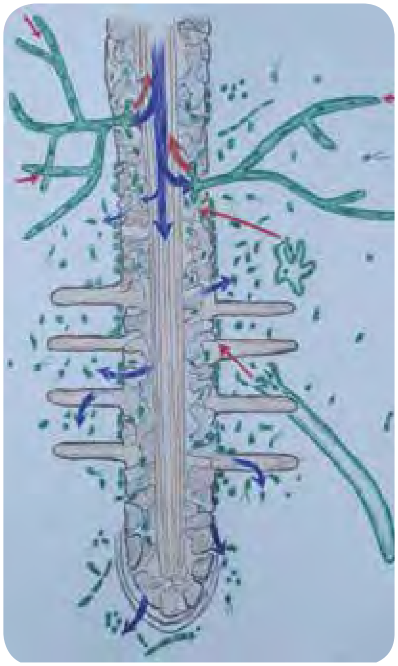

Figure 3 – The rhizosphere, or root zone, hosts great numbers and diversity of soil organisms (green). Nourished by plant photosynthetic product delivered via the root system (blue), bacteria and fungi multiply on or near the root surface, and some grow within root tissues as endophytes. Mycorrhizal symbionts and microbial grazers such as protozoa and nematodes provide plant-available nitrogen (N) and other nutrients (red).

The central role of plants in the soil food web

No soil ecosystem would survive without living plants, the bridge between above- and below-ground life, and the "solar collector" on which all terrestrial life depends. As the primary food source for the soil biota, as well as the main "consumer" of soil food web services, plant roots play a central role in the soil ecosystem. Roots occupy roughly 1% of the soil volume, account for a quarter to a third of total soil respiration, and create an enriched habitat for soil organisms known as the "rhizosphere" (Weil and Brady, 2017; Figure 3). Prolonged fallow periods without living roots put soil life on a "starvation diet," deplete SOM, and harm soil health (Engel et al., 2017; Moncada and Sheaffer, 2010).

The growing root feeds soil life by exuding sugars and other organic compounds, and by sloughing spent cells from the root cap and root surface. These inputs are collectively known as "rhizodeposition."

Plants also deliver organic materials directly to mycorrhizal fungi, N fixing-rhizobia (legumes), and other microbial symbionts. Many plants associate with *arbuscular mycorrhizal fungi* (AMF), whose mycelia grow out into the soil and into root tissues, where they form distinctive structures called *arbuscules* in which the mutualistic exchange of photosynthetic product for phosphorus (P), other nutrients, and moisture takes place. Forest trees and some other woody perennials host *ectomycorrhizal fungi*, which form a dense, close-fitting network of mycelia around the root to accomplish a similar exchange.

Mycorrhizal fungi can link root systems of different plant species to mutual benefit in forest, prairie, and agricultural ecosystems. A grass-legume crop mix features a four-way symbiosis, in which a single AMF mycelium can "ship" legume-fixed N to the grass, and surplus P absorbed by the grass to the legume (Figure 4). AMF can enhance N-fixing efficacy of legume nodule rhizobia, as well as rhizosphere species such as *Azotobacter* and *Azospirilum* (Drinkwater, 2011; Hamel, 2004).

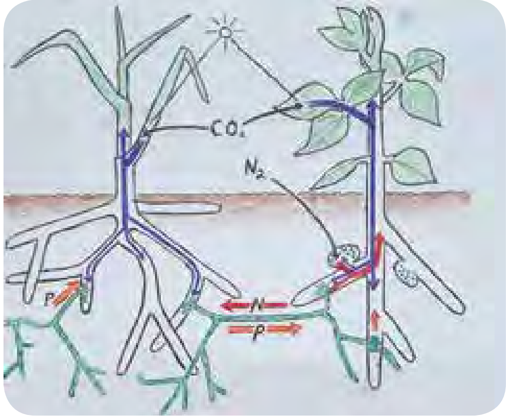

Figure 4 – A four-way symbiosis among grass, legume, rhizobia, and AMF fungi enhances forage vigor in pasture. The plants support their microbial symbionts with photosynthetic product (blue), while the rhizobia fix N (red) and AMF absorb P (orange) for their hosts. The grass is more effective in P uptake, and isotope tracer studies confirm that a two-way exchange of N and P takes place via AMF links between the two plant types. Based on information provided by Weil and Brady, 2017, page 501.

In healthy soils with low to moderate levels of soluble nutrients, plants may contribute 20 – 40% of their photosynthetic product to the soil life through rhizodeposition, mycorrhizae, and other symbiotic relationships. For example, legumes may invest 20% of their production in rhizobia (Grossman, 2010), and mycorrhizal hosts may contribute 5 – 30% to the fungus (Weil and Brady, 2017). However, when crops are well supplied with readily available N, P, and other nutrients, they share less of their energy with soil microbiota. While this saves photosynthetic output for plant production in the short run, it also limits soil biological activity and may hurt soil health in the long run (Khan et al., 2007).

In addition to sugars, starches, amino acids, and other microbial "food" compounds, roots release specific chemical signals that stimulate the growth of microbial allies or deter potentially harmful organisms. Chemical signaling travels both ways between roots and microbes. Legume nodulation results from "a complex biochemical conversation" between plant and rhizobia (Weil and Brady, 2017, p. 605), while plant species and AMF strains appear to select each other for greatest mutual benefit (Kiers et al., 2011). Corn roots respond to corn rootworm attack by releasing a compound that attracts entomopathgenic nematodes such as *Heterorhapbditis* and *Steinernema*, thus enhancing their efficacy when applied as biopesticides (Hiltpold et al., 2010).

Some soil organisms can play multiple functional roles. For example the entomopathogenic fungi *Beauvaria* and *Metarhizium*, marketed to organic farmers as biopesticides, can also grow as endophytes that improve nutrient uptake, plant growth, and pest resistance. Researchers at Pennsylvania State University have documented a single *Metarhizium* mycelium consuming an insect and growing into plant root tissues, transferring some N from former to latter (Gruber, 2017).

As the primary source of food for soil life, plant roots also play a central role in building stable SOM and sequestering carbon (C). Annual crops send about 25% of their photosynthetic product below ground into root systems growing 3 – 6 feet deep. Perennial prairie flora and forest trees send roughly half of their photosynthetic product into root systems that may extend to 15 feet or more (Weil and Brady, 2017). Roots build SOM throughout the soil profile, and are now believed to constitute the primary source of stable SOM (Kell, 2011; Rasse et al., 2005).

For more information on soil organisms and the soil food web, see **Resources 1 – 6** in the Resources listing on page 40, and Taxonomic Tour of the Soil Biota beginning on page 47.

The Downside of Earthworms

The common nightcrawler (Lumbricus terrestris, native to Europe) aids crop production by creating 6-ft deep channels for soil drainage and aeration, incorporating organic residues, and releasing plant-available nutrients. Yet, L. terrestris and several other earthworm species introduced from Europe have become invasive exotic pests of some North American forest ecosystems, in which trees, understory plants, and their fungal symbionts depend on a thick surface layer of plant litter and slowly-decomposing organic matter. In Minnesota, these exotic earthworms, likely brought in by fishers, have invaded boreal forests, rapidly degraded the surface organic layer, and upset nutrient cycling and native soil biota (Weil and Brady, 2017).

One research question that emerges here is whether high levels of earthworm activity could be similarly detrimental to some woody perennial crops or agroforestry production systems.

Organic Practices for a Living Soil

Challenges in managing the soil life for sustainable organic production

The sheer complexity of the soil biotic community creates challenges for farmers and agricultural professionals. This guidebook, along with other resources, can provide science-based practical information about the soil biota, but cannot give formulas for measuring and optimizing soil life for the following reasons:

- It is not practical to inventory the thousands of species in the soil biota in the way farmers track their crops, livestock, insect pests, and beneficial insects. Soil life is most often evaluated by total biomass, larger taxonomic groups, or functional groups.
- Producers need practical, reliable tools and methods for monitoring soil life. Protocols for in-field measurements of microbial respiration, active SOM, N mineralization, and earthworm populations exist but may be too time-consuming for busy farmers.
- It is not easy to predict the impacts of a particular input or practice on the soil food web or crop production. Benefits often vary widely from field to field and from year to year.
- Impacts of soil organisms depend on context. For example, while AMF benefit most crops, crucifers and chenopods may suffer a mild parasitism when colonized by AMF. Even the revered earthworm can damage some plant communities (see Sidebar).

The rich network of plant-soil-biota relationships gives healthy soils their resilience and lasting fertility. Organic practices generally enhance soil life. However, organic producers face several challenges, including:

- Organic production of annual crops generally requires some tillage and cultivation, which alter soil biota, fragment fungal mycelia, and damage earthworms and other macrofauna.
- Regular use of compost, manure, and some organic fertilizers can push soil phosphorus (P) to levels known to inhibit mycorrhizal fungi (Rillig, 2004). High rates can also flood the soil with soluble N, depress activity of N-fixing and N-cycling microbes, and weaken plant root-microbe interactions (Bhowmik et al., 2016, 2017; Dick, 2012).
- Modern crop cultivars, bred and selected for high-input conventional systems, may have lost some of their genetic capacity to partner with soil organisms for nutrient uptake, disease and pest resistance, and drought-resilience (Cobb et al., 2016; Goldstein, 2016; Hiltpold et al., 2010; Zubieta and Hoagland, 2017).
- Not all soil organisms benefit crop production, and even the best organic farmers will encounter serious soilborne plant diseases from time to time.
- Other potentially harmful organisms include invasive exotic plants that upset indigenous soil microbiomes (Wolfe and Klironomos, 2005), animal and human pathogens (e.g., in manure), and microbes that accelerate SOM breakdown or convert soluble soil N into the greenhouse gas nitrous oxide (N2O).
- Benefits of commercial microbial inoculants, biofungicides, and biostimulant products, are often inconsistent and difficult to predict.
- Finally, climate change may alter soil food web function. For example, warmer temperatures will likely accelerate the loss of SOM through microbial respiration.

Soil biology monitoring and assessment

The first step toward enhancing the soil life in a given field is to gain an understanding of its current condition. A good microscope can provide a direct look at soil bacteria, fungi, protozoa, and nematodes (Wander, 2015), but few farmers have time for the systematic sampling and counting needed to gather meaningful information. Most farmers assess soil biology through its visible effects, including prompt digestion of organic residues into SOM; dark, crumbly topsoil; visible earthworm castings; rain infiltration, drainage, and moisture retention; and crop resilience and yield. Some producers track abundance and activity of earthworms, ground beetles, other macrofauna, and visible fungal mycelia in their soil.

Total soil organic matter (SOM), interpreted in the context of soil texture (sand-silt-clay contents) and climate, provides a general index of soil biological function. However, total SOM responds slowly to improved management, and the "loss on ignition" procedure used by most labs is only moderately accurate. The dry combustion method for total soil organic carbon (SOC ~0.5X SOM) is far more precise but is not widely available to farmers (Soil Survey Staff, 2014). Several measures of "active" SOM respond more rapidly to management, but are not yet available on standard soil tests.

Laboratory methods to measure quantity (biomass), biodiversity, and activity (respiration, enzyme levels) of the soil microbiota have been developed, including genomic (DNA) and biochemical (proteins, fatty acids) analyses to characterize microbial community structure and function (Lori et al., 2017; Morrow et al., 2016; Sheaffer et al., 2016). Researchers use these measurements to determine impacts of management practices on soil biology, and are working to develop practical applications for farmers (Sheaffer et al., 2016).

Nematode community structure can also provide an index of soil condition. A diversity of bacterial and fungal feeding, predatory, and omnivorous nematodes suggests healthy, balanced soil, while a preponderance of bacterial feeders may reflect frequent tillage and excess soluble N (Ugarte and Wander, 2008; Ugarte et al., 2013).

Relatively simple lab methods have been developed to estimate two vital soil food web functions: *mineralization*, consumption of organic materials to release plant-available nutrients; and *stabilization*, conversion of organic materials into stable or long-lived SOM, important for long term soil health and carbon sequestration. A four day soil respiration assay to estimate *potentially mineralizable carbon* (PMC) reflects mineralization, and a procedure to measure *permanganate-oxidizable organic carbon* (POX-C) reflects stabilization. Both PMC and POX-C are positively correlated with microbial biomass, total SOC, and crop yield (Hurisso et al., 2016; Morrow et al., 2016).

An increase in microbial activity indicates that soil health is improving, provided the functions of mineralization and stabilization are in balance. Two indicators of this balance are *microbial growth efficiency* (MGE), the proportion of organic inputs that become new microbial biomass; and *metabolic quotient* (qCO_2), respiration rate per unit microbial biomass (Figure 5). Abundant soil fungi tend to enhance MGE, and organic systems can maintain higher MGE than conventional (Kallenbach et al., 2016; Grandy and Kallenbach, 2015).

Increased qCO_2 indicates greater use of organic residues for maintenance respiration at the expense of microbial growth and SOM accrual, and can result from stresses such as intensive tillage, prolonged fallow, or excessive soluble N (Dick, 1992; Lori et al., 2017; Zuber and Villamil, 2016).

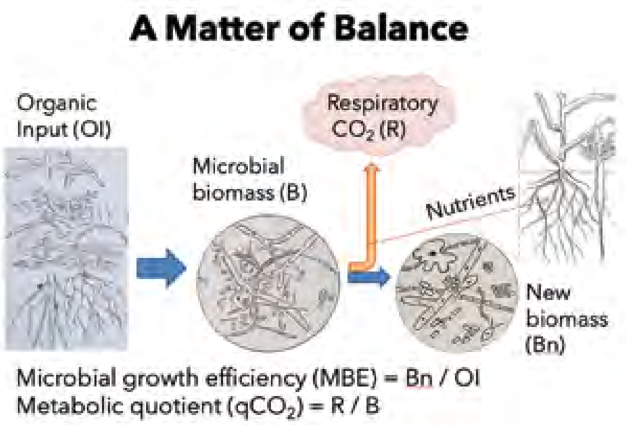

Figure 5. Two parameters describe the balance between the processes of mineralization (respiration and release of plant nutrients) and formation of new microbial biomass. Ratios are calculated on the basis of carbon (C).

In summary, methods that farmers can use to monitor soil biological function, from the simplest to the more advanced include the following:

- Visual assessments of soil health: color, tilth (aggregation), surface porosity (rain infiltration), drainage, and resistance to root growth (test with wire field flag).
- Crop performance and resilience to diseases, drought, and other stresses.
- Total SOM (track trends in soil test reports).
- Crop nutrition from soil (how much fertilizer is needed to sustain yield).
- Earthworm counts, other macro organisms, and visible fungal mycelia (especially in perennial crops with no or minimal soil disturbance).
- Lab tests for PMC and POX-C, or a soil health test such as the Cornell Comprehensive Assessment of Soil Health (CASH, Moebius-Clune et al., 2016).
- Participation in funded research projects to assess soil life through more sophisticated tests such as microbial biomass, enzyme assays, or microbial community analysis.

For more on monitoring soil biological activity, see **Resources 7 – 9** on page 41.

Managing soil biology for optimum soil, crop, and environmental health

Generally, organic practices that build SOM also enhance soil biology. Requirements for a thriving soil food web include adequate food, water, air, and habitat, as well as an abundance and diversity of organisms. In agricultural fields, insufficient food or habitat often limits soil biological activity. The "food" consists of sugars, amino acids, and other organic materials that soil organisms can utilize for energy and nutrition. Practices and amendments that build soil structure and porosity provide habitat (physical spaces and surfaces for organisms of different sizes and needs) and build the soil's capacity to hold sufficient water and air to sustain soil life. No single input meets all of these needs; for example, compost tea adds organisms, succulent plant residues provide food, and soil conditioners such as biochar mainly build habitat. Thus, experienced organic farmers use diverse and complementary inputs to sustain the soil biotic community (Table 3).

Table 3. Soil food web needs provided by different organic inputs.

Sources	Organisms	Food	Habitat
Living plants (roots)		XXX[1]	XXX
Plant residues, green		XXX b	
Plant residues, dry		XXX f	XX
Manure	XX	XXX	
Compost, worm castings	XXX	X	XXX
Organic fertilizers		X	
Biochar, humates			XXX
Compost tea	XXX	X	
Microbial inoculants	XXX		

[1] XXX = major source, XX = secondary source, X = minor; b = bacterial food; f = fungal food

The USDA Natural Resources Conservation Service (NRCS) has established four Principles of Soil Health: keep soil covered, maintain living roots, diversify crops, and minimize soil disturbance (USDA NRCS). These principles provide a good basic roadmap for optimizing soil biology. Plant roots play a leading role in providing food and habitat (Table 3), and soil life thrives in direct proportion to annual plant biomass production, percent of the year in plant cover, and the depth, extent, and duration of living roots. In addition cropping system diversity supports soil microbial diversity (Tiemann et al., 2015).

Practices that support soil life include the following:

- High biomass, mixed-species cover crops.
- Tight, diversified crop rotation with minimal fallow time.
- Intercropping and relay planting.
- Perennial sod phase in the rotation.
- Living plant cover for orchard floor, vineyard, and berry crop alleys.
- Agroforestry, alley cropping, and silvopasture.

Organic farming protects soil life by avoiding the use of synthetic fertilizers, pesticides, herbicides, fungicides, and nematicides, thereby minimizing chemical soil disturbance. While some tillage and cultivation—physical soil disturbances—are needed to manage weeds and cover crops in annual crop production, tillage tools and methods can be selected to minimize negative impacts on soil biota (see Concept #1). Some invasive exotic plants can create *biological* soil disturbance by releasing root exudates harmful to indigenous soil microbiomes; these plants should be excluded or controlled. Examples include garlic mustard in New World forests, and diffuse knapweed in western U.S. range (Wolfe and Klironomos, 2005).

Can Soil Organisms Live with Tillage?

Tillage strongly affects soil life. Plowing turns homes upside down, while disking or rotary tillage pulverizes aggregates and destroys microbial habitat. Most tillage kills some earthworms and other macrofauna, and fragments fungal mycelia. Tillage stimulates the growth of bacteria and their consumers (protozoa, nematodes), and speeds mineralization of SOM and nutrients. However, several tools can mitigate the impacts of necessary tillage on soil life.

Microbial biomass and function in organic systems remains higher in chisel-plowed or shallow (3") tilled soils than moldboard-plowed or disked soils (Sun et al., 2016; Zuber and Villamil, 2016). The spading machine works deeply without inverting, pulverizing, or compacting the soil, and can improve vegetable yields over plow-disk. (Cogger et al., 2013). The blade plow undercuts cover crops, leaving residue on the surface and most of the soil profile undisturbed, conserving moisture and soil health in dry regions (Wortman et al., 2016).

Ridge tillage and strip tillage stimulate microbial activity and mineralization within crop rows where the released nutrients are utilized efficiently, while leaving SOM, fungi, and microfauna intact in the undisturbed soil between rows. In ridge tillage, mid-season cultivation and ridge building moves additional organic residues into the crop rows. This approach, known as “soil functional zone management,” has been shown to support both mineralization and stabilization functions of the soil food web (Williams et al., 2017). Compared to moldboard plow, either ridge or shallow tillage significantly protects AMF (Bowles et al., 2017).

For more information on reduced-tillage strategies, see the Soil Health and Organic Farming Guide on Practical Conservation Tillage, available at ofrf.org.

Organic amendments such as compost play an important supplementary role in building soil biology. For example, while succulent green manures stimulate mineralization and finished compost favors SOM stabilization, cover crops with compost or manure can build more active and stable SOM, microbial activity, and fertility than either practice alone (Delate et al., 2015; Hooks et al., 2015; Hurisso et al., 2016). A balanced ratio of carbon to nitrogen (C:N) in organic inputs supports both mineralization and stabilization. Compost based on dairy manure, bedding and yard waste (moderate C:N ratio) builds far more SOM and sustains higher microbial activity than poultry litter (low C:N) (Bhowmik et al., 2017). When applied alone, nutrient-poor residues such as corn stover (C:N>35:1) also build less SOM, since microbes become N-limited and simply "respire-away" the excess C (Grandy and Kallenbach, 2015).

Integrating crops and livestock, an important principle since the beginning of the organic movement (Howard, 1947; Pfeiffer, 1943), can enhance soil life if grazing is managed well. While continuous grazing degrades pastures, *management intensive rotational grazing* (MIG), in which brief (1-3 days) intense grazing is followed by a sufficient recovery period (1 – 6 months depending on climate, season, and pasture condition), enhances forage vigor, root growth, rhizodeposition, and dramatically increases SOM (Teague, 2016-17). Rotational grazing of cover crops or the sod phase of a crop rotation can build cropland soil biota and SOM, and livestock-crop integration has been recognized as the fifth core principle of soil health (Brown, 2018). See **Resources 10, 11c**, and **11f** on pages 41 and 42 for more on MIG.

Individual organic inputs or practices have distinct impacts on soil life and soil processes (Table 4). Different suites of practices can build stable SOM, enhance mineralization and plant nutrition, or degrade SOM and soil life (Figure 6). Sustainable organic farming systems that maximize living root biomass, diversify crops, and balance input C:N can enhance both mineralization and stabilization of SOM, as well as total microbial biomass, diversity, and activity (Hurisso et al., 2016; Lori et al., 2017; Morrow et al., 2016; Osterholz et al., 2017).

Table 4: Effects of farming practices on soil organisms and functions.

Practice	Increases	Decreases
INPUTS		
Manure	Bacteria, protozoa, bacteria-feeding nematodes; SOM (if moderate C:N)	Mycorrhizal fungi (if P builds up) SOM (if low C:N)
Compost	SOM stabilization	Mycorrhizal fungi (if P builds up)
Green crop residues	Bacteria, SOM & N mineralization	
Dry crop residues	Beneficial fungi	Short term N mineralization
Concentrated NPK	Breakdown of high-C:N residues and SOM, qCO_2	N fixing & N-cycling microbes, mycorrhizal and other fungi.
CROPPING SYSTEM		
Diverse rotation without fallow	SOM, microbial diversity, nutrient cycling.	
Cover crops	Microbial biomass, active SOM, tilth (soil aggregation), mycorrhizal fungi (grasses, legumes)	N leaching
Sod phase	Active & stable SOM, biomass & diversity of most soil organisms, tilth, nutrient cycling	N leaching, erosion, compaction
Unplanted fallow	Soil erosion & compaction, nutrient losses	All soil life, especially plant symbionts, SOM, nutrient cycling
Livestock integration	Active and total SOM, nutrient cycling, most soil organisms	Mycorrhizal fungi if P excesses accumulate.
TILLAGE		
Routine tillage (at least one pass/year)	Bacteria, protozoa, bacteria-feeding nematodes; mineralization	Most fungi, earthworms, other macrofauna, SOM stabilization
Intensive tillage	qCO_2, mineralization, soil erosion	All soil life, SOM, tilth
No-till, reduced till	Fungi, macrofauna, SOM stabilization	Mineralization of SOM & N, some bacteria

Fine-tuning the system: crop-preferred microbiomes

Different crops may prefer different rhizosphere microbiomes. In healthy soil, most crop species can recruit (through chemical signaling) the soil organisms they need to thrive. Yet, soil biology management practices can be adjusted for the crop. For example, vegetable crops in the crucifer and chenopod families prefer a "bacteria-dominated" soil food web and do not benefit from AMF symbiosis. Moderate tillage, near-neutral soil pH, succulent green manures, and higher-analysis organic amendments generally favor these crops by promoting the growth of bacteria and their grazers, which enhance N mineralization (Figure 6, top right). However, *intensive* tillage and over-application of soluble NPK can develop an excessively bacterial-dominated and fungal-depleted soil biota; encourage the growth of "nutrient-responder" annual weeds such as pigweed, lambsquarters, and foxtails; intensify maintenance respiration and qCO_2; and reduce microbial growth, active and stable SOM, nutrient retention, and overall soil health (Dick, 1992; Lori et al., 2017; Morrow et al., 2016; Zuber and Villamil, 2016; Figure 6, bottom).

Grains, legumes, forages, and some vegetables especially allium and solanaceous families, thrive with a balanced mix of bacteria and fungi, including AMF. Reduced tillage, mixed-species cover crops, diverse organic inputs with moderate C:N ratio (~20:1), and nutrient management for sufficient but not surplus N and P promote this balanced microbiome, build soil biodiversity, biomass, and SOM (Figure 6, top left).

Fruit and nut trees, grape vines, and other perennial horticultural crops prefer a fungal-dominated soil microbiota. Many rely on specific ecto-mycorrhizal symbionts for nutrition and moisture uptake. Woody, decay-resistant organic amendments, an undisturbed soil profile (no tillage), and continuous ground coverage with living vegetation and/or organic mulches support a soil microbiome dominated by beneficial fungi.

Building Biomass and Stable SOM

Promoting Mineralization

Stressed Soil Microbiome

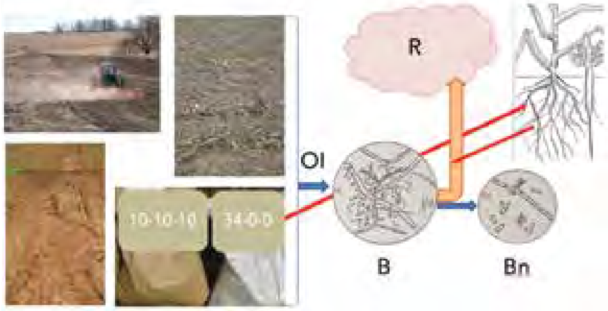

Figure 6. Top Left: Mature cover crops, finished compost, and reduced tillage build stable SOM and enhance microbial growth efficiency (MGE). Top Right: Succulent green manures, tillage, and higher-analysis organic fertilizers promote SOM mineralization and nutrient release to the crop. Bottom Left: Excessive tillage, unplanted fallow, and inadequate residues reduce microbial growth, elevate metabolic quotient (qCO2), and burn up SOM, even when organic fertilizers are used. OI = organic inputs;
B = microbial biomass; Bn = new microbial biomass;
R = respiratory CO2.

Plant-soil-microbe interactions contribute to the "rotation effects" in which the performance of a given crop is affected by the preceding crop(s). For example, mycorrhizal host cash crops benefit from winter cereal grain or legume cover crops, which provide a "green bridge" to sustain AMF populations, while non-mycorrhizal crucifer cover crops or winter fallow may reduce AMF populations and delay colonization of the cash crop. In the mid-Atlantic region, spring-planted spinach gives better stands and yields after a fall cover crop of tillage radish than after legume or cereal grain covers. Residues of the crucifer may favor spinach by suppressing fungal pathogens as well as AMF, which are not beneficial to spinach.

Fine-tuning the system: nutrient cycling, N_2 fixation, and mycorrhizal fungi

Microbial N mineralization converts soil organic N into ammonium (NH_4^+) N, but most crops utilize nitrate (NO_3^-) N more effectively. Thus *nitrifying bacteria*, which derive energy by oxidizing NH_4-N to NO_3-N, play a significant role in crop nutrition. Since NO_3-N is readily lost to leaching, runoff, or denitrification into N_2O, efficient N cycling that meets crop N needs without flooding the soil with soluble N is a vital function of the soil life. Organic production of heavy feeders such as corn, broccoli, or tomato can lead to N losses if crop needs are met with concentrated N sources such as feather meal or poultry litter (Bowles et al., 2015; Han et al., 2017; Li et al., 2009).

Organic crop rotations that derive half or more of their N requirement via N_2 fixation can improve N efficiency and reduce losses. In addition, researchers in California have documented *tightly coupled N cycling* in some organic tomato fields, which gave top yields despite low, non-polluting NO_3-N levels (Bowles et al., 2015; Jackson, 2013). These fields:

- Had a long history of organic practices, high SOM, and high microbial activity.
- Received finished compost (moderate C:N) as their primary nutrient source.
- Received small amounts of concentrated N banded in crop rows.
- Showed high levels of enzymes associated with N cycling.

Some tips for optimizing biological N cycling include:

- Manage soil to maintain low-to-moderate soluble N levels.
- Select organic inputs to balance C and N; include finished compost.
- Use concentrated N sparingly, band or drip-fertigate in crop rows.
- Design crop rotations for biodiversity and year-round living roots.
  - Include legumes for N_2 fixation and deep-rooted crops to scavenge soluble N.

Mycorrhizal fungi play multiple roles in nutrient cycling, and crop and soil health (Rillig, 2004). The mycorrhizal symbiosis effectively expands the root system several-fold, and:

- Enhances moisture uptake and drought resilience, reduces irrigation costs.
- Enhances nutrient uptake efficiency, reduces fertilizer costs.

- Mobilizes P and micronutrients from insoluble soil minerals.
- May reduce N_2O emissions by helping plants “mop up” excess moisture and N.
- Releases sugar-proteins (*glomalins*) that stabilize SOM and soil aggregates.
- Protects host plant roots from pathogens.

Some tips for promoting AMF activity and diversity in annual crop rotations include:

- Manage for optimum soil biology (see Concept #2).
- Follow non-AMF crops (crucifers, chenopods, buckwheat, amaranth), with grain, legume, or other strong host to restore AMF populations.
- Avoid full-field soil treatments with fungicides, including biofungicides and other NOP-allowed materials, and vinegar-based herbicides, which can harm mycorrhizal fungi.

Some tips for promoting ectomycorrhizal activity in woody perennial crops include:

- Treat root balls of new planting stock with a suitable ectomycorrhizal inoculant.
- Amend soil surface with chipped brush, bark, leaves, and other woody materials.
- Maintain mildly to strongly acidic soil pH, depending on crop needs.
- Avoid tillage. Control weeds in new plantings with weed mat or organic mulch.
- Maintain alleys and orchard floor in living plant cover once crops are established.

Best Management Practices for Soil Life

- Feed the soil biota via plant roots – maximize year round living plant cover.
  - Maintain dormant vegetation or surface residues during dry or frozen seasons.
- Supplement with finished compost or mixed amendments with balanced C:N.
- Diversify the farming system with:
  - Crop rotation, cover and sod crops, intercropping, relay planting.
  - Perennial plantings.
- Integrate livestock with crops; use management-intensive rotational grazing (MIG).
- Reduce tillage when practical, and minimize other disturbances including:
  - Excessive nutrients, especially N and P.
  - Fallow periods without plant or residue cover.
  - Invasive exotic plant species.
- Adjust crop rotation, cover crop species, and management practices for site specific factors, including: climate, rainfall, soil type and condition, and production system.

For more on managing soil life and nutrients see **Resources 10 – 13** on pages 41-43, and the Soil Health Guides on Nutrient Management and Cover Crops at https://ofrf.org.

Biological Management of Crop Diseases

Figure 7. The plant disease triangle, in which a susceptible host (H) growing in the presence of a pathogen (P) in environmental conditions favorable to the pathogen (E) results in visible disease.

The biotic communities of most agricultural soils include some organisms that can harm crops. For example about 10% of soil nematodes feed on plant roots (Weil and Brady, 2017). Plant pathogens include virulent strains of *Pythium, Rhizoctonia, Phytophthora, Alternaria, Fusarium*, and *Verticillium,* which cause damping-off, root rot, or foliar symptoms; and root-knot nematodes (*Meloidogyne* spp.), which block the roots internally and interfere with root function. These organisms cause serious production problems when a *conducive environment* and a *susceptible host crop* allow them to multiply and cause disease (Figure 7).

Healthy, biologically active soils with ample SOM and good tilth and drainage generally reduce plant disease problems. Such soils produce vigorous, resilient crops, and their abundant benign microbes tend to crowd out pathogens (general disease suppressiveness). In addition, biodiverse soils include more natural enemies (predators or parasites) of pathogens than soils with lower microbial diversity, as observed in organic *versus* conventional lettuce fields in California (Ariena et al., 2015). Soil biodiversity can also protect livestock and human health; for example, increased activity and diversity of dung beetles and manure-decomposing bacteria on organic farms help control pathogenic *E. coli* and livestock parasites (Jones et al., 2019).

Some soil microbes elicit a plant immune response called *induced systemic resistance* (ISR), which can protect plants against foliar as well as soilborne pathogens. For example carrot roots host a diversity of endophytic microbes, including *Pseudomonas* spp., which enhance crop vigor and resistance to carrot leaf blight (*Alternaria dauci*). Carrots growing in healthy, organically managed soils have higher populations of these protective organisms than conventionally grown carrots (Abdelrazek, 2018). The soil fungus *Trichoderma harzianum*, which parasitizes several root-pathogenic fungi, can also contribute to ISR in tomato (Zubieta, and Hoagland. 2017).

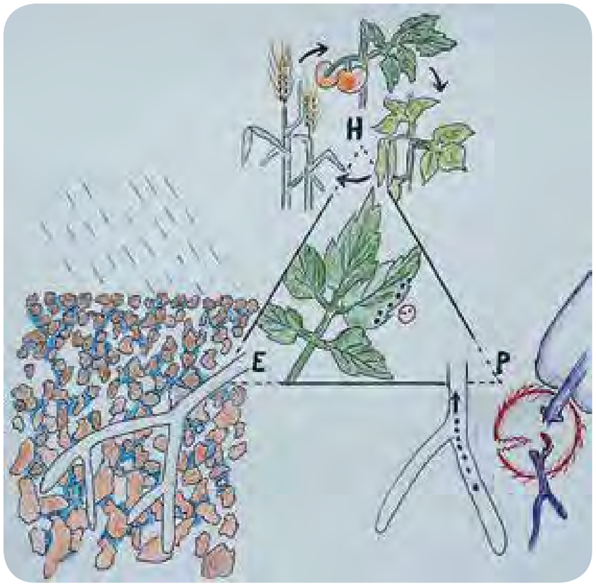

Figure 8. Soil health practices reduce crop disease in several ways. Improved physical soil condition leads to better drainage and aeration, making the environment (E) less favorable for many pathogens and more so for crop roots. Increased soil biodiversity often includes natural enemies (blue) that consume pathogens (P), or release chemical signals that induce systemic disease resistance (blue dots). Crop rotation reduces disease risks by alternating the host crop (H) with non-susceptible crops from different plant families.

Soil health management practices can reduce disease problems by “breaking” one or more legs of the plant disease triangle (Figure 8). Crop rotation removes the susceptible host for sufficient time to control some pathogens (see **Resource 14** on page 43). Cover crops improve soil tilth and drainage, and can be roll-crimped to create mulch that protects pumpkins and other fruiting vegetables from soilborne pathogens (Stone, 2012). Deep-rooted cover crops like sudan-grass penetrate subsurface hardpan, improve soil aeration, and thereby reduce root rot in a subsequent snap bean crop (Wolfe, 1996). Organic amendments suppress pathogens by stimulating a burst of competing microbial growth (e.g., raw manure, succulent green manures); promoting natural enemies of pathogens; releasing compounds toxic to pathogens (hardwood bark, sorghum or crucifer residues, etc.); improving soil structure and drainage; or stimulating plant ISR response (Eastburn, 2010; Wang and Mazzola, 2019).

Nevertheless, serious diseases can affect crops even on the best-managed organic farms (O’Brien et al., 2016), and some wind-borne epidemics such as late blight and downy mildew can sweep through an entire region. Such threats necessitate an integrated strategy of disease-resistant cultivars, crop rotation, biological controls, and judicious use of copper and other disease-control products allowed by USDA National Organic

Program (NOP) standards (Hoagland et al., 2018). Varietal resistance is an important tool for organic disease management but cannot alone prevent all disease. Pathogens rapidly evolve the capacity to overcome *vertical disease resistance* based on a single genetic trait, while varieties with *horizontal resistance* based on several genetic traits typically confer stable but partial disease resistance. In nationwide and statewide (Ohio) surveys, organic farmers cited biologically based crop disease management as a high priority for organic systems research (Jerkins and Ory, 2016; McSpadden Gardener, 2013).

Biological strategies for plant disease management include the following:

- Incorporating cover crops or organic residues to release substances toxic to pathogens, sometimes with tarps or plastic mulch to retain the toxin ("biofumigation").
- Modifying the soil environment to become less favorable to the pathogen and more favorable for its natural enemies and/or the host crop.
- Adding organisms that consume, parasitize, or otherwise suppress the pathogen.

Soil habitat modifications

Organic alternatives to conventional soil fumigants include *soil solarization, biofumigation, biosolarization*, and *anaerobic soil disinfestation*, which kill pathogens through heat, oxygen deficit, and/or release of natural toxins. While the biocidal effects are short-lived, these treatments can cause a shift in soil microbiome that provides lasting disease suppression.

Crucifers and their residues contain a group of compounds called *glucosinolates*, which soil organisms degrade into *isothiocyanates* that are toxic to plant pathogens. In one biofumigation procedure, a glucosinolate-rich cultivar of mustard or other crucifer is grown to high biomass, chopped, tilled, and sealed-in by irrigation, rolling or cultipacking (See **Resource 16d**, page 44). Similarly, amending soil with mustard seed meal, a byproduct of oil production, can suppress the pathogen complex responsible for "apple replant disease". However, the benefits apparently result not from biofumigation *per se*, but from a proliferation of disease-suppressive micro-organisms stimulated by the seed meal (Mazzola et al., 2015). High-glucosinolate crucifer green manure crops may also prevent disease by "feeding" pathogen antagonists.

Biosolarization combines incorporation of cover crop residues or other organic materials with solarization under clear plastic for 4 – 6 weeks to kill weeds, pest nematodes, and pathogens (Tubeileh, 2018). In addition to killing pathogens by heat, this treatment stimulates the growth of disease-suppressive microbes and promotes plant ISR responses (Egel et al., 2018)

Anaerobic soil disinfestation (ASD) was first developed by greenhouse growers in the Netherlands and Japan, and recently adapted for field production of organic strawberries in California. In ASD, a carbon source such as rice hulls is tilled in at 5 – 9 tons/ac, after which the soil is watered to saturation and covered with plastic mulch for 3 – 6 weeks. The resulting burst of anaerobic microbial activity kills some pathogens and may also modify the soil microbiome to favor long-term disease suppression (Shennan et al., 2015; Mazzola, 2017). When implemented just before strawberry planting in a four year vegetable-strawberry rotation, ASD reduced populations of the virulent strawberry pathogen *Verticillium dahliae* by 80%, and improved yields and net returns (See **Resources 16a** and **16b**, page 44). Although the anaerobic period might deliver a significant "jolt" to the soil food web, the technique is at least as effective as methyl bromide, with far less harm to soil and environment. It has been widely adopted by organic and other farmers in California (Shennan et al., 2014).

Clubroot is a severe disease of cabbage and other cruciferous vegetables. The causal pathogen *Plasmodiophora brassicae* can persist many years in the soil, and multiplies in conditions of high moisture and acidic pH (<6.5). Researchers at Oregon State University have developed an integrated management strategy of long crop rotation (one year crucifer followed by six years in unrelated vegetable, grain, and cover crops); other soil health practices (compost, reduced till) maintaining near-neutral pH; and care to avoid over-irrigation. This strategy reduced clubroot incidence to below economic thresholds (see **Resource 16f** on page 44).

Common scab of potato, caused by the actinomycete *Streptomyces scabies*, is one disease that can be suppressed by keeping the soil fairly acidic. Potatoes can yield well at a pH of 5.5, which is sufficiently acidic to inhibit the scab-causing pathogen.

Biofungicides

Vendors of organic input products market a growing array of beneficial soil organisms, formulated as biofungicides to prevent or control plant diseases. Some of these products act specifically against a certain pathogen or group of pathogens, while others suppress a wider range of pathogens or enhance crop disease resistance. Efficacy can vary with soil and weather conditions, management system, product formulation, and method of application, as well as the quality of the research upon which the product is based. Biofungicides are most effective when used as one component of an integrated disease management strategy.

The soil-dwelling fungus *Coniothyrium minitans* is a specific parasite of the plant pathogen *Sclerotinia sclerotiorum,* which causes white mold, a serious disease of soybean, dry bean, and vegetable crops (Pethybridge and Ryan, 2018; Stone, 2014). Soil treatment with a commercial formulation of *C. minitans* has facilitated management of white mold through crop rotation and sanitation, and a single application increased parasitism of the pathogen's sclerotia (propagules) for several years (See **Resource 16j** on page 45).

Trichoderma, another fungal genus, has been formulated and marketed as a biofungicide for control of a wide range of plant diseases. *Trichoderma* can play multiple roles, growing as beneficial root endophytes that enhance crop vigor, ameliorate stresses related to saline-alkaline soils, and induce systemic resistance to foliar diseases, as well as parasitizing a wide range of pathogenic fungi (Colla et al., 2017; Fu et al., 2019; Zubieta and Hoagland, 2017).

Soil organisms that have been formulated and marketed as biofungicides include selected strains of the fungi *Gliocladium catenulatum, G. virens, Trichoderma harzianum, T. virens,* and *Aureobasidium pullulans;* the bacteria *Bacillus mycoides, B. amyloliquifaciens,* and *B. subtilis;* and the actionbacterium *Streptomyces lydicus,* (Seven Springs Farm, 2019). Research indicates that each of these organisms can outcompete or attack target pathogens, elicit ISR, or both.

Tips for Successful Biological Management of Plant Diseases

- Build the foundation: manage for optimum soil health and soil food web function.
- Get to know the *locally-prevalent* pathogens of each crop grown, including:
  - Life cycle, seasonal patterns, conditions that favor disease development.
  - Known microbial antagonists and effective management strategies.
- Diversify crops and design the crop rotation to deter these pathogens.
- Plant disease-resistant cultivars that are:
  - Regionally-adapted.
  - Developed for organic production systems.
  - Protected by *horizontal resistance*, based on multiple genes.
- Modify soil microbiome to suppress pathogens known or likely to be present – green manure, mustard meal or other amendments, anaerobic soil disinfestation, etc.
- When disease symptoms occur, get a *positive identification* of the causal pathogen.
- Use disease biocontrol products effectively:
  - Select product labeled for the identified pathogen(s)
  - Store materials carefully and apply before expiration date.
  - Apply when disease may be imminent, but *before* symptoms appear.
  - Apply as directed on label (seed or root treatment, whole field spray, etc).
  - Do not tank-mix biologicals with fungicides with a chemical mode of action, such as copper, sulfur, or peroxides.
- Conduct side-by-side trials of different varieties or biological control treatments.
  - Repeat trials over two or three years.
  - Remove visibly diseased cultivars or treatments before the pathogen spreads.
- If other disease-control treatments are needed, choose those least disruptive to soil life.
  - Some newer copper (Cu) formulations are effective at low Cu rates.
  - Ensure that all materials used are compliant with NOP rules.

For more on biological plant disease control, see **Resources 14 – 16** on pages 43-45.

Soil Restoration on a Large Scale

When rancher and author Gabe Brown purchased 5,000 acres near Bismarck, ND (16 inches of rain annually), he found depleted, compacted, dusty soils with 2% organic matter and limited productivity. Using cover crops, diversified rotation, no-till, and rotational grazing, he restored productivity and drought resilience, and built SOM up to 7% over a 20-year period–without applying a single microbial inoculant.

> *“No matter what you do to the soil, there will still be some small bit of life in it, even in the most chemically dependent or heavily tilled operations. If you give that life a chance to grow, it will respond. That is what I realized when I suddenly saw the earthworms. If you build it…or if you stop destroying it, they will come.” (Brown, 2018, p 25)*

Microbial Inoculants and other Biostimulant Products

Do agricultural soils need to be repopulated with beneficial organisms in order to regain biological function? In addition to finished compost, various commercial and homemade microbial inoculants and biostimulants have been promoted for this purpose. While these materials sometimes provide important benefits, depleted soils have been successfully restored simply by providing food and habitat for the desired organisms (see Sidebar).

The decision whether to invest time, money, and effort to bring new organisms into your soil will depend on several considerations:

- Scale of operation–what is practical and affordable at 1, 50, or 1,000 acres?
- Recent history and current health of the soil.
- On-farm resources for restoring and maintaining soil biota, such as:
    - Pastured livestock and poultry.
    - Feedstocks and infrastructure for composting.
- Specific need of crops to be grown, such as:
    - Rhizobia, mycorrhiza, or other root symbionts.
    - Anticipated disease risks.

Purchased products: navigating the microbial input smorgasbord

Open any organic amendments catalog, and, in addition to NOP allowed nutrient sources like rock phosphate and pelleted poultry litter, you will find myriad microbial inoculants and soil life enhancers claimed to solve one, several, or all of your production problems. Products include:

- *Rhizobium* inoculants for legumes (a standard practice validated by extensive research).
- Ectomycorrhizal and AMF inoculants.
- Other plant symbionts to enhance nutrient and moisture uptake.
- Biofungicides (discussed above) and biopesticides.
- Biodynamic preparations.
- Compost teas, worm castings tea.
- Preparations such as “bokashi” and “effective micro-organisms” (EM) to convert organic “wastes” via anaerobic fermentation into organic fertilizer.
- Individual organisms or suites of organisms claimed to build soil food web function and:
  - Enhance soil structure and build SOM.
  - Improve nutrient cycling and moisture retention.
  - Kill pests, pathogens, and weed seeds.
  - Enhance crop vigor, stress resilience, yield, and quality.
  - All of the above.
- Microbial “foods” to stimulate existing soil organisms include:
  - Molasses or another sugar source to promote bacterial growth and mineralization.
  - Seaweed/kelp and humic substances to support fungal growth.
- Biochar, humates, and other soil conditioners to improve habitat for soil life.
- Kits and instructions for making bokashi, compost tea, or other inoculants on farm.

One challenge is to determine which product might benefit your farm, and which will simply add costs. As one respondent in OFRF’s 2015 organic farmer survey stated:

“We need more research on the different fertility inputs. There are many “snake oil” products out there which cost people money.” (Jerkins and Ory, 2016).

A team of researchers at Ohio State University is working with organic growers to address this concern by evaluating the efficacy of *biostimulants* and *biofertilizers*–microbial inoculants thought to enhance crop nutrition, growth, and yield directly, not through disease suppression (Wang et al., 2016). Three years of trials at two research stations and 19 organic farms across seven states found no significant yield benefits from 13 commercial products tested on seven different vegetable crops (Kleinhenz, 2018). Negative results like this can occur for any of several reasons:

- Indigenous soil organisms in the field already perform the function(s) for which the product is applied.
- Indigenous organisms outcompete, inhibit, parasitize, or consume the added microbes.
- Soil conditions—temperature, moisture, aeration, pore size and structure, active SOM and nutrient levels, etc.—do not favor the applied organisms.
- Inoculant viability is lost due to improper storage conditions or application methods.
- Specific requirements for crop root-microbe partnership are not met, e.g., AMF application during production of a non-host crop.

An inoculant can show no effect because the soil is too degraded to support added microbes (inadequate active SOM, poor aeration, lack of pore space; extreme pH), or because it is already healthy (inoculant not needed) or rich in plant-available nutrients (deters N fixers, mycorrhizal fungi, and other root symbionts). Soils at the 21 sites in the Ohio State study might have been sufficiently healthy and fertile not to respond to the products tested. The research team has suggested that mycorrhizal inoculants and other microbial products are most likely to boost crop nutrition and yield on soils of moderately low fertility, in which the applied microbes can thrive and provide nutrient or other services needed by crops (Wang et al., 2016). Examples might include the highly weathered Ultisols of the southern US, and some soils of semiarid regions.

Inoculants applied to crop seeds or roots for specific purposes related to that crop, such as rhizobium, mycorrhizal, or other plant symbionts, may be more likely to establish successfully and yield measurable benefits than broadcast applications of microbial products, which are likely to be overwhelmed by the indigenous microbiome.

Rarely, soil inoculants can become detrimental; for example, poorly-made compost tea can propagate plant or human pathogens (Carpenter-Boggs and Crosby, 2015). Most often, the main harm arises from incurring materials and labor costs without reaping benefits, a risk that grows with the scale of operation.

Products that do not contain microbes per se but are claimed to improve habitat for soil life or crop performance include various humic substances, and biochar, which are often broadcast-applied to the soil or worked in. While the macro-molecular “humic substances” once thought to comprise most stable SOM have been shown to consist largely of artifacts of alkaline extraction, these same substances—derived from compost, worm castings, or mined lignite—can enhance plant growth when applied at concentrations of 5 – 300 ppm (Weil and Brady, 2017). Results have been mixed, and these products may have little effect in already-fertile soils with sufficient SOM. In contrast, a dilute (30 ppm) foliar spray of humic substances acted synergistically with inoculation with the N_2-fixing endophyte *Herbaspirillum seropedicae* to improve corn grain yields in a highly weathered, low-fertility soil in Brazil (Canellas et al., 2013). While either the microbial inoculant or humic substance alone improved yields about 20%, the two inputs together boosted yields some 65%.

Growing your own soil inoculants

Some farmers prepare soil inoculants on farm. Two approaches are to purchase starter inoculants to process on-farm organic residues into compost tea, bokashi compost, or other amendments; and to utilize indigenous (on-farm) sources of microbiota. The Korean system of natural farming includes procedures for gathering indigenous micro-organisms (IM) from soils under forest or other native plant community on or near the farm, propagating them on readily-available organic materials such as cooked rice, and applying them to fields, potting media, or compost windrows (see **Resource 13** on page 43). Researchers have also developed a simple protocol for propagating indigenous AMF for use in crop production (see Concept #4).

Making On-Farm AMF Inoculant

Commercial AMF inocula for use on crops can vary in efficacy and add significantly to production costs. Douds (2009, 2015) has developed a simple procedure for on-farm production of AMF inoculum. Basic steps include:

- Inoculate bahiagrass seedlings with indigenous AMF from healthy soil under native plant community or productive cropland on the farm.
- Fill grow bags with compost-vermiculite mix and grow the bahiagrass through the season until it winterkills (the AMF is hardy).
- Utilize the medium with root residues as inoculum.
- Mix this inoculum into potting mix at 5 – 10% by volume.
- Grow solanaceous and other AMF host vegetable starts in the inoculated potting mix.
- Avoid excess P in bahiagrass and vegetable potting media.

For details on this procedure, see **Resource 12g** on page 43.

Compost tea is a liquid organic fertilizer and microbial inoculant derived from compost mixed with water at 1:1 to 1:100 ratio and fermented for periods ranging from one hour to one week, with or without aeration or agitation, and with or without added microbial “foods” such as molasses, kelp extract, humates or various commercial products. Compost tea may be purchased (OMRI lists 23 brand names) or produced on-farm, and is applied to soil or foliage to enhance plant nutrition and health, suppress plant pathogens, or induce systemic resistance (ISR).

The tea-making process dislodges compost micro-organisms and extracts small amounts of plant nutrients and soluble organic materials into the tea. Final product quality depends on starting material (compost makeup and maturity) and process (time, aeration, temperature, and additives). Research results with compost teas range from disease suppression and improved crop yield to increased disease, lower yield, and even human foodborne pathogen risks (Carpenter-Boggs and Crosby, 2015). Thus, caution is warranted in making and utilizing compost teas. Some tips for realizing benefits and avoiding pitfalls include the following:

- Use high quality compost.
- Avoid immature or poorly made compost, especially from animal sources.
- Keep the tea aerated unless an anaerobic product is desired for a specific objective.
- Be sure to comply with NOP rules in using compost tea.
  - Tea brewed with additives is considered “raw manure” and requires a 120 day application to harvest interval.
- Try it out on a small scale, in side-by-side trial to verify efficacy before investing in equipment for large scale application.

For more on making and using compost tea, see **Resource 12e** on page 42.

Getting the Most out of Microbial Inoculant Applications

Navigating the dizzying array of products, methods, and claims for adding "good bugs" to the farm's soil ecosystem can be overwhelming. Does a particular field need one of these products, and if so, which one? Some tips include the following:

- Clarify your goals in utilizing an inoculant or soil life enhancer product.
  - Can your goals be met by crop rotation or on-farm resources?
  - Does the product under consideration address your goals?
- Research products carefully.
  - What research-based specific benefits (e.g., rhizobia for N fixation; drought resilience from AMF) can be expected from the product?
  - Take sweeping claims of multiple benefits with a grain of salt.
- Conduct a side-by-side trial with vs. without the product.
  - Compare crop yields and quality; watch for effects on soil condition.
  - Repeat the trial in different fields for a few seasons to verify trends.
- Follow product instructions for storage, application, and post-application management.
- Protect the product from direct sun (UV), excessive heat, drying, or freezing.
- Use rhizobia, mycorrhizal fungi, root-protectants, and other root symbionts effectively.
  - Apply directly to seeds, roots, or transplant plugs; or as a root drench.
  - Inoculate legume seed with appropriate rhizobia if the field has not been planted with that legume crop for several years.
  - Use recommended species of ectomycorrhizal fungi on perennial planting stock (associations are often species-specific and can be quite effective).
  - Manage nutrients to avoid excessive ("very high") soluble N and soil test P.

- For whole-field applications of soil inoculants and soil conditioners:
  - Apply living organisms in the evening or in mild, cloudy weather. Apply before a gentle rainfall or light overhead irrigation to move organisms into the soil.
  - Combine materials with complementary functions; e.g., biochar + finished compost, or decomposer microbes just before incorporating crop residues.
  - Side-by-side trials may require annual applications and monitoring for a few years to develop observable impacts on soil health or crop performance.

For additional information on legume inoculants see **Resources 11a, 12b,** and **12 c**. For more on biodynamic preparations, see **Resource 12f**. For making and using other inoculants and soil life enhances on farm, see **Resources 11d, 11e, 11g, 12e, 12g,** and **13** on pages 42-43.

Resources

Getting to know the soil biotic community

1. **Soil Biology Primer**. Elaine R. Ingham, Andrew R. Moldenke, and Clive A. Edwards. 2000. Soil and Water Conservation Society, Ankeny, IA. The classic educational booklet that introduced the soil food web to mainstream agriculture. https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/biology/.

2. **Soil Microbial Interactions and Organic Farming.** Brian Baker, Diana Jerkins, Joanna Ory, and Vicki Lowell, Organic Farming Research Foundation, 2016, 12 pp. https://ofrf.org/sites/ofrf.org/files/staff/OFRF.Soil_.brochure.4.16.v4.Web_.pdf.

3. **Teaming with Microbes: a Gardener's Guide to the Soil Food Web**. Jeff Lowenfels and Wayne Lewis, 2006, Timber Press. 196 pp. Excellent descriptions and photos of soil organisms, and use of compost, organic mulch, and compost tea to augment soil life.

4. **The Nature and Properties of Soils, 15th Edition**. Ray R. Weil and Nyle C. Brady, 2017. Pearson. 1086 pp. Chapter 11 *Organisms and Ecology of the Soil*; and Chapter 12, *Soil Organic Matter*. Excellent science-based information presented in accessible language, covering major functional groups of soil organisms, their roles in soil and plant health, soil-microbe-plant-root interactions, soil health management, and a balanced assessment of microbial inoculant products.

5. **The Role of Soil Protozoa and Nematodes**. James Hoorman. 2011. Ohio State University Extension Fact Sheet SAG-15-11. 5 pp. N mineralization by these organisms. https://ny24000991.schoolwires.net/cms/lib03/NY24000991/Centricity/Domain/10/the%20role%20of%20soil%20nemotodes%20and%20protozoa%20%20OSU%20fact%20sheet.pdf.

6. **Soil Nematodes in Organic Farming Systems**. Carmen Ugarte and Ed Zaborski. 2014. https://articles.extension.org/pages/24726/soil-nematodes-in-organic-farming-systems.

Monitoring soil life and soil health

7. **Comprehensive Assessment of Soil Health: the Cornell Framework. Edition 3.1**. Moebius-Clune, B.N., et al., 2016. Cornell University, Geneva, NY. 123 pp. Protocols for soil health measurements, including POX-C, PMC (4-day respiration), and mineralizable organic N. http://soilhealth.cals.cornell.edu/training-manual/.

8. **Measures of Soil Biology and Biological Activity**. Michelle Wander, 2015. https://articles.extension.org/pages/18626/measures-of-soil-biology-and-biological-activity.

9. **Recommended Soil Health Indicators and Associated Laboratory Procedures**. USDA NRCS Soil Health Technical Note No. 450-03. https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=43737.wba.

Practical applications: enhancing soil food web function and on-farm production of microbial inoculants

10. **Dirt to Soil: one family's journey into regenerative agriculture,** Gabe Brown, 2018. Chelsea Green Publishing, White Junction, VT. 223 pp. The author restored soil life on 5,000 acres of degraded land near Bismarck ND with cover crops, no-till, rotationally grazed livestock, and very few inputs.

11. **The Natural Farmer** https://thenaturalfarmer.org/. In-depth supplements on specific topics with research information and case studies from working organic farms.

    a. **Summer 2011 – Legumes as Cover Crops**: The biology of the legume-rhizobia symbiosis and practical guidelines for optimizing legume N fixation.

    b. **Summer 2014 – Building Soil Carbon**: The central role of soil life in building soil organic matter (SOM) = biological carbon sequestration.

    c. **Winter 2014-15 – Grazing**: Management intensive rotational grazing methods to enhance soil biology, SOM, and soil, forage, and livestock health.

- d. **Fall 2015 – Biochar in Agriculture**: Making and using biochar to enhance soil organic matter, microbial habitat, and fertility.
- e. **Winter 2015-16 – Worms**: Making and using vermicompost and worm casting tea.
- f. **Winter 2016-17 – Carbon Farming**: Cover cropping, reduced tillage, rotational grazing, and integrated systems to build stable SOM and soil life.
- g. **Fall 2018 – Fungal Friendly Farming**: The role of mycorrhizal and other fungi in soil fertility and crop production; how to make fungal-rich compost and bokashi (Asian traditional organic fertilizer) using indigenous (on-farm) microorganisms.

12. **Extension Organic Agriculture**, https://articles.extension.org/organic_production, articles, videos, webinars sorted by topic. The following can be found under *Soil and Fertility Management* except where otherwise indicated.
    - a. **Soil Fertility in Organic Farming Systems: Much More than Plant Nutrition**. Michelle Wander, University of Illinois, 2019. Biological approaches to organic nutrient management.
    - b. **Legume Inoculation for Organic Farming Systems**. Julie Grossman, North Carolina State University, 2015.
    - c. **Assessing Nitrogen Contribution and Rhizobia Diversity Associated with Winter Legume Cover Crops in Organic Systems** (webinar). Julie Grossman, North Carolina State University. 2010.
    - d. **Researcher and Farmer Innovation to Increase Nitrogen Cycling on Organic Farms** (webinar). Louise Jackson and Tim Bowles, UC Santa Cruz. 2013. Explores tightly-coupled N cycling and N use efficiency in organic tomato.
    - e. **Making and Using Compost Teas** (webinar). Lynne Carpenter-Boggs and Catherine Crosby, Washington State University, 2015. Procedures, benefits and pitfalls, research findings, factors in outcomes, and recommendations for best results.

   - f. **The Science Behind Biodynamics**. Lynne Carpenter-Boggs, Washington State University, 2011. The Biodynamic system, founded by Austrian philosopher Rudolf Steiner in the 1920s, emphasizes on-farm nutrient cycling, crop-livestock integration, and biodynamic preparations that modulate soil biota. The article offers guidelines for on-farm trials of BD preps and other products.
   - g. **On-Farm Production and Utilization of AM Fungus Inoculum**. David Douds, 2015. Practical instructions and guidelines for growing indigenous AMF inocula using bahiagrass in grow bags.
   - h. **Dung Beetles: How to Identify and Benefit from Nature's Pooper Scoopers**. Matthew Jones and William Snyder, Washington State U, 2017. Biology and management of dung beetles, and how they improve soil health, control livestock pests and parasites, and reduce foodborne illness risks in manure-fertilized or crop-livestock integrated systems. *Listed under Insect Management*.

13. **How to Cultivate Indigenous Micro-organisms**. Hoon Park and Michael W. DuPonte, 2010. Photo illustrated instructions for collecting, propagating, and applying indigenous microbiota from local native plant communities, based on the Korean Natural Farming method. https://www.ctahr.hawaii.edu/oc/freepubs/pdf/BIO-9.pdf.

Practical applications: managing pathogens and pests

14. **Crop Rotation on Organic Farms – a Planning Manual**. (Mohler, C. L. and S. E. Johnson, editors, 2009. Cornell University and SARE, 156 pp). Includes information on rotations to manage a range of pathogens and pest nematodes. Available at www.sare.org.

15. **Extension Organic Agriculture**, https://articles.extension.org/organic_production. Articles and videos under topics as indicated:
   - a. **Managing Disease by Managing Soils.** David Eastburn, Illinois State University, 2010. Eastburn, D. 2010. Mechanisms of soil disease suppressiveness, and practical implications. (Plant Disease Management)
   - b. **Managing the Soil to Reduce Insect Pests**. Geoff Zehnder, Clemson University, 2015. Tips for managing nutrients, tillage, organic inputs, and soil biology to reduce pest pressure and enhance plant resilience. (Soil and Fertility Management)

   c. **CalCORE Research: Controlling Soilborne Diseases in California's Strawberry Industry with Anaerobic Soil Disinfestation (ASD)**. Mark Bolda, Joji Muramoto, Steve Pederson, Carol Shennan, Tim Campion, and Jaime Lopez. 2016. Video clips. (Plant Disease Management)
   d. **Composting to Reduce Weed Seeds and Plant Pathogens**,.Ed Zaborski, University of Illinois, 2015. Temperatures and management practices required to kill various species of weed seeds and pathogens. (Plant Disease Management)

16. **eOrganic Webinar and Broadcast Recordings by Topic,** https://articles.extension.org/pages/68066/eorganic-webinar-and-broadcast-recordings-by-topic, click on Disease Management.
    a. **A Novel Strategy for Soil-borne Disease Management: Anaerobic Soil Disinfestation (ASD).** Carol Shennan and David Butler. 2011.
    b. **Anaerobic Soil Disinfestation to Control Soil Borne Pathogens: Current Research Findings and On-farm Implementation**. Carol Shennan and Joji Muramoto, 2014. Practical instructions on field application of ASD for effective control of *Verticillium dahliae* in organic strawberry.
    c. **Advances in Biosolarization Technology to Improve Soil Health and Organic Control of Soilborne Pests**. James Stapleton, UC Kearney Ag Research and Extension Center. Recorded at the Organic Agriculture Research Symposium, 2016.
    d. **Use of High Glucosinolate Mustard as an Organic Biofumigant in Vegetable Crops**. Heather Darby and Abha Gupta (University of Vermont) and Katie Campbell-Nelson (University of Massachusetts). April, 2017. Practical guidelines for using biofumigant cover crops
    e. **Cover Crops for Disease Suppression**. Alex Stone, Oregon State University. 2012. Successes, limitations, and research priorities.
    f. **Integrated Clubroot Management Strategies for Brassica Crops**. Aaron Heinrich and Alex Stone (Oregon State University). February, 2017. Managing club root by modifying soil conditions, crop rotation, and varietal resistance,

g. **Organic Tomato Foliar Pathogen IPM Webinar**. Dan Egel, Lori Hoagland, and Amit-Kum Jaiswal. March 2018. Disease management through soil health, microbial diversity, ISR, crop rotation, reduced tillage, compost, biochar, and biosolarization.

h. **Linking Cover Crops, Plant Pathogens, and Disease Control in Organic Tomatoes**. Brian McSpadden Gardener. 2013.

i. **Grafting for Disease Management in Organic Tomato Production**. Frank Louws and Cary Rivard, 2011. Utilizing rootstock genetics to optimize plant-soil-microbe interactions to suppress pathogens and root-feeding nematodes.

j. **Using Contans (*Coniothyrium minitans*) for White Mold Management on Organic Farms.** Alex Stone (Oregon State U). 2014. White mold IPM with *C. minitans*, crop rotation, moisture management, and other cultural practices.

k. **Using Biofungicides, Biostimulants and Biofertilizers to Boost Crop Productivity and help Manage Vegetable Diseases**. Giuseppe Colla, Mariateresa Cardarelli, Dan Egel, and Lori Hoagland. March, 2017. Practical guidelines for effective utilization of AMF and other microbial inoculants, biostimulants (humates, seaweed extracts, silicon, etc.) and biofungicides.

Keeping up with research developments in soil biology and organic agriculture

17. **eOrganic**: Upcoming and archived webinars, monthly e-newsletter with updates on organic research including soil biology, soil health, and plant disease management. https://articles.extension.org/organic_production.

18. **Organic Farming Research Foundation**: Updates on new and emerging results from OFRF-funded and other research, proceedings of annual Organic Agriculture Research Forums, and a monthly e-newsletter. https://ofrf.org.

19. **The Organic Center:** Organic research including soil health research updates, articles on leading researchers, and a monthly e-newletter. https://www.organic-center.org/.

20. **Pennsylvania Association for Sustainable Agriculture** (PASA): Ongoing Soil Health Benchmark Study engaging organic farmers in documenting soil life and soil health on their farms. https://pasafarming.org/soil-institute/farm-based-research/soil-health-benchmark-study/.

21. **University of Minnesota – Organic Agriculture**: Updates on UMN organic systems research, including soil bacterial community functions, legume-rhozobia symbiosis, and soil microbial impacts on weed seed banks. http://sustainablecropping.umn.edu/organic-agriculture, links to *projects* and *publications*.

22. **Ohio State University - Microbial-based Biofertilizers in Vegetable Production ListServ:** Links farmers and researchers in an evaluation and discussion of commercially available microbial inoculants intended to enhance soil food web function, nutrient cycling, and crop yield, maintained by Dr. Matthew Kleinhenz and colleagues. http://u.osu.edu/vegprolab/microbial_inoculants_in_vegpro/.

23. **USDA Sustainable Agriculture Research and Education (SARE)**: Searchable database of all SARE funded projects 1988-current, including progress and final reports. Several hundred projects have addressed soil biology. https://www.sare.org/.

24. **ATTRA Sustainable Agriculture**: Information sheets and articles on soil health and many other topics, as well as current research news. https://attra.ncat.org/.

A Taxonomic Tour of the Soil Biota

Except where otherwise referenced, the following information is based on *Organisms and Ecology of the Soil,* Chapter 11 (pp 464 – 525) in *Nature and Properties of Soils* (Weil and Brady, 2017).

Bacteria

Soil bacteria are small (0.5 to 5 μm diameter; 1 μm = 1/1,000,000 meter or 1/25,000 inch), simple, prokaryotic (genetic material not enclosed in a distinct nucleus), unicellular organisms that comprise a substantial part (300 – 4,000 lb/ac live weight) of the soil biota. A single teaspoon of topsoil contains billions of bacteria representing several thousand distinct genotypes. Bacterial habitats include fresh organic residues, manure, the plant rhizosphere (Figure 9, left), and soil micropores, the smallest of which offer refuge from predators. Some bacteria live within root tissues as beneficial endophytes or pathogens, and others inhabit the digestive tracts of earthworms, mites, and nematodes in mutualistic relationships.

Figure 9. Rhizosphere bacteria (left). Legume root nodules contain N_2-fixing Rhizobia (right). Ingham et al., 2000. Soil Biology Primer. SWCS, Ankeny, IA.

Soil bacteria perform many vital functions. Because bacterial biomass is protein-rich, decomposer bacteria on manure or succulent green manures help stabilize N before it can leach away or denitrify into N_2O. While such N immobilization can temporarily limit plant-available N (PAN), other bacteria contribute PAN by fixing atmospheric N_2, or by converting NH_4-N into NO_3-N, the form preferred by most crops. In addition to *Rhizobium* symbionts in legume nodules (Figure 9, right), N_2-fixing bacteria include free-living and associative (rhizosphere) species such as *Azospirillum*, *Azotobacter*, *Beijerinckia* and some strains of *Clostridium;* non-nodule-forming endophytes such as *Herbaspirillum seropedicae* in corn, and photosynthetic cyanobacteria (“blue-green algae”). The cyanobacterium *Anabaena* enters into symbiosis with the aquatic fern *Azolla*, and can provide 150 lb N/ac in paddy rice production (Weil and Brady, 2017; Canellas et al., 2013).

Diverse species of plant growth promoting rhizobacteria proliferate in the plant root zone and aid plant growth by mobilizing N, P, sulfur (S), and other nutrients from active SOM, suppressing or excluding plant pathogens, or releasing plant growth hormones. Certain bacteria mobilize iron (Fe), zinc (Zn), and other micronutrients from soil minerals by forming *chelates* (organo-mineral compounds) from which plant roots can obtain the micronutrients.

A minority of soil bacteria can harm plants, either directly by invading plant tissues and causing disease, or more indirectly by releasing substances that slow plant growth or damage plant tissue (*deleterious rhizobacteria*).

Soil bacteria play a significant role in maintaining aggregation by secreting glue-like polysaccharides (carbohydrates) and forming biofilms on surfaces of plant roots and soil minerals. The remains of soil bacteria adsorb tightly to silt and clay particles, thereby contributing to stable SOM and carbon sequestration.

Most soil bacteria derive energy from starches, proteins, and other readily-decomposable organic materials of plant or animal origin. Some bacteria derive energy through oxidation of Fe and other soil mineral elements, a process that can facilitate micronutrient availability to plants. Others consume methane (CH_4), making a small contribution (1-2 lb/ac-year) to the removal of this GHG from the atmosphere (Topp and Pattey, 1997).

Archaea

Originally considered a type of bacteria, the archaea are similar in size, shape, and diversity of function to true bacteria. Toward the end of the 20th century, genetic analysis showed that the archaea are no more related to bacteria than they are to ourselves, and were thus assigned their own domain. Archaea include specialized organisms of extreme environments, such as the anaerobic methanogens that release CH_4 from wetlands and rice paddies, and others that tolerate extremely saline, alkaline, or acidic soils, or the intense heat of geysers and undersea hydrothermal vents. However, recent research indicates that some 10% of microbial biomass in typical upland soils may consist of archaea. Their functions include oxidation of sulfur into plant-available sulfate-S, and breakdown of hydrocarbons including petroleum-based soil contaminants.

Actinobacteria or Actinomycetes

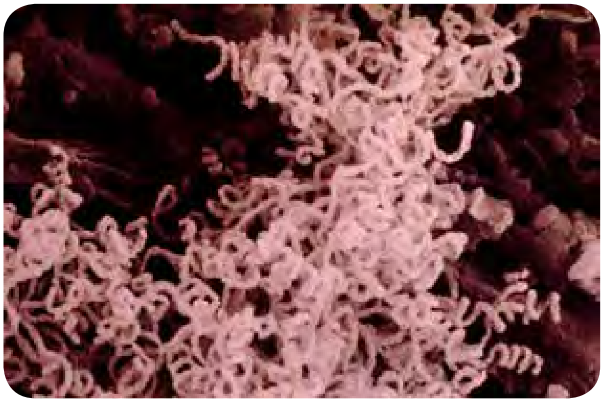

Figure 10. Soil actinobacteria. Ingham et al. 2000. Soil Biology Primer. SWCS, Ankeny, IA.

Once classified as fungi, these filamentous soil bacteria (prokaryotes) form hyphae with fungus-like functions in the soil. Actinobacteria comprise 350 – 4,000 lb/ac (live weight) of the soil food web, and they help decompose organic residues by digesting cellulose and chitin that resist attack by other bacteria. Their activity releases volatile substances that give biologically active soils their "earthy" aroma. Some Actinobacteria form symbiotic or parasitic relationships with plant roots, and others (genus *Frankia*) play a vital role as symbiotic N fixers on the roots of certain forest trees and shrubs.

Actinobacteria thrive in warm, moist, near-neutral soils (pH 6.0 -7.5), but many are quite tolerant of drier and/or saline conditions, and help sustain biological activity in arid region soils or during drought.

Fungi

Soil fungi are filamentous organisms comprised of long, branching chains of cells (hyphae) that often twine together into visible fungal growth (mycelium), and, in some species, coalesce into larger fruiting bodies such as mushrooms, puffballs, and bracket fungi. In contrast to the prokaryotes, fungi are eukaryotes, with their DNA enclosed in membrane-bound nuclei in each cell. While individual hyphae are microscopic (Figure 11, left), a fungal mycelium in an undisturbed ecosystem can cover acres, weigh more than a ton, and live for many years.

Fungi have a wide soil pH tolerance range and can thrive on woody (lignin-rich) residues that bacteria cannot digest (Figure 11, center). Fungi often comprise half or more of the soil microbial biomass, with live weights ranging 900 – 10,000 lb/ac. Soil fungi are especially efficient in converting organic materials they consume into new biomass (up to 50% versus ~20% for bacteria), and thus play a leading role in forming stable SOM (Kallenbach et al., 2016). Although they reach their greatest abundance in the litter and duff (organic) surface layers of acidic forest soils, fungi perform vital functions in cropland soils as well: digesting "resistant" organic materials including some pesticides, sustaining soil fertility and aggregation (tilth), building SOM, and providing crop nutrients.

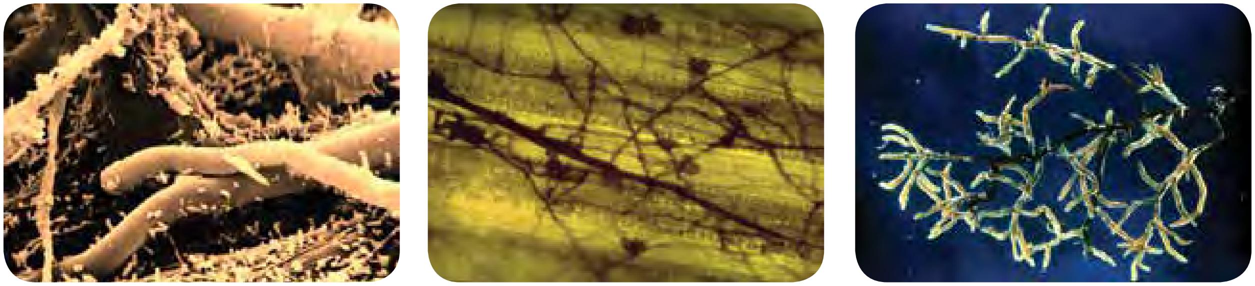

Figure 11. Photomicrographs of fungal hyphae with associated bacteria, showing the larger diameter of the former (left); decomposer fungi on fallen leaf (center), and ectomycorrhizal fungi on tree roots (right). Ingham et al. 2000. Soil Biology Primer. SWCS, Ankeny, IA.

Soil fungi include two functional groups: the *saprophytic* (decomposer) species, and *mycorrhizal fungi*, whose vital role in soil and plant health was described earlier. While most crops associate with arbuscular mycorrhizal fungi (AMF), the roots of many trees including fruit and nut crops form ectomycorrhizae in which the fungal symbiont forms a dense mycelial sheath around the root (Figure 11 right).

Both forms of mycorrhizal fungi send mycelia several inches beyond the root surface into the soil, effectively multiplying the root system's absorptive capacity several-fold. Mycorrhizae solubilize and absorb mineral-fixed phosphorus (P) and micronutrients that unaided plant roots could not access. At the same time, the symbiosis can protect roots from toxic excesses of Fe, Zn, copper (Cu), nickel (Ni), and aluminum (Al).

Protozoa and slime molds

Protozoa such as amoebas, flagellates, and ciliates are the larger (4 – 250 μm), more complex unicellular organisms that are so fascinating to watch under a light microscope. They prey mostly on soil bacteria (Figure 12), require free moisture to move about and feed, and go dormant as stress-resistant cysts when the soil dries out. Protozoa do not need all of the N in their protein-rich diet of bacteria, and they mineralize (release) the surplus as plant-available NH_4-N. Although protozoa make up a small part of the soil biomass (18 – 250 lb/ac live weight), they play a key role in delivering PAN by feasting in the bacteria-rich rhizosphere.

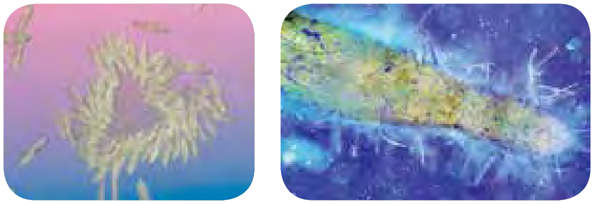

Figure 12. Ciliate protozoa consuming bacteria (left), bacteria and protozoa proliferate in plant rhizosphere (right). Photo credits Fotosearch Waukesha, WI (left); James Hoorman, Ohio State University (right).

Soil micropores provide a refuge for bacteria where protozoa cannot reach them and help to maintain predator/prey balance. Moderate grazing by protozoa can stimulate bacterial growth; in addition, protozoa help suppress disease by consuming pathogens (Hoorman, 2011).

Slime molds consist of unicellular protozoan-like microbes that, at certain stages of their life cycle, aggregate into macroscopic masses (sometimes to several inches across). They consume micro-organisms and contribute to the decomposition of plant litter and other organic residues.

Algae

Soil algae are small (2-20 μm) motile, photosynthetic eukaryotic unicellular organisms that comprise a relatively small portion of soil biomass (10 – 450 lb/ac), yet make significant contributions to organic matter and soil aggregation.

Nematodes

Soil nematodes are tiny, simple worms 4 - 100 μm in diameter by 40 – 1,000 μm long that become active when soil moisture is sufficient, and survive prolonged dry periods in a dormant state. Although they comprise a relatively small part of the soil biomass (10 – 260 lb/ac live weight), they occupy a wide range of niches and perform multiple functions in the soil food web.

Well-known pests such as root knot, sting, lesion, and other plant root feeding nematodes can devastate some crops. Yet, the majority of soil nematodes provide essential services. Nutrient release by nematodes feeding on bacteria, archaea, algae, and fungi may account for 30 – 40% of PAN in some soils. In one study, bacteria-feeding nematodes facilitated release of PAN from soil-incorporated plant residues with a C:N ratio as high as 32:1; without nematodes, the threshold C:N for PAN release decreased to 22:1 (Ferris et al., 1998).

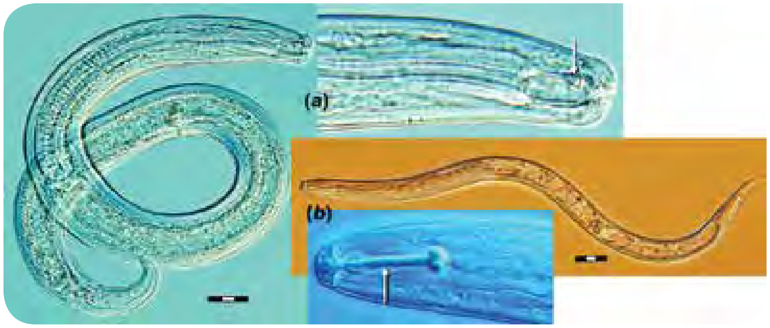

Figure 13. Predatory nematode and closeup of mouth part (a). Soybean cyst nematode, a root feeder, showing its pierce-and-suck mouth part (b). Photos by Lisa Stocking Gruver, U Maryland; courtesy of Joel Gruver, Western Illinois University.

Predatory nematodes (Figure 13a) feed on protozoa and other nematodes including root-feeders (Figure 13b). Entomopathogenic nematodes parasitize soil-dwelling insect pest larvae. When it enters the larva, the nematode releases its microbial symbionts, which digest the insect's tissues into food for another generation of nematodes. Entomopathogenic *Heterorhabditis* and *Steinernema* are marketed as biopesticides allowed by NOP for organic production.

Light grazing by nematodes on soil microbes can stimulate the growth of the latter, whereas heavier grazing reduces their numbers. Similarly, light infestations of root-feeders can actually stimulate root growth and plant vigor; thus, as with most pests, the goal of management is balance and not extermination.

Micro-arthropods: mites and springtails

Springtails (small insects in the order *Collembola*) and mites (eight-legged relatives of spiders and ticks) make up most of the soil's *mesofauna* (creatures just visible to the naked eye, 0.5 – 1 mm, or 1/50 to 1/25 inch in length), (Figure 14). Micro-arthropods, which comprise about 4 to 450 lb/ac (live weight) of the soil biota, shred plant litter and other organic residues and mix them into the soil. The shredding action facilitates microbial access to the organic materials, and speeds the conversion of residues into active and stable SOM. In addition, predatory mites feed on protozoa, nematodes, and fungi, which contributes to nutrient cycling and crop nutrition.

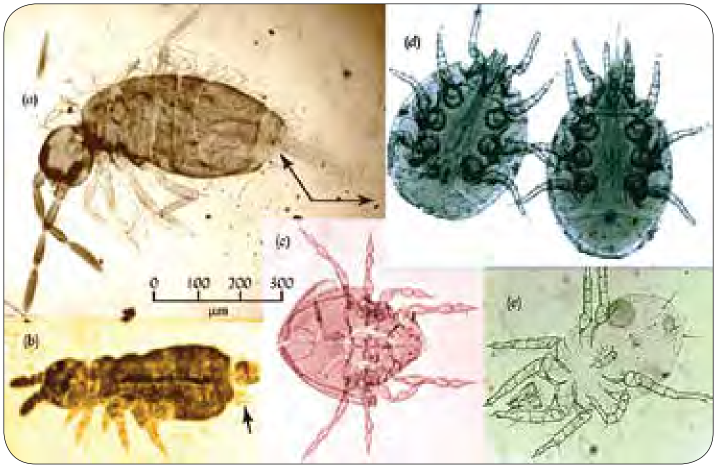

Figure 14. Springtails (left) and orbatid mite (center) consume residues and fungi; predatory mites (right) eat smaller arthropods and nematodes. Photos by Ray Weil, University, Maryland.

Micro-arthropods play prominent roles in the food web of acidic forest soils rich in high C:N organic residues, while nematodes become more prominent in prairie soils with higher pH and lower C:N ratios. In a California farming systems trial, predatory, fungal-feeding, and decomposer mites were more abundant in organic vs. conventional systems, and in conservation tillage vs. full tillage systems (Epstein, 2007). Springtails are highly sensitive to tillage, and occur in greater numbers in sod than during annual crop production (Cogger et al., 2013).

The soil mesofauna also includes the waterbears (tardigrades), which are small (~0.5 mm), eight-legged, creatures that feed on microbes or plant tissues. Their role in the soil food web has not been widely researched.

Earthworms

Earthworms are the most visible and well-known indicators of soil health in agricultural fields and grazing lands, and they play structural roles in soil ecosystems, which might be likened to "composter," "bio-tiller," and "ecosystem engineer" (Weil and Brady, 2017). They feed by ingesting plant litter and other residues along with mineral soil, mixing them with gut microbes, extracting the nutrition they need, and ejecting the residue as casts. The casts consist of highly aggregated soil enriched with organic matter, microbes, and plant nutrients. Some species, such as the compost worm *Eisenia foetida,* process fresh residues on and near the soil surface, while others, such as the European night crawler *Lumbricus terrestris* (Figure 15) burrow deeply (to 5 feet or more), and thereby mix fresh residues into the soil, promote soil drainage, create nutrient-enriched macropores and channels for plant roots to follow, and build and maintain habitat for other soil organisms. Research has shown that *L. terrestris* can integrate corn residue into the soil profile, greatly enhancing availability of residue N to a subsequent crop, but also increasing the potential for losses of N (Amador and Gorres, 2005).

Ray Weil, University of Maryland

Figure 15. The European nightcrawler and some of its castings.

Soil earthworm populations comprise 90 – 3,500 lb live weight per acre, and can process twice their own weight of soil into casts daily. Thus, in a climate that supports earthworm activity for six months of the year, the worms might turn over 9 to 450 tons soil/ac–effectively performing biological tillage. Finally, earthworms release additional nutrients when they die and decay; large earthworm populations can contribute 45 – 80 lb plant-available N per acre per year in this way.

Larger arthropods: ants, termites, dung beetles

In some soils, ants and termites play the “ecosystem engineer” roles of earthworms. The impacts of ants on nutrient cycling, soil microbes, and other organisms are incompletely known and require further study. Termite colonies occur over about two-thirds of the world’s land area. In the drier tropics (≤30 inches/year), their biomass surpasses that of earthworms, and, in conjunction with their microbial symbionts, they perform a similar range of functions.

Ray Weil, University of Maryland

Figure 16. Dung beetle forming ruminant dung into a ball, which it will bury in the soil as a food source on which to lay its eggs.

In grasslands, dung beetles (Figure 16) consume and disperse the fecal deposits of cattle and other grazing animals, burying them in the topsoil. In this process, dung beetles conserve and cycle nutrients, protect surface water quality, and reduce pathogen and parasite loads. In addition to protecting livestock health, dung beetles can reduce human foodborne pathogens in crop-livestock integrated systems (Jones et al., 2019). Grazing ecosystems (pasture, prairie, etc.) that have lost their native dung beetle populations can show greatly improved vegetative growth after appropriate dung beetle species are reintroduced.

A great many other arthropods (joint-legged animals) live in the soil, including centipedes, millipedes, symphylans, pill bugs, wood lice, spiders, ground beetles, and the larval and pupal stages of many other insects.

Burrowing vertebrates

Groundhogs, gophers, prairie dogs, moles, snakes, toads, salamanders, and other vertebrates make their homes in the soil. While some of these creatures damage crops and others protect them by consuming pests and weed seeds, most contribute to the mixing of organic residues with mineral soil through their burrowing activities.

Viruses

Viruses consist of units of genetic information (DNA or RNA) packaged in a protein coat, which can only multiply within the cells of bacteria, plants, or other organisms. In addition to causing a plethora of plant, animal, and human diseases, viruses play significant roles in the transfer of genetic information among other organisms, and hence, evolution and speciation. However, researchers have only begun to study the potential roles of viruses in agricultural soils, in which their abundance has been estimated to range from 10 million to a billion viral particles per gram (1/28 oz) of topsoil (Williamson et al., 2017). Many soil viruses live in bacteria or archaea, either multiplying within and destroying their host, or integrating their DNA into the host genome for a period of time before detaching again as a separate particle. Viral roles in soil carbon and nutrient cycling, and in transfer of genetic material among soil bacteria and other organisms may be substantial, and remain little known at this time (Williamson et al., 2017).

Research Topics

Assessing soil biotic communities and biological functions

Laboratory methods to assess the soil microbiota include direct measurements of microbial biomass and activity, enzymes related to mineralization and cycling of C, N, P, and S; genomic (DNA) analyses; and biochemical analyses such as phospholipid fatty acid (PFLA) and fatty acid methyl ester (FAME) assays (Bunemann et al., 2018; Lori et al., 2017; Morrow et al., 2016; Wander, 2015, Wolfe and Klironomos, 2005). DNA analysis provides an index of microbial biodiversity and a means to compare soil microbiomes from different treatments, and PFLA estimates biomass of five major microbial guilds: gram-positive bacteria, gram-negative bacteria, actinobacteria, saprotrophic (decomposer) fungi, and AMF (Vereecke et al., 2017). The BIOLOG Ecoplate method yields a profile of organic substances (sugars, amino acids, etc) consumed by the soil microbiome (Wander, 2015; Chinmay et al., 2017).

Researchers use these measurements and various derived indices such as fungi:bacteria (F:B) ratio, microbial growth efficiency (MGE), and community composition matrices (based on PFLA or DNA) to evaluate impacts of production practices on soil life (Bhowmik et al., 2017; Brennan and Acosta-Martinez, 2017; Lori et al., 2017; Vereecke et al., 2017). Scientists at University of Minnesota have documented bacterial community responses to cover crops and amendments, and are working to develop practical interpretation and applications (Sheaffer et al., 2016).

Nematode community indices based on the relative abundance and diversity of functional nematode groups—bacterial and fungal feeders, root feeders, predators, and omnivores—can help researchers evaluate impacts of tillage, fertility inputs, orchard floor management, and other practices in organic systems (Moore-Kucera et al., 2008; Ugarte and Wander, 2008; Ugarte et al., 2013). Indices include enrichment index (EI; high values indicate abundant soluble N and a bacterial dominated soil biota) channel index (CI, ratio of fungal- to bacterial-feeding nematodes reflecting F:B ratio); and structure index (SI; high values indicate diversity of all nematodes groups and reflect a complex and balanced soil food web) (Chen et al., 2015; Moore-Kucera et al., 2008).

Simple, reliable protocols have been developed for *soil respiration*, and *permanganate oxidizable carbon* (Hurisso et al., 2016; Moebius-Clune et al., 2016). In the Solvita respiratory CO_2 test developed as a field estimate of microbial activity, a small sample of air-dried soil is enclosed with a CO_2 trap in an airtight jar, moistened to field capacity, and incubated at about 70°F for 24 hours to measure the amount of *soil organic carbon* (SOC ~ 0.5 X SOM) converted to CO_2 (Haney et al., 2018). Additional research has found that a 4-day incubation provides a more reliable index of readily-decomposable SOC, known as *potentially mineralizable carbon* (PMC) (Morrow et al., 2016; USDA-NRCS, 2019).

In the permanganate oxidizable soil organic carbon test (POX-C), a soil sample is mixed with a dilute (0.02 M) solution of potassium permanganate ($KMnO_4$) for two minutes, then allowed to settle, after which the color of the solution is assessed with a spectrophotometer to determine how much permanganate was consumed by reaction with SOC (Weil et al., 2003).

Several other indices of active SOM have been developed, including particulate SOC and water-extractable SOC. However, PMC and POX-C show the most consistent positive correlations with microbial biomass, vital soil functions, total SOM, and crop yields, and both parameters respond rapidly to improved soil management (Delate, 2013; Ghabbour et al., 2017; Hurisso et al., 2016; Lori et al., 2017; McDaniel et al., 2014; Morrow et al., 2016).

In practice, direct assessments of soil biological activity (respiration, microbial biomass, N mineralization, earthworms) have played a smaller role than chemical (pH, total SOM, nutrients) and physical (water infiltration and storage, structure, compaction) properties in multi-parameter soil health evaluation protocols (Buneman et al., 2018). Additional research and development is needed to develop practical application of management-sensitive indicators, such as nematode and arthropod communities, disease-suppressive soil microbiomes, and molecular (DNA, RNA, protein) assessments of microbial diversity and function. As the costs of lab procedures continue to decline, soil microbial profiles and interpretation guidelines may become commercially available to producers in the near future (Sheaffer et al., 2016).

Soil life, soil organic matter, and moisture holding capacity

An ingenious laboratory study has yielded strong evidence that essentially all stable SOM is derived from microbial processing of root exudates and other organic inputs (Kallenbach et al., 2016). Starting with sterile sand-clay mixtures devoid of organic matter, researchers added a microbial inoculum (1 mg per 100 grams of sterile mix), then weekly additions of organic C at rates similar to root exudation from a vigorous crop, plus Hoagland's solution to provide inorganic nutrients. Organic C was added in the form of sugars, syringol (a phenolic compound), or a water extract of switchgrass. At the end of 15 months, the sand-clay mixtures resembled well-aggregated topsoil and contained 1.5 – 3% SOM, whose chemical composition resembled the SOM in field soil, regardless of the form of organic C used. Both MGE and SOM accrual increased with the relative abundance of fungi, yet even the most bacterial-dominated systems converted some of the input C into "typical" SOM. Thus, total SOM provides an index of long term biological activity, biodiversity, and balance.

In another laboratory experiment, investigators stimulated microbial activity in a sandy soil with a mixture of sugars, organic acids, and amino acids designed to simulate plant root exudates, after which they measured rates of evaporative water loss from soil cores. This treatment significantly slowed moisture loss compared to unamended soil, while chemical treatment to suppress microbial activity accelerated soil drying (Choudhury et al., 2018).

Impacts of crop rotation, inputs, and management practices on the soil biota and nutrient cycling

Crop rotation diversity, farming system, soil amendments, cover crops, and other individual practices can each alter the soil microbiome. For example, in the Wisconsin Integrated Cropping Systems Trial (WICST), 27 years under different rotations have resulted in distinct bacterial and fungal communities (Vereecke et al., 2017). Inclusion of perennial crops in the rotation had the greatest impact, followed by legumes, manure inputs, tillage intensity, and cropping system diversity. Permanent pasture had highest levels of actinomycete, AMF, saprophytic (decomposer) fungal, and total microbial biomass, followed by forage rotations that included both annual (corn) and perennial (alfalfa) crops. Conventional or organic rotations consisting of only annual crops had the lowest fungal, actinomycete, and total microbial biomass.

Other studies have found more diverse and qualitatively different soil biotic communities in organic *versus* conventional systems (Drinkwater, 2012, Epstein, 2007; Ishaq et al., 2017). In New York, fields under organic management with diverse rotations and compost for 20 years developed a more diverse bacterial community and twice the capacity to mineralize soil organic N compared to nearby conventional fields with simpler rotations and soluble fertilizer (Berthong et al., 2013). The addition of small amounts of sugar (to simulate root exudation) to soil from organic fields stimulated microbial N mineralization, but elicited little response from conventionally managed soil. The capacity of the organic soil microbiome to respond to plant nutrient demand by mineralizing N in the rhizosphere can reduce the need for concentrated fertilizers and protect water quality (Berthong et al., 2013; Drinkwater, 2012).

In California, organic tomato fields managed for tightly coupled N cycling (finished compost with C:N 15-18; limited use of concentrated N) maintained soil NO_3-N ≤5 ppm through the season (well below the sufficiency level of 16 ppm for tomato), yet tomato N nutrition was sufficient to support high yields (Bowles et al., 2015). These soils showed high levels of microbial activity, active and total SOM, and enhanced expression of a crop root enzyme involved in N uptake and metabolism.

N deficient fields had similarly low NO_3-N, but low levels of SOM and microbial activity reduced N uptake and yield in organic tomato. N-saturated fields (heavily amended with low C:N materials including guano, poultry litter, and all-legume green manures) had higher NO_3-N and high tomato yields. Total biological activity was similar to the tightly coupled fields, but with more enzyme activity associated with SOM breakdown and less related to N mineralization (Bowles et al., 2015). Since the root enzyme involved in N uptake occurs widely across plant species, these findings indicate a potential to manage other organic crops for tight N cycling (Jackson, 2013).

N_2-fixing microbes become active on an as-needed basis. For example, in upstate New York, legume cover crops generally fixed more N_2 when grown with N-demanding grasses than in monoculture, yet the cowpea component of cover crop mixes fixed little N_2 because its deep roots accessed subsoil NO_3-N (Drinkwater, 2011). Non-symbiotic N_2 fixation was lowest in soils with the highest SOM and N mineralization potential (Drinkwater and Buckley, 2010). In Minnesota, poultry litter or commercial organic 8-2-4 fertilizer reduced soil populations of rhizobia, while non-legume cover crops did not (Fernandez et al., 2016; Sheaffer et al., 2016).

Organic inputs with a balanced C:N ratio generally support soil microbial abundance, diversity, and function. Researchers at Washington State U compared the effects of finished compost (moderate C:N) versus poultry litter (low C:N) applied at the same total N rate in an organic vegetable rotation. After 11 years, compost-amended soil had 43% more total SOM, 60% more POX-C, 35% higher microbial respiration, and significantly higher enzyme activities than litter-amended soil (Bhowmik et al., 2017). The microbiome in compost-amended soil showed enhanced nitrification potential, yet reduced N leaching and N_2O emissions by immobilizing excess NO_3-N (Bhowmik et al., 2016). In contrast, poultry litter promoted nematode species associated with high levels of soluble N (Cogger et al., 2013).

Crop root biomass supports both nutrient mineralization and SOC stabilization by soil life (Cates et al., 2015; Wuest and Reardon, 2016). The fine roots of winter annual legume cover crops provide substantial PAN to the following crop (Hu et al., 2015). In an organic vegetable rotation in Salinas, California, winter cover crops promoted microbial activity and greatly enhanced N cycling and spring lettuce yield, while yard waste compost built stable SOM and further enhanced microbial activity (Brennan and Acosta-Martinez, 2017).

Scientists at University of Minnesota evaluated effects of organic inputs on soil bacterial community structure (“who is there”) and function (“what they are doing”) on three long-term (10+ yr) organic farms. Incorporating cover crop residues, cattle manure, pelleted poultry litter, or 8-2-4 organic fertilizer temporarily reduced microbial diversity as decomposer species multiplied (Sheaffer et al., 2016). The poultry litter also doubled soil respiration at two sites. As decomposition progressed, microbial diversity recovered and respiration rates subsided to pre-amendment levels. Corn yield on the fertile, healthy soils at these sites was not affected by cover crop species or fertility inputs. The study also documented lower bacterial diversity in the corn rhizosphere than in bulk soil (Sheaffer et al., 2016). This may reflect the crop's ability to select preferred microbes through chemical signaling, and suggests a mechanism for the strong link between crop diversity and soil biodiversity.

Inputs and practices also affect soil nematode communities. In central California, organic systems showed greater nematode populations and biodiversity than conventional systems (Epstein, 2007). In organic vegetable rotations in Maryland, cover crops enhanced bacterial feeding nematode populations (higher EI), while no-till and strip-till enhanced nematode diversity (SI) compared to tilled cover crops with or without plastic mulch (Chen et al., 2015). Treatments with higher SI and CI (more fungal-feeders) also reduced N_2O emissions.

Studies on organic transition strategies at the University of Illinois showed increased bacterial activity, nematode EI, and PAN in the organic systems. Spring tillage sharply reduced SI, and plant parasitic nematodes increased with PAN (Ugarte et al., 2013). The authors recommended reduced tillage and practices that build SOM and soil structure. In an earlier transitions study, amending plots in spring with raw or composted dairy manure (90 lb total N/ac) enhanced predatory and microbe-feeding nematode populations and reduced plant-parasitic nematodes by the following autumn (Nahar et al., 2003).

Conventional inputs can stress soil microbiomes. In the Morrow Plots maintained for well over a century by University of Illinois, high rates of soluble NPK fertilizer significantly altered bacterial community structure and metabolism and caused net losses of SOM and soil organic N despite higher crop biomass (Chinmay et al., 2017; Khan et al., 2007; Mulvaney et al., 2009). Researchers identified certain bacterial taxa that may indicate soil degradation (Chinmay et al., 2017).

Soil applied nematicides, fungicides, or insecticides are likely to knock out corresponding components of the soil food web for a period of time, while most herbicides are thought to exert relatively minor impacts on soil biota (Rose et al., 2016). However, diluted solutions of glyphosate damaged the soil fungus, *Aspergillus nidu-*

lans, and field applications of glyphosate at normal rates substantially reduced soil AMF spore viability, root colonization, and arbuscule formation (Druille et al., 2013; Nicolas et al., 2016). In some studies, herbicides have upset earthworm ecology, inhibited soil N_2 fixation and N cycling, or increased disease pressure (Rose et al., 2016). In North Carolina, cover crops terminated by mowing supported 16-25% greater microbial biomass, C and N mineralization than herbicide-sprayed or disked covers (Hu et al., 2015).

Orchard floor soils kept "clean" with either tillage or herbicides show elevated qCO_2 and severely depleted SOM (Lorenz and Lal, 2016; Lori et al., 2017). Compared to bare-soil, orchard floor in living cover enhanced microbial biomass, activity, MGE, N cycling, and tree nutrition (Azarenko et al., 2009; Reeve, 2014).

In conventionally managed soils, microbial biomass and functional diversity increased as crop diversity increased from monoculture to five-crop rotation, resulting in improved soil aggregation, nutrient cycling, total SOM, and organic N (McDaniel et al., 2014; Tiemann et al., 2015). In an oat-corn rotation, cover crops planted after oat harvest enhanced soil bacterial, fungal, protozoan, and total microbial biomass two and eight months after cover crop planting, compared to a no-cover control (Finney et al., 2017). Organic systems trials show the same trends, with improved SOM and soil health in corn-soy-cereal rotations with perennial sod or cover crops, and soil degradation in organic corn-soy with winter fallow (Moncada and Sheaffer, 2010).

In northwest China, intercropping corn with fava bean, chick pea, soybean, or oilseed rape for 6 – 7 years enhanced soil macro-aggregates by 15 – 56% compared to monocultures of any of these crops (Tian et al., 2019). The intercropping effect was related to changes in the soil microbiome, including increased AMF and saprophytic fungi, and decreased nitrifying bacteria.

Crop species can also affect soil biota. For example, cover crops of oats and rye enhanced AMF populations, hairy vetch promoted non-AM fungi, and an 8-species mix (four legumes, oats, rye, and two crucifers) had the highest bacterial, AMF, protozoan, and total microbial biomass (Finney et al., 2017). In North Carolina, winter cover crops of hairy vetch, crimson clover, and Austrian winter pea had different impacts on C and N cycling, and winter pea supported the highest MGE (Hu et al., 2015). Preceding crop (corn vs. canola) and tillage (moldboard plow vs. shallow cultivation) affected bacteria and archaea species composition in wheat crops in Germany (Babin et al., 2019). In the northeastern U.S., the multifunctional beneficial fungus *Metarhi-*

zium showed greater abundance with corn or field pea than with wheat or soybean, while crucifer crops did not support this organism at all (Gruber, 2017; Barbercheck et al., 2018).

Introducing new plants into an ecosystem to build diversity requires care. Invasive exotic plant species can displace native vegetation or hurt crops through direct or indirect impacts on the indigenous soil microbiome (Wolfe and Klironomos, 2005). The European perennial crucifer garlic mustard (*Alliaria petiolata*) releases glucosinolates that inhibit the ectomycorrhizal fungi of New World forests. Diffuse knapweed (*Centaurea diffusa*), also native to Europe, releases an antimicrobial chemical that upsets the soil microbiota of western U.S. rangeland. Other invasive plants modify soil microbiomes through altered resource availability (residues, root exudates, root architecture), hyper-accumulation of sodium from subsoil, or new N-fixing symbioses (Wolfe and Klironomos, 2005).

Promoting Mycorrhizal Fungi

Mycorrhizal fungi can play a vital role in crop nutrition, especially in lower-fertility soils such as the highly weathered Ultisols and Oxisols of tropical and subtropical regions, or very sandy soils of temperate regions. Organic vegetable growers in the lower Rio Grande Valley of Texas must deal with low-SOM soils that are also alkaline, very high in calcium (Ca), and sometimes poorly drained. Farmer interest in optimizing AMF activity has led to field trials of various strategies from cover cropping to applied inocula (Soti and Racelis, 2017).

Microcosm studies based on Netherlands dune grassland communities (sandy soils with very low plant-available N and P levels) showed that AMF play a key role in supporting effective N_2 fixation by the indigenous legumes white clover (*Trifolium repens*) and birdsfoot trefoil (*Lotus corniculatus*) (Van der Heijden et al., 2016). The legumes accrued significant biomass and N only when both rhizobia and AMF were present; with rhizobia only, they failed. In addition, the AMF enabled legume seedlings to emerge and grow in established sod.

Diverse rotations, cover crops, and minimum tillage support AMF activity and diversity, while excessive tillage, high nutrient levels, fungicide and herbicide use, and prolonged fallow periods hurt AMF (Gruber, 2017; Hamel, 2004; Rillig, 2004). In a meta-analysis of 54 studies from five continents, reduced tillage and winter cover crops each enhanced cash crop root colonization from indigenous AMF by 30% (Bowles et al., 2017). Leguminous cover crops were most effective, but even non-AMF host covers (crucifers) improved cash crop

AMF by 17% over fallow. In another meta-analysis, legume and/or grass cover crops enhanced AMF by up to 50%, and improved P uptake and yield in subsequent AMF-host crops (Hallama et al., 2019).

In field trials conducted at four organic vegetable farms in the Rio Grande Valley, cover crops of cowpea, sunnhemp, sudangrass, or a three-way mix increased soil AMF spore counts two to three-fold, while no increase occurred in a weedy fallow dominated by pigweed, a non-host for AMF (Soti and Racelis, 2017). Following a cash crop of kale (non-host) with cover crops of lablab bean, sunnhemp, or sudangrass grown for eight weeks yielded similar enhancement in soil AMF spore numbers, while pearl millet was not effective (Soti et al., 2016).

Ridge tillage and shallow tillage were nearly as effective as no-till in conserving AMF (25, 28 and 30% increase over moldboard plow, respectively) (Bowles et al., 2017). Reduced tillage made the greatest difference in sandy soils (45%), and after cover crops (40%), and increased AMF species diversity by 11%. AMF diversity can extend benefits to a wider range of host crops (Bowles et al., 2017). In irrigated organic vegetable production in Montana, soil AMF populations decreased significantly with one or more tillage passes, and were further reduced by an NOP-allowed vinegar-based herbicide (6.25% acetic acid) sprayed three times during the season (Atthowe, 2010).

Individual AMF species can colonize roots of multiple plant species, and vice-versa (Weil and Brady, 2017). Yet, species and cultivar-specific interactions of AMF strains and crops have been documented, and may contribute to both positive and negative “rotation effects” (Hallama et al., 2019). Cultivars of pepper and tomato can differ three-fold in level of AMF colonization, and different cover crops favor different AMF species (Douds, 2009; Soti et al., 2016). Plants and AMF apparently regulate each other to optimize the mutualistic relationship: plants selectively provide carbohydrates to the “best” fungal symbionts, and the AMF deliver nutrients to roots that provide them with the most carbohydrates (Kiers et al., 2011).

In a meta-analysis of 1,167 individual comparisons reported in 134 publications, plants inoculated with AMF or ectomycorrhizal fungi generally accrued greater biomass (average ~50% increase) than uninoculated controls (Hoeksema et al., 2010). Crops growing in P-limited conditions showed enhanced response to the mycorrhizal inoculant, while high levels of N and P reduced or eliminated response. In growth chamber trials, root colonization of pepper and tomato by a multispecies AMF inoculum ranged from 10-30% at low

(0.3 – 3 ppm) P levels in the nutrient solution but dropped to nearly zero at the standard 31 ppm P level (Douds, 2009). The AMF allowed tomato and pepper starts to grow satisfactorily at the lower P levels. Colonization of the strong AMF host baihagrass (*Paspalum notatum*) showed less sensitivity to P, decreasing from 50% at 3 ppm P to 25% at 31 ppm P (Douds, 2009).

In greenhouse and growth chamber studies, plants inoculated with multiple species of AMF showed twice the growth response seen with single-species AMF inocula, and providing other soil microbes along with the AMF (e.g., whole soil as inoculum) further improved response (Hoeksema et al., 2010).

Inoculating crop seeds or seedlings with AMF may be more effective than whole-field soil applications of AMF, as the latter are often outcompeted by native soil biota (Douds, 2009). Because commercial AMF inoculants give mixed results and can be costly to farmers when they fail, researchers have recommended utilizing the farm's indigenous AMF by propagating them on container-grown host crops inoculated with the farm's best topsoil, or simply by adding mycorrhizal-host cover crops to the rotation (Douds, 2015; Soti and Racelis, 2017).

Disease and pest suppression

Organic production practices can reduce many though not all crop diseases. In a comparison of several pairs of organic vs. conventional vegetable farms in central CA, lettuce crop losses to corky root (bacterial pathogen *Rhizorhapis suberifaciens*) were substantially less in the organic systems (Ariena et al., 2015). Organic practices reduce disease pressure by protecting soil microbial abundance, diversity, and disease-suppressive capacity. In conventional lettuce production, soluble N fertilizer and the herbicide Pronamide reduced microbial competition and antibiosis against the pathogen.

In a multi-year survey of plant disease incidence in two long-term diversified organic vegetable farms in Oregon and California, many regionally-prevalent crop pathogens were absent or remained below economic thresholds. However, *Fusarium* wilt in cucurbits, *Verticillium* wilt in watermelon, and *Fusarium* basal rot in the onion family caused serious and increasing problems (O'Brien et al., 2016). While soils become suppressive toward pathogens such as *Pythium* within a few years of adopting organic practices, *Fusarium* and *Verticillium* pose greater challenges and require additional research. One potential lead is a recent observation that the soil fungus *Talaromyces flavus* produces an enzyme that converts sugar in root exudates into hydrogen peroxide at sufficient levels to kill root-damaging Verticillium (Gruber, 2017)

In addition to improving soil health and diversifying the rotation, cover crops may suppress pathogens by modifying the soil microbiome, though effects are not consistent (Stone, 2012). For example, in Minnesota, soil incorporation of winter rye or radish cover crops stimulated the growth of disease-suppressive actinobacteria in some but not all trials (Sheaffer et al., 2016). In upstate New York, high yields and low incidence of white mold (*Sclerotinia sclerotiorum*) in organic soybean planted no-till into roll-crimped cereal rye suggests a suppressive effect of the rye mulch on this pathogen (Pethybridge and Ryan, 2018).

Genetic analysis of soil microbiomes from plots managed differently during the three-year organic transition period in Ohio showed increased levels of "bacterial biological control agents" under perennial sod versus annual vegetable cropping or summer tilled fallow with winter cover crops (Benitez et al., 2007). Organic tomato or soybean grown after perennial sod showed significantly less damping-off (*Pythium* and *Phytophthora*) than after annual crops or summer fallow, even when the pathogens were experimentally added to the soil (Baysal-Tustas et al., 2006).

Some organic amendments may contain disease antagonists. For example, microbes in dairy manure-based vermicompost appear to suppress the damping-off pathogen *Pythium aphanidermatum*. Cucumber seeds germinated for the first eight hours in vemicompost, then transfered to sterile sand and exposed to the pathogen did not develop disease, while autoclaved vermicompost provided no protection (Jack, 2012).

The orchard replant disease complex, caused by pathogenic fungi (*Rhizoctonia, Cylindrocarpon*), oomycetes (*Pythium*, *Phytophthora*), and the lesion nematode (*Pratylenchus penetrans*) imposes severe constraints on organic fruit production and orchard renovation. Soil incorporation of mustard seed meals (a two-species mix of *Brassica juncea* and either *B. napa* or *Sinapis alba* meal) at 3 tons/ac the autumn before tree planting suppressed the pathogen complex and improved tree survival and growth more effectively than the conventional fumigant Telone C17 (active ingredients 1,3 dichloropropene and chloropicrin) (Mazzola et al., 2015). Fungicidal isothiocyanates released from the seed meal played at most a minor role, as these "biofumigants" dissipated within two days, while suppression of *Pythium* and *Pratylenchus* continued for several years after a single application (Mazzola, 2016, 2017; Weerakoon et al., 2012). Pathogen numbers returned to pre-treatment levels by the second season after application of Telone C17. Tree survival and growth during three years after treatment were: seed meal > Telone C17 > untreated control (Mazzola, 2017).

The mustard seed meal treatments induced marked changes in the soil microbial community, with increased populations of known pathogen antagonists such as *Trichoderma* spp. and nematode-trapping fungi. In contrast, the conventional fumigant simply caused a temporary depression in the existing microbial community, which showed little change in composition after recovery (Mazzola et al., 2015). Apple rootstock genotype further modulated microbiome responses to the seed meal, and the use of tolerant rootstocks (Geneva type) showed potential for preventing replant disease at lower (1 – 2 ton/ac) use rates, which are more economically feasible for producers (Wang and Mazzola, 2019).

Growing certain cultivars of wheat, especially ‘Lewjain,’ in orchard soil prior to planting apple stock greatly reduced *Rhizoctonia* damage to apple roots by enhancing the growth of disease-suppressive strains of fluorescent *Pseudomonas* bacteria. In greenhouse trials, sterilization of soil after growing ‘Lewjain’ wheat or adding mustard seed meal eliminated the disease-suppressive effects, thus confirming that these treatments prevent disease through biological and not direct chemical effects (Mazzola, 2016).

Similarly, anaerobic soil disinfestation (ASD) works in part by modifying the soil microbiome (Shennan et al., 2015; Mazzola, 2017). ASD requires a *readily available* organic carbon source, such as orchard grass, rice bran, or mustard seed meal to suppress disease. When *finished compost* was incorporated before irrigation and tarping, the ASD treatment had little impact on soil microbiome, the target fungal pathogen *Rhizoctonia*, or lesion nematodes (Mazzola, 2017). While ASD is far less harmful to soil biota than conventional fumigants, other studies have shown that flooding can alter nutrient cycling, reduce AMF and actinobacteria populations, and increase CH_4 and N_2O emissions (Sanchez-Rodriguez et al., 2019).

Recent advances in gene sequencing methods have been applied to soil microbiomes to clarify mechanisms of general and specific disease suppression, and the impacts of organic amendments and management practices (Schlatter et al., 2017). Some key findings include:

- Wheat take-all, caused by the fungus *Gaeumannomyces graminis* var. *tritici*, is suppressed by antibiotics from certain rhizosphere strains of *Pseudomonas*. Since these strains thrive only in the presence of both pathogen and host, wheat monoculture paradoxically develops highly take-all-suppressive soils after four to six years.

"Rather than identifying, testing, and applying potential biocontrol agents in an inundative fashion, research into [disease] suppressive soils has attempted to understand how indigenous microbiomes can reduce disease even in the presence of the pathogen, susceptible host, and favorable environment." (Schlatter et al., 2017, Abstract).

- Wheat root rot, caused by a strain of *Rhizoctonia solani*, initially increases in no-till wheat, but again, disease-suppressive rhizosphere microbiota reduce disease severity after seven years of continuous wheat.
- Actinobacteria in the genus *Streptomyces* suppress many plant pathogens by releasing antibiotics and siderophores (iron-binding compounds), and by competing vigorously for root exudates and plant residues. Ubiquitous in soils, many *Streptomyces* species proliferate in the crop rhizosphere, often benefiting the plant.
- Potato scab (*Streptomyces scabies*) has been observed to diminish after 15 years continuous potato, during which disease suppressive *Streptomyces* increased.
- Organic amendments and green manures induce disease-suppressiveness by supporting a proliferation of *Streptomyces* spp. and other pathogen antagonists.

Although planting the same crop year after year suppresses certain diseases (Schlatter et al., 2017), caution that this approach may not provide stable protection over time, and may increase risks of other pest or disease outbreaks. Monoculture also reduces soil biodiversity and soil health, and violates the NOP crop rotation standard. Cover cropping and other soil health practices to maintain general disease suppression protects crops through multiple mechanisms against which pathogens cannot readily evolve renewed virulence (Schlatter et al., 2017).

Other studies indicate that crop rotation (potato after corn or alfalfa vs. continuous potato), buckwheat or canola green manures, or rice bran soil amendments can reduce common scab and verticillium wilt in potato (Tomihama et al., 2016; Wiggins and Kinkel, 2005). Populations of disease suppressive *Streptomyces* increased in green manure and rice bran treatments.

In Maine, compost amendments, crucifer cover crops, and applied pathogen-antagonist inoculants exerted additive and complementary effects on the soil biotic community that improved yields and reduced disease in potato (Bernard et al., 2012; Tavantzis et al., 2012).

Many rhizosphere and root-endophytic microorganisms can induce systemic resistance (ISR) to pathogen attack above or belowground (Bakker et al., 2012). These include disease-suppressive fluorescent *Pseudomonas* spp and *Bacillus* spp, and several other bacterial genera; *Trichoderma*, non-pathogenic *Fusarium,* and other fungi, including some AMF strains. When attacked by pathogens or pests, plants can recruit and "feed" microbes that stimulate ISR and/or suppress pathogens directly. The efficacy of ISR depends on populations of the inducing microbes and their interactions with other soil biota (Bakker et al., 2012).

Soil biota can also affect insect pests. When corn seed was treated with *Metarhizium robertsii* before planting, 91% of seedlings contained the fungus as an endophyte, which enhanced plant growth and reduced the growth of black cutworm feeding on the corn, but did not affect fall armyworm (Barbercheck, 2018). In a greenhouse experiment with tomato, one species of earthworm enhanced plant production of a defense compound, jasmonic acid, in response to western flower thrips infestation, resulting in a 65% reduction in thrips populations (Xiao et al., 2019). On the other hand, plant growth promoting strains of *Pseudomonas* and *Bacillus* has been shown to enhance the growth of aphids and reduce parasitism by their natural enemies in broccoli (Blubaugh et al., 2018).

Plant genetics and plant-microbe interactions

Crop cultivars show wide genetic variation in their capacity to host beneficial endophytic and rhizosphere microbes. In many cases, breeding and selecting crop cultivars for high-input conventional systems seems to have compromised the plant's capacity to enter into beneficial partnerships with soil life. For example, open pollinated land races of grain sorghum form much stronger AMF associations than modern hybrids. When grown in low-fertility soil with AMF but without fertilizer, land races gave 3-fold higher yields than the hybrids, and the grain had higher protein and mineral content (Cobb et al., 2016).

Rhizosphere microbiomes of some Mexican and Central American land races of corn include N_2-fixing and N cycling microbes that greatly enhance crop N use efficiency (Goldstein, 2015, 2016). Endophytic N_2-fixing *Burkholderia, Herbaspirillum*, and *Gluconacetobacter* appear especially efficient, meeting 40% of the crop's N requirement. Root microbiomes of modern hybrids include *Fusarium* strains that inhibit the N_2 fixers; conversely, the N_2 fixing endophytes in land races suppress *Fusarium*. Breeders at Mandaamin Institute have utilized land race germplasm to develop promising N-efficient and N_2 fixing hybrids that give competitive yields of high-protein grain on low-N soils and limited fertility inputs (Goldstein, 2018).

Both crop and microbial genetics play a substantial role in efficacy of legume N_2 fixation (Drinkwater and Grossman, 2018). In vetch cover crops in North Carolina, native rhizobia often outcompeted applied inoculant, and varied greatly in N fixation efficacy (Hu et al., 2015). Hardarson and Atkins (2003) cited a "wealth of genetic diversity among legumes and their *Rhizobium* symbionts" that can be utilized to improve N_2 fixation.

Plant root-mycorrhizal associations are modulated through both plant and fungal genetics, resulting in species-specific variation in AMF efficacy. Substantial varietal differences in AMF colonization have been documented in carrot, pepper, corn, other grains, and legumes, leading to recommendations that plant breeders select for AMF efficacy (Douds, 2009; Hamel, 2004; Silva, 2016; Weil and Brady, 2017).

Evidence from a growing number of crops indicates that breeding and selection for disease-suppressive rhizosphere microbiome and ISR response can advance organic disease management. For example, wheat cultivars differ in their capacity to host take-all-suppressive *Pseudomonas* bacteria in their root zones and thereby protect themselves from the disease (Schlatter et al., 2017). Several tomato grafting rootstocks, including 'Beaufort,' 'Maxifort,' and 'Big Power' confer resistance to southern root knot nematode (*Meloidogyne incognita*), Southern blight (*Sclerotium rolfsii,* and fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici)*, all of which cause severe damage to non-grafted heirloom tomato cultivars (Louws and Rivard, 2011). Modern tomato cultivars show less ISR protection against late blight *(Phytophthora infestans)* and leaf mold *(Botrytis cinerea* leaf mold) in response to rhizosphere *Trichoderma* than land races (Hoagland, 2018). However, recent breeding efforts have shown promise for restoring ISR response in tomato (Amit Jaiswal and Lori Hoagland, 2019, pers. commun.).

Carrots growing in healthy soil can recruit a rich diversity of endophytes that confer resistance to leaf blight (*Alternaria dauci*), enhance crop nutrition by solubilizing P and fixing N_2, and produce growth promoting substances. Researchers have documented genotypic variation among cultivars in responsiveness to beneficial soil biota, pointing to an opportunity for varietal selection to optimize plant-root-microbe partnerships (Abdelrazek, 2018; Abdelrazek and Hoagland 2017).

Some but not all corn cultivars respond to rootworm attack by emitting a substance that attracts the entom-pathogenic nematodes *Heterorhabditis* and *Steinernema*. Cultivars with this capacity can enhance the efficacy of applications of these biopesticide organisms, yielding control commensurate with conventional pesticides (Hiltpold et al., 2010).

Priorities for additional research

Based on tremendous progress in the understanding of soil biology and the impacts of different organic systems and practices, and the need for further research and development of practical applications in organic production, the following research priorities emerge:

- Developing microbial and nematode community structural analyses into farmer-ready practical methods to assess soil function and select best practices.
- Plant breeding for enhanced capacity to:
    - Partner effectively with mycorrhizal fungi, N_2 fixing microbes, and other beneficial soil biota.
    - Recruit and host natural enemies of crop pathogens and pests.
- Interaction among plant genotype, rhizobium strain, AMF, and soil N in N fixation and vigor in legume cover, forage, and cash crops.
- Strategies to promote tightly coupled N cycling in a wider range of crops, soils, and regions.
- Integrated organic management—crop rotation, nutrients, etc.—to optimize mycorrhizae.
- Effective use of on-farm (indigenous) and purchased mycorrhizal inoculants.
- Organic practices to optimize soil biological activity, biodiversity, and function in different soils and climates, especially:
    - Low rainfall regions (dryland and irrigated production)
    - Saline, alkaline, and otherwise challenging soils
- Crop specific impacts on soil life and practical guidelines for designing crop rotations.

- Optimizing the soil microbiome for orchard and other woody perennial crops, including the role and impact of earthworms.
- Integrated biological disease management strategies that include:
    - Utilization of indigenous soil microbiome and root endophytes.
    - Crop rotation, cover crop, and managing soil moisture, pH, and nutrient levels.
    - Management strategies to elicit ISR.
    - Current or new cultivars with horizontal disease resistance, robust ISR response, or enhanced association with disease suppressive organisms.
    - Application of biofungicide and biopesticide products.
    - IPM for challenging pathogens such as *Fusarium, Verticillium,* and *Phythophthora*.
- Fine tuning microbiome-modification treatments—anaerobic soil disinfestation, bio-solarization, and incorporation of green manures, crucifer seed meals, and other biologically active organic amendments—for a wider range of crops, soils, and regions.
    - Explore impacts of anaerobic and heat treatments on beneficial soil organisms, nutrient cycling, and GHG emissions.
- Continue impartial evaluation of efficacy of commercial biostimulants, biofertilizers, and soil conditioners, including net economic returns on their use, to develop practical guidelines for farmers.

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* For project proposal summaries, progress and final reports for USDA funded Organic Research and Extension Initiative (OREI) and Organic Transitions (ORG) projects, enter proposal number under “Grant No” and click “Search” on the CRIS Assisted Search Page at:

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