

Soil Life in Organic Farming: the Central Role of Soil Organisms in Soil Health and Resource Conservation

*A Webinar for NRCS
[Month, day, time], 2022*

Presented by:

Mark Schonbeck, Research Associate, Organic Farming Research Foundation (OFRF)

Presentation Notes

Introduction (Slides 1-3)

Slide 2 - *Tiny yet mighty: soil organisms perform all key functions of a healthy soil*

Slide 3 – Organic farmers rely on soil life for crop nutrition

Feeding the soil life – with compost, green manures, livestock manure, and other organic residues – to provide for crop and livestock nutrition has been a foundational principle of organic nutrient management since the dawn of the organic agriculture movement in the early 20th Century. Early practitioners sought to meet most of the farm’s nutrient needs from on-farm sources and efficient nutrient cycling within the farm ecosystem, and composted residues to stabilize nutrients and organic matter (Howard, 1947).

Soil Biology 101: a Brief Tour of the Soil Food Web (Slides 4-13)

Slide 5 – *The soil food web*

This image was created by Dr. Elaine Ingham et al. (2000) and has been widely used in the Soil Biology Primer and other NRCS educational materials on soil health. Much of the information on individual soil organisms in the next 8 slides is based on Chapters 11 and 12 in Weil and Brady (2017).

Slide 6 – *Bacteria and archaea*

Soil prokaryotes – very small simple single-celled organisms without a distinct nucleus – include a tremendous genetic and functional diversity of bacteria, and a significant number of archaea, which look like bacteria yet are no more related to true bacteria than they are to humans!

A single spoonful of soil may contain billions of bacteria representing thousands of distinct genotypes or species though the constant exchange of genetic material and evolution of soil microbes renders the concept of “species” hard to define. Soil bacteria occupy a wide range of niches including fresh organic residues; soil micropores; on, near, or within plant roots

(rhizosphere); and within the digestive tracts of larger soil organisms such as nematodes, mites, insects, and earthworms.

Most soil bacteria feed on organic residues (decomposers) or plant root exudates. They live on readily-assimilated materials such as sugars, starches, amino acids, proteins, and organic acids, and are less able to attack more resistant materials such as lignins, waxes, and cellulose. Bacterial cells are rich in protein and plant nutrients; thus initial bacterial processing of residues tends to immobilize N and cause a temporary drop in plant-available nutrients.

Some bacteria play more specialized roles such as fixing atmospheric N₂ into plant-available form, oxidizing ammonium-N into nitrate-N, or living as gut symbionts in larger soil organisms helping them to digest the organic residues or prey they consume.

Soil bacteria proliferate on and near living plant roots, where they derive nourishment directly from plants. Most of these organisms are harmless or beneficial (plant growth promoting rhizobacteria), while some deplete plant vigor to some degree (deleterious rhizobacteria) and a few are virulent plant pathogens.

Archaea may make up about 10% of the soil prokaryote biomass, and often have specialized niches and functions. They include methanogens (creating methane from organic residues in saturated anaerobic soils), chemotrophs including nitrifiers and others that derive energy from conversion of other soil minerals from one form to another (which regulates their availability to plants), and species that thrive in extremely hot, cold, or dry conditions.

Slide 7 – *Actinobacteria*

Actinobacteria, also known as actinomycetes, are filamentous bacteria that can form extensive, visible, fungus-like masses (e.g., the fine, white mold-like filaments that permeate compost piles at certain stages of the compost process). They were kicked out of the fungal kingdom by astute taxonomists who noticed that the individual cells are prokaryotic (lacking a distinct nucleus around the genetic material).

Like fungi, actinobacteria can degrade resistant woody materials that other bacteria cannot digest; but like bacteria they prefer near-neutral over acidic soil conditions. Actinobacteria are most active in warm, moist soil, but can tolerate drier or saline conditions, helping to sustain biological activity during drought and in arid climates.

One genus of actinobacteria, *Frankia*, forms N₂-fixing nodules on the roots of alder and several other families of forest trees and woody shrubs, providing a major portion of the plant's N requirement similar to *Rhizobium* bacteria on legumes.

Streptomyces spp. play important roles in many agricultural soils; many suppress a range of plant pathogens by releasing antibiotics, while at least one – *S. scabies* – is itself a pathogen, causing common scab of potato.

Slide 8 – *Fungi*

The soil contains a tremendous diversity of fungi, including saprotrophic (decomposer), mycorrhizal (root-symbiotic), parasitic (living on or within other soil organisms), and pathogenic species. While some of the worst root rots and other plant diseases are caused by fungal pathogens, the fungal kingdom provides essential services without which healthy soil as we know it, agricultural production, and most higher organisms would simply not be possible. The fossil record contains evidence that mycorrhizal fungi and land plants co-evolved together around 450 million years ago, and that the fungi made it possible for plants to begin to occupy barren lands and convert rocks and dirt into soil.

Decomposer fungi effectively convert bacterial-decay-resistant materials such as grain straw, fallen tree leaves, and dead wood into long-lasting stable SOM.

In healthy agricultural soils, fungi and bacteria play roughly equal roles in soil microbial biomass and function. About 80% of plant species on earth enter into symbiosis with arbuscular mycorrhizal fungi (AMF) and/or ectomycorrhizal fungi, and many depend on this mutualism to thrive, grow, and reproduce. Finally, parasitic fungi such as *Trichoderma*, *Beauveria*, and *Metarhizium* are such valuable natural enemies of plant-pathogenic fungi and soil borne insect pests that they are now marketed or are under development as organic bio-fungicides and bio-pesticides.

Some strains of *Trichoderma* appear to play multiple roles: living as a growth-promoting root endophyte (living within plant tissue) and inducing systemic resistance to foliar and root diseases as well as attacking soilborne pathogens directly. Similarly, the entomopathogenic fungus *Metarhizium* can also grow as a beneficial root endophyte that can enhance the growth of corn and slow that of some of its pests; in fact, researchers at Pennsylvania State U have documented a single mycelium of *Metarhizium* parasitizing an insect pest and partnering with crop roots, transferring detectable amounts of N from former to latter.

Slide 9 – Protozoa

While protozoa make up a relatively small percentage of the soil biomass (18 – 250 lb/ac live weight, compared to 1,000 lb/ac or more each for bacteria, fungi, and earthworms), they play an important role in mineralizing N and other nutrients when and where plants need them. As plant roots give off bacterial “food” in the form of root exudates and fine root sloughing, bacteria proliferate in the rhizosphere, thereby attracting protozoa (and also microbe-feeding nematodes) whose grazing activities release nutrients for roots to take up. When this system is in optimal balance, tightly-coupled nutrient cycling takes place, which enhances crop nutrient efficiency, reduces fertilizer needs, and can protect water quality. Photo credit: Hoorman (2011) Weil and Brady, 2017, cited earlier.

Slide 10 – Nematodes

The word nematode still strikes fear in the hearts of many farmers, and indeed this phylum includes some severe pests such as root knot, sting, lesion, and spiral nematodes. Yet about 90% of the nematodes in a healthy soil occupy other niches and perform valuable functions. There is even evidence that light attack by root feeders can stimulate root growth and improve plant health; it is only when the root feeders get out of balance that crops suffer damage.

Like protozoa, nematodes account for a small percentage of soil biomass (10 – 260 lb/ac live weight) but they play several important roles in soil biological function. The grazing activities of bacteria- and fungal-feeding nematodes can account for 30 – 40% of plant-available N in cropland soils, since they do not need all of the N in the microbes they consume, and excrete the surplus in soluble forms. When this activity is concentrated in the rhizosphere, it can contribute to tightly coupled (efficient) N cycling; when the soil is amended with an abundance of N-rich organic residues (such as an all-legume green manure), the bacterial and nematode bloom throughout the soil can result in excess soluble (leachable) N for a period of time.

Predatory and omnivorous nematode species help keep pests and pathogens in check, including root-feeding nematodes, while entomopathogenic nematodes parasitize and kill larvae of several soil dwelling insect pests.

Feeding habits of nematodes are reflected by mouth parts: bacterial-feeders have relatively ornate “lips” that sweep bacteria into their mouth. fungal and root feeders have spear-like mouth parts for piercing and sucking fungal or root tissues, and predators have hard tooth-like structures for seizing prey.

Note that the use of nematicides to deal with pest nematodes could also hinder nutrient cycling by killing the microbe-grazers, and cause secondary pest outbreaks by killing the predators, thus increasing reliance on external fertility and crop protection inputs.

The structure of nematode communities in the soil has emerged as a potentially valuable index of soil health and the impacts of recent management practices; for example, a proliferation of bacterial feeders may follow tillage and addition of N-rich organic residues and indicate possible net losses of SOM, while a high diversity including all the functional groups (and not too many root feeders) suggest a healthy, balanced soil biota overall. Further research is needed to develop guidelines for interpretation and practical application to soil management decisions in organic and sustainable production.

In addition to agricultural fields, grassland soils with near-neutral pH and relatively low C:N ratio in the organic fraction generally have high populations and diversity of nematodes.

(References: Cogger et al., 2013; Epstein, 2007; Hooks et al., 2015; Moore-Kucera et al., 2008; Ugarte and Wander, 2008; Ugarte et al., 2013)

Slide 11 – *Micro-arthropods*

Microarthropods – mainly mites (eight-legged) and springtails (insects – six-legged) are major components of the soil mesofauna – small animals barely visible to the naked eye. They feed primarily on plant litter and fungi; in the process, they shred the residues into fine bits, thereby facilitating further decomposition by bacteria and fungi. Micro-arthropods are especially abundant and important members of the food web of forest and woodland soils with low (acidic) pH and high C:N ratio in the organic matter. They are highly sensitive to tillage; thus no-till and minimum-till systems allow their numbers and activity to increase in cropland soils (Cogger et al., 2013; Epstein et al, 2017; and Weil and Brady, 2017).

Slide 12 – *Earthworms*

Earthworms are nature’s tillers and compost turners.

Epigeal (above the soil) earthworms such as the red wiggler (*Eisenia foetida*) live in organic residues, converting them into nutrient rich, biologically active castings. These worms are used in vermicomposting operations to make the worm castings marketed as an organic fertilizer and ingredient for potting mixes.

Soil dwellers such as the European nightcrawler (*Lumbricus terrestris*) build macropores and deep channels in the soil, incorporating organic residues throughout the soil profile and leaving their nutrient-enriched castings on or near the surface. They ingest organic residues along with mineral soil and mix them with their own gut microbiome to extract the nourishment they need, then excrete castings consisting of well-aggregated mineral soil enriched with organic matter, plant-available nutrients, and diverse microbiota. Earthworms play central roles in digesting organic residues, maintaining soil drainage and moisture infiltration, and cycling and releasing nutrients in cropland and grazing land soils. Where earthworm populations are high, their activities can turn over tens or hundreds of tons of soil annually, amounting to biological tillage – hence the description of earthworms as “ecosystem engineers.”

There can be a downside to earthworms, in that their activity can increase N leaching risks (by speeding both mineralization and deep drainage of water through soil profile) and, when exotic earthworm species invade forest ecosystems, upset the particular soil biota and ecosystem on which the trees depend (Amador and Gorres, 2005; Weiland Brady, 2017).

Slide 13 – *Other soil macro-fauna*

In the Pacific Northwest, organic vegetable farms had higher diversity of dung beetles and coprophagous (manure-consuming) microbes than conventional farms and showed potential for accelerating the attenuation of human foodborne pathogens in surface-deposited manure, thereby contributing to food safety in crop-livestock integrated systems (Jones et al., 2019; Weil and Brady, 2017).

Soil Life and Soil Functions (Slides 14-23)

Slide 15 – *Crop production*

Soil organisms support crop production in several ways that organic producers consider essential to the success of their operations. The bacteria and fungi that proliferate on fresh organic residues take up the nutrients therein. Protozoa and nematodes feeding on the bacteria and fungi release some of the nutrients in plant-available form, thereby providing for crop nutrition (Ingham et al., 2000; Schonbeck et al., 2019; Weil and Brady, 2017). Mycorrhizal fungi form symbioses with the roots of 80% of crop species and greatly facilitate nutrient and moisture uptake.

The entire community of soil life works together to maintain soil structure – their habitat – binding soil particles and bits of organic matter into aggregates (bacterial glues and fungal filaments or hyphae) and continually forming pores and channels throughout the soil profile (micro-arthropods, earthworms, other larger organisms, and plant roots) (Ibid).

Soil microbes can also protect plants against pathogens and pests, by directly consuming or parasitizing the harmful organisms, crowding them out, or forming a protective shield around plant roots. Some beneficial rhizosphere and endophytic microbes also stimulate *induced systemic resistance* (ISR) that can protect the whole plant against both soil-borne and foliar pathogens (Abdelzarek, 2018; Abdelrazek and Hoagland, 2017; Bakker et al., 2013; Zubieta and Hoagland, 2017).

Slide 16 – *An ancient partnership*

The exchange of plant photosynthetic product (sugars, amino acids, and other soluble organic compounds) for nitrogen, phosphorus, and other mineral nutrients has sustained plant and soil microbial communities ever since the first land plants evolved some 450 million years ago.

Slide 17 - Rhizosphere (root zone)

The plant root microbiome includes endophytic (within root tissue), root-surface, and rhizosphere (within ~0.1 inch of root surface) microbes.

A large percentage of the microbiome of many crop plants consists of arbuscular mycorrhizal fungi (AMF), which establish highly efficient “trading posts” called arbuscules within root cortical tissue (plant and fungal cell membranes in direct contact to exchange nutrients) and grow out into the soil for one or more inches beyond the root surface, thereby greatly expanding the

effective volume of the root system. As a result, moisture and nutrient uptake becomes much more efficient, and mycorrhizal plants show increased resilience to drought as well as improved nutrient status. The fungus gains a tremendous advantage as the plant feeds it directly through the arbuscule so that it does not have to compete with other fungi and bacteria for organic residues in the soil; in return it can solubilize and absorb phosphorus and other nutrients from soil minerals that uncolonized roots could not use directly.

Another important plant nutrition pathway is via the second trophic level of the soil food web. As rhizodeposition (root exudates and sloughing of root hairs and surface cells of growing roots) stimulates a “bloom” of bacteria and other microbes in the rhizosphere, the grazers – protozoa and microbe-feeding nematodes – are drawn to the banquet table, shedding surplus nutrients right in the root zone for plants to absorb.

Both of these mechanisms promote *tightly coupled nutrient cycling*, in which plants obtain adequate N and other nutrients even while bulk soil soluble N and P levels are low enough to pose no threat to water quality or climate – and also low enough to result in high fertilizer recommendations on a standard soil test!

When recommended rates are applied in a readily plant-available form, the plant may reduce its investment in the soil life – why “waste” 10% or more of the photosynthetic product if the soil is flooded with soluble nutrients? In the short run, this can improve crop yield, but in the long run the multiple benefits of the root microbiome to soil, crop, and environmental health are lost.

Slide 18 – *How a biologically active soil absorbs and retains a downpour*

The continual maintenance of soil structure by soil biological activity allows a healthy soil to absorb and retain moisture, thereby reducing runoff while enhancing the soils’ capacity to sustain crops through dry spells.

This vital function depends on the soil remaining covered year-round by crop canopy, crop residues, or organic mulch. Even the healthiest soil will begin to crust over or wash away under the impacts of severe downpours, which are becoming more common with climate change. The cover breaks the force of falling raindrops and allows the water to trickle gently into the soil.

Slides 19-20 – *The plant disease triangle and how soil life can help break it*

A vigorous and diverse community of soil life can reduce crop disease problems by breaking or weakening the “plant disease triangle” in several ways. The structural maintenance activities of various organisms improve drainage, making the environment (E) less conducive to most pathogens. Other microbes consume or suppress pathogens (P) or induce systemic resistance in the host crop (H) (Abdelrazek and Hoagland, 2017; Bakker et al., 2013; Eastburn, 2010; Egel et al., 2018; Schlatter et al., 2017; Wang and Mazzola, 2019; Zubieta and Hoagland, 2017). Organic management can support these beneficial organisms while agrichemicals may suppress them, leaving the soil more friendly to certain pathogens (Abdelrazek, 2018; Ariena et al., 2015).

Slide 21 – *Ecosystem services*

Recent research indicates that soils treated regularly with pesticides host those microbes that can break down those chemicals (Walder et al., 2022).

Slide 22 – *Soil self-maintenance*

Slide 23 – *Soil microbes maintain soil structure and sequester carbon*

Soil microbes consume and process virtually all organic inputs to the land, including root exudates, above- and below-ground plant residues, manure, animal remains, and organic mulches applied for crop production. The microbes utilize part of the residues for their life processes, releasing CO₂ through respiration, and convert the rest into microbial metabolites and microbial remains (“necromass”), which comprise active SOM (available for re-processing by soil life) and stabilized SOM (protected from further breakdown). The most stable SOM forms when microbial byproducts and necromass become adsorbed to soil clays and silt particles, forming *mineral associated organic matter* (MAOM) (Bhattacharyya et al., 2022; Grandy and Kallenbach, 2015; Kallenbach et al., 2016; Prescott et al., 2021).

Thus, the soil life plays a central role in carbon sequestration as well as the dynamic processing of crop residues and active SOM that underpins soil fertility and crop nutrition, especially in organic systems that do not use soluble inorganic fertilizers.

SOM can also become stabilized when it becomes integrated into the interior of soil aggregates, where it becomes less accessible to microbes and oxygen. Active SOM turns over in a few months to a couple of years. Aggregate-protected SOM may last for years to decades, and MAOM for centuries or millennia. Although SOM concentrations are greatest in the top 6 to 12 inches of the soil profile, substantial quantities of organic carbon become sequestered at greater depths as soluble organic matter is leached into the subsoil, deep roots release exudates, and their associated microbiome converts these resources into subsoil MAOM, which can persist for three or four times as long as topsoil MAOM (Button et al., 2022; Dynarski et al., 2020).

Organic Farming for Soil Biology: challenges, opportunities, and recent research findings – (Slides 24-42)

Slides 25 and 26 – *Challenges in managing soil life in organic systems*

The overarching challenge for all farmers in managing soil life for sustainable production is that soil biology is complex, locale-specific, and difficult to monitor and predict in practice. Ongoing research into soil-plant microbiomes, including organic systems research funded by the USDA Organic Research and Extension Initiative (OREI) and Organic Transitions Program (ORG) aims to elucidate soil processes, the impact of farming practices, and management strategies for best soil health and production outcomes. The following slides address specific challenges and relevant recent research findings.

Slide 27 – *Soil organisms can mineralize nutrients and build SOM.*

When the soil microbiome (B) processes fresh residues and root exudates, part of this organic input (OI) becomes new microbial biomass (B_n) and part is released as respiratory carbon dioxide (R) and plant-available nutrients. R reflects mineralization and B_n reflects the soil biota’s longer term capacity to sustain both carbon stabilization (formation of MAOM) and nutrient mineralization.

Soil biologists have developed two parameters to describe the balance between these two vital processes: microbial growth efficiency (MBE) – the fraction of organic input that becomes new biomass; and the metabolic quotient (qCO₂), the ratio of respiration rate to existing biomass, or maintenance respiration. These indices are calculated in terms of *carbon* – i.e. how much of the carbon in organic inputs becomes new microbial biomass, and how much CO₂-C is released per unit microbial biomass C (Six et al., 2006).

Soil respiration rates are generally positively correlated with SOM stabilization and total SOM, and both respiration and stabilization are positively correlated with crop yields (Hurisso et al., 2016; Morrow et al., 2016). A three-day soil respiration test (“soil test biological activity” or STBA) has shown strong positive correlations with multiple soil health parameters including microbial biomass and the soil’s capacity to provide N to crops (Franzluebbers, 2018a).

Slide 28 – *Building microbial biomass and stable SOM*

Practices and inputs that promote microbial growth efficiency (MGE) and formation of stable SOM include diverse rotation, reduced or no tillage, and diverse inputs with balanced carbon-to-nitrogen (C:N) ratio, such as a mixed cover crop including cereal grains (high carbon) and legumes and/or crucifers (high nitrogen), and compost based on mixed starting materials (manure and food waste for N and other nutrients, bedding, yard waste, and mature crop residues for C).

More decay-resistant materials such as tree leaves, chipped brush, other forestry byproducts, and grain straw support beneficial fungi, which have high MGE and play a key role in building stable SOM. However, if *only* high-C:N inputs are provided, the soil microbiome becomes N-limited, and produces less new biomass and stable SOM, as it must respire-off all the excess C (Grandy and Kallenbach, 2015).

Finished compost is especially effective in building stable SOM, and, when used in moderate amounts in combination with high biomass cover crops, can promote an abundant, diverse, and balanced soil microbiome, especially when tillage is also reduced (Cogger et al., 2013; Delate et al., 2015; Hurisso et al., 2016; Wander et al., 1994).

Slide 29 – *Promoting mineralization*

Tillage acts as a stimulant, accelerating microbial respiration, releasing plant-available nutrients and consuming some of the active SOM. MBE (Bn/OI) tends to decline, and qCO_2 (R/B) may increase (Zuber and Villamil, 2016).

Cover crops, especially succulent legumes or crucifers, also tend to promote the mineralization function over stabilization (Brennan and Acosts-Martinez, 2017; Hurisso et al., 2016). Tilling in a high-N green manure stimulates the growth of soil bacteria and their immediate consumers, including protozoa and bacterial-feeding nematodes. Concentrated organic fertilizers such as poultry litter, blood meal, and feather meal have similar effects on soil biology. Because the resulting bacterial-dominated soil microbial community has a lower microbial growth efficiency than microbiomes richer in fungi, these practices generally do not build much SOM, but can enhance nutrient availability to the current season’s crop.

Slide 30 – *Stressed soil microbiome*

When the soil microbiome experiences certain stresses, their respiration rates per unit biomass increase (higher qCO_2 , and index of stress on the soil life), and the positive correlation between soil respiration and soil health parameters such as total SOM or microbial biomass no longer holds true.

Farming practices that stress the soil life include intensive tillage, heavy applications of soluble nutrients, unprotected soil surface (exposure to temperature extremes, drying by direct sun, sealing by raindrop impact, and erosion), and prolonged fallow periods (absence of living root with their daily input of exudates and fine root sloughing). In these conditions, the soil biota must devote a greater percent of their C intake to maintenance respiration (higher qCO_2), leaving

less available for microbial growth and SOM formation (lower MBE) (Dick, 1992; Morrow et al., 2016; Zuber and Villamil, 2016). These systems also tend to provide less organic input than sustainable organic or conservation agriculture systems. As a result, microbial biomass, active and total SOM, and soil N mineralization capacity all decline.

Organic agriculture generally enhances microbial activity (Lori et al., 2017). However, organic systems that rely on concentrated nutrient sources like poultry litter for crop nutrition and on repeated tillage and cultivation for weed control can incur a similar suite of stresses and resultant depletion of SOM (Bhowmik et al, 2016. 2017).

Orchard floor soils maintained as bare fallow through herbicides or tillage are highly stressed, showing two-fold higher qCO_2 and 50% reduction in SOM compared to organic orchard soils maintained under living cover (Lorenz and Lal, 2016). In addition, long term use of soluble NPK fertilizers tends to reduce microbial biomass, increase qCO_2 , deplete SOM, compromise the soil food web's capacity to mineralize N and other nutrients for crop utilization, and thereby increase the farming system's dependence on further N inputs in the future (Dick, 1992; Khan et al., 2007; Mulvaney et al., 2009).

Slide 31 – *Enhancing root exudation for a vibrant soil biota*

In an extensive research review, Prescott et al (2021) identified three key strategies for providing optimum nourishment for the soil microbiome. First, providing N, P, and water to crops at rates *slightly below the optimum for top growth* results in a surplus of organic carbon compounds in the foliage, as these input levels do not restrict photosynthesis, nor do they seriously affect yields or quality. The surplus sugars and other simple organic compounds are translocated into the roots, enhancing both root growth and root exudation, which directly feeds the microbes. Extensive root systems and high exudation rates also enhance the formation of MAOM and hence long-term carbon sequestration. Conversely, providing ample soluble N and P (from organic or synthetic sources) greatly reduces the export of photosynthetic product from shoot to root, and the microbial community goes hungry and may decline.

Second, the authors found that including legumes in the crop rotation or perennial production system enhances microbial activity and MAOM formation. Unlike soluble N, the N-rich exudates from legume root systems provide an optimum ratio of carbon and nitrogen for microbial nutrition, and growth.

Finally, rotational grazing managed so that grazing occurs *late in the rapid growth phase of the forage* maximizes total root exudation over the course of the grazing season. Root exudation under forages reaches its maximum during the rapid growth phase and declines during maturation, so grazing either too early (inadequate recovery) or too late (overmature forage, which is also lower quality and can aggravate livestock enteric methane production) can result in far less root exudation, microbial activity, and MAOM formation. Variations in grazing schedule may explain why studies of net GHG flux during rotational grazing have given results varying from no effective C sequestration to sequestration rates exceeding one ton per acre of managed pasture annually.

Slide 32 – *Mycorrhizal networks build soil and Plant health in forestland*

Forest Ecologist Suzanne Simard and other researchers have found that an underground mycorrhizal network links together many individual trees, shrubs, and forest floor plants of different species. Both ecto- and arbuscular mycorrhizal fungi have an amazing ability to link multiple plants, and often different species of plants, together through a single mycelium (hyphal

network). Similarly, a single plant may be colonized by several species of mycorrhizal fungi that can serve complementary functions. In forest ecosystems, mature trees can feed saplings via mycorrhizal networks, some of which may occupy hundreds of acres and live for centuries. This “mycorrhizal internet” enhances forest health and vigor in several ways:

- Trading plant photosynthetic product for mycorrhiza-scavenged nutrients the plant needs (as described above)
- Sharing of resources, moving photosynthetic product, nitrogen, and mineral nutrients from areas of surplus to areas of deficit.
- Trading of resources, often between different species, enhancing the vigor of both compared to monoculture reforestation plantings, which often suffer poor health.
- Supporting the next generation – mature “mother” trees provide both organic carbon and nutrients to young trees, allowing them to thrive and grow in dense shade, so that they can replace aging trees as they die and fall.
- Sending chemical signals; for example when trees at one location are attacked by insect pests, they send out a “warning signal” via the mycorrhizal internet that induces defensive responses such as ISR in neighboring trees, thereby slowing the outbreak and reducing damage.

Slide 33 – Four-way symbiosis in grass-legume pasture.

In prairie, pasture, and mixed-species cover crops, AMF can link grass and legume and help distribute nutrients for mutual benefit. As the legume-rhizobia symbiosis fixes abundant N, and the large, fibrous, and mycorrhizal root system of the grass absorbs P more efficiently, the mycelial connection may facilitate an exchange of these two nutrients. Although the plants are investing a substantial fraction of their photosynthetic product in the rhizobia and AMF symbionts, the four-way cooperative relationship generally enhances the health and vigor of all four components (Weil and Brady, 2017). Other studies have shown the importance of AMF to N₂ fixation efficacy in the legume-rhizobium symbiosis (Drinkwater, 2011; Hamel, 2004; Rillig, 2004).

Slide 34 – *Meeting organic farming’s phosphorus challenge*

Organic farms that rely on manure and compost for fertility can accrue excessive amounts of phosphorus (P) in their soils, which can in turn inhibit mycorrhizal activity (Douds, 2009; Hamel, 2004; Rillig, 2004). Using organic nutrient sources to meet the entire N requirement of crops in an organic rotation generally accrues surplus P, and is often not necessary, especially as soil biological activity improves with years of organic management. For example, organic field crop rotations have maintained top yields on half the recommended N and no P or K in a sandy coastal plain soil in South Carolina (Kloot, 2018), and organic vegetables grown after a rye-clover cover crops did not require any N (Robb and Zehnder, 2016). In multi-site field studies to determine the economic optimum N application rates (EONR) for field corn and fescue forage, actual N need was inversely related to soil test biological activity (STBA), and EONR reached zero at one-third of sites where STBA was high (Franzluebbers, 2018b, Franzluebbers et al., 2018)

Slide 35 – *Balancing C and N in organic inputs*

Global meta-analyses of the impacts of management practices on soil life showed that using organic (versus soluble) nutrient sources more than doubled the biomass of soil bacteria, fungi, and nematodes feeding on bacteria and fungi (Morugán-Coronado et al., 2022, Puissant et al., 2021). High rates of organic N, or low C:N sources (all-legume green manure, poultry litter) increased N leaching and nitrous oxide (N₂O) emissions, whereas using organic N sources at rates to provide *total* N similar to soluble fertilizer recommendations reduced N leaching while sustaining yields (Davis 2019, Wei et al., 2022).

A research team at Washington State University compared the crop and soil impacts of two nutrient sources in organic vegetable production in a maritime soil in Washington State: on-farm mixed compost made from dairy manure and bedding and yard waste (higher C:N) at rates of 6 to 8 tons/ac annually, and composted poultry litter (low C:N) at 1.8 – 2.6 tons/ac annually. The total N amounts applied in the two treatments were similar. Crop yields, soil physical, chemical, and biological properties, and potential to emit nitrous oxide (N₂O), were monitored over an 11-year period.

The higher C:N mixed compost clearly improved overall soil health, with higher microbial activity, higher levels of enzyme activities involved in nutrient cycling, increased active SOC (65% higher permanganate-oxidizable carbon, POX-C), and a more balanced nematode community (Bhowmik et al., 2016, 2017; Cogger et al., 2013). Formation of N₂O depends on soil biological processes and microbial species composition, and higher levels of nitrifying bacteria and bacterial feeding nematodes in the poultry litter treatment suggest a risk of increased N₂O emissions.

Other research outside the Western regions indicates that poultry litter inputs and succulent green manures can lead to sharp spikes in N₂O emissions. In one farming systems trial, an organic grain rotation using poultry litter (4.5% N) at 1.5 to 2.2 tons/ac-year showed five-fold greater total N₂O emissions than the conventional system (Baas et al., 2015). Most of the emissions occurred when poultry litter + cover crop incorporation + high rainfall created a “perfect storm” for microbial formation of this greenhouse gas: ample soluble N and active organic C, high microbial activity, and high soil moisture levels that temporarily restricted oxygen levels.

Slide 36 – *Meeting organic farmers' tillage challenge*

While SOM that is physically protected within near-surface aggregates can become subject to oxidation after a single tillage pass, MAOM is less vulnerable to the effects of judicious tillage, and total SOM may not be seriously affected by infrequent or shallow tillage (Dynarski et al., 2020). In a global meta-analysis, Morugán-Coronado et al. (2022) found that soil bacterial and fungal biomass averaged nearly twice as high under reduced tillage (full field, non-inversion tillage no deeper than 6 inches) as under moldboard plowing (8 – 10 inches), while strict no-till only increased fungal biomass 25% and bacterial biomass not at all. The authors cited reduced pore space and restricted gas exchange as a constraint on microbial activity under no-till and did not explore the possibility that greater dependence on herbicides for weed control in the no-till systems may have also affected the soil microbiome.

Other multi-site studies showed that tillage practices had less impact on soil bacterial, fungal, and nematode communities than pesticides (Puissant et al, 2021; Vahter et al., 2022; Walder et al., 2022).

Vahter, T., S-K Sepp, A. Astover, A. Helm, T. Kikas, S. Liu, J. Oja, M. Öpik, P. Penu, M. Vasar, E. Veromann, M. Zobel, and I. Hiiesalu. 2022. *Landscapes, management practices and their*

interactions shape soil fungal diversity in arable fields – Evidence from a nationwide farmers' network. Soil Biology and Biochemistry, Volume 168, May 2022, 108652

Slide 37 – Does organic agriculture entail more soil disturbance?

When some conventional farmers began to implement herbicide-based no-till systems to reduce soil erosion and compaction, organic producers began switching from moldboard plow to shallower noninversion tillage (Kuepper and Schahczenski, 2020), and similar percentages (~39%) of organic and conventional farmers currently use some form of conservation tillage (Shade, 2021).

While soil health research has historically focused on the impacts of physical disturbances (tillage, traffic, overgrazing), a number of recent studies have shown that agrochemicals can have significant adverse effects, sometimes exceeding those of tillage (Puissant et al, 2021; Vahter et al., 2022; Walder et al., 2022). Glyphosate at normal field use rates can seriously limit AMF activity (Druille et al., 2013). A global meta-analysis confirmed that most classes of synthetic plant protection chemicals reduce populations, reproduction, and/or health of soil invertebrates from springtails to earthworms (Gunstone et al., 2020). Tillage poses obvious hazards to earthworms, yet a meta-analysis of multiple studies showed significantly higher earthworm numbers and biomass in organic production systems with tillage than conventional systems (Pelosi et al., 2014).

NOP-allowed pesticides can also hurt soil life. Vinegar pesticides have been shown to depress AMF activity (Atthowe, 2010), and a literature review identified adverse effects on the soil microbiome from copper fungicides as well as a wide range of conventional pesticides (Klein, 2019).

Slide 38 - *Meeting Organic Farmers' Seed Challenge: have Modern Cultivars Forgotten How to "Talk" with Soil Life?*

Slide 39 – *Research Findings on Plant Genetics and Soil Microbes*

A growing body of research findings indicates that plant genetic factors play a major role in the efficacy of beneficial plant root – soil microbe interactions, and in the species composition of endophytic (within plant tissue) and rhizosphere (root zone) microbiomes. Evidence is accumulating that 20th century breeding and selection for high input conventional production systems may have attenuated crop genetic capacity to recruit and support AMF, N-cycling and N fixing bacteria, and other organisms that help roots access nutrients from SOM or low-solubility sources, as well as natural enemies of pests and pathogens, and organisms that induce systemic resistance (ISR) to foliar and belowground pathogens (Goldstein, 2016; Hiltbold et al., 2010; Hoagland, 2018; Hultengren et al., 2016). Reversing this trend through plant breeding and selection in and for organic production systems constitutes a key plant breeding frontier. Initial findings have been promising for carrot (Zubieta and Hoagland, 2017), tomato (Hoagland, 2018), sorghum (Cobb et al., 2016), corn (Goldstein, 2015), pepper (Douds, 2009) and other crops.

Evidence from breeding research and literature review by Dr. Goldstein and colleagues at Mandaamin Institute suggest that breeding and selecting modern corn hybrids *in and for* conventional systems with high N inputs may have modified the relationships between corn roots and soil microbiome so that *Fusarium* fungi proliferate and carry over to future generations via seed. While the *Fusarium* benefits the crop in some ways, including enhancing resistance to some pests and diseases, it also inhibits the establishment of diazotrophic (N fixing) bacteria in and near corn roots, and increases plant susceptibility to N deficiency (Goldstein, 2016).

Both plant genetics and management system (organic versus soluble N sources) have major impacts on the endophyte (within root tissue), rhizoplane (on root surface) and rhizosphere (soil in the immediate vicinity of roots) microbiota, and this in turn impacts ability to fix N and utilize N from organic materials, as well as corn response to applied N. Even a few years' seed increase under organic versus conventional management can improve the resilience of corn breeding lines to low soil soluble N (Ibid.).

Slide 40 – *Another organic challenge: smart shopping for microbes*

Today's organic soil amendment catalogs offer a dizzying array of microbial inoculants, microbial "foods," and other biostimulants claimed to restore soil life and soil function; improve crop nutrition, resilience, growth, and yield; suppress disease; or induce systemic plant resistance (ISR) to pathogens. How is an organic farmer to know which one – if any – to buy and use? Following are some general guidelines:

- Of the inoculant types listed, rhizobia inoculants for legume seeds are the most "tried and true," thoroughly researched, and widely used. Their use is strongly recommended when a particular legume is planted in a given soil for the first time in several years. Their efficacy decreases as soil soluble N levels rise (the legume won't invest energy in a rhizobial symbiont if soluble N is plentiful) and they can be outcompeted by indigenous rhizobium strains.
- Establishment of woody perennial planting stock can be enhanced by application of specific ecto-mycorrhizal fungal inoculants to the roots at planting, and AMF inoculants seed treatments can benefit annual crops. In a meta-analysis of 134 studies, mycoirrhizal inoculation enhanced plant growth by as much as 50% in P-limited conditions (Hoeksema et al., 2010). Multispecies inoculants were most effective, and high soil N and P levels eliminate crop responsiveness to mycorrhizal inoculants.
- Colonization of crop roots by indigenous AMF is enhanced by reduced or shallow tillage, and by preceding grass or legume cover crops, which are effective hosts (Bowles et al, 2017).
- Microbial biofungicides and biopesticides with activity against a specific pathogen or pest are often effective when used as part of a sound IPM strategy.
- Research results with microbial "biostimulant" and "biofertilizer" products that are applied to the soil have given mixed results at best. They seem to offer no benefits on fertile, biologically active soils under organic management, and may be most appropriate for restoring biologically depleted soils (Kleinhenz, 2018; Wang et al., 2016; Weil and Brady, 2017).

While many biostimulant and biofertilizer products are backed by sound research, they often show little effect in practice, mainly because the soil's indigenous microbiome outcompetes the added microbes. The main risks from using these products are the materials and labor cost that may or may not pay off. There is also some risk of introducing a non-indigenous microbe that becomes invasive and upsets soil microbiome functions.

Compost made from on-farm or locally sourced materials, and inoculants of "effective micro-organisms," "indigenous micro-organisms., or bokashi derived from on-farm soil inocula (from a fertile field or nearby forest or prairie) are likely to be safe and may help to restore a worn-out field.

Compost, worm castings, and teas made therefrom are often used to build up the soil biota – and again, it is not clear if their benefits relate to their microbial inoculant effects or simply to the quality of organic matter, nutrients, and plant growth factors they contain. In addition, there is some risk that compost or worm casting teas, especially those brewed with microbial foods such as sugars or seaweed extract, may propagate harmful microbes rather than the desired beneficials if brewing temperature, aeration, and duration are not optimal.

Slide 41 - *Do we Need to Introduce Microbes to Restore Soil?*

Gabe Brown I(2018) started with 5,000 acres of depleted land near Bismarck, ND (16 inches of rain per year). He adopted diverse rotations with cover crops, eliminated tillage, gradually reduced fertilizer, herbicide, and other inputs (approaching though not fully attaining certifiable organic status), integrated crop and livestock production, and implemented management-intensive rotational grazing. Over a 20 year period, topsoil SOM levels recovered from an extremely low 2% to about 7%, compared to a “natural” level for the region of about 8% under native prairie. At no time did he add a purchased soil inoculant to achieve this degree of soil restoration.

Slide 42 - *How will climate change affect soil life and SOM?*

Increasing mean atmospheric and soil temperature will accelerate SOM losses, especially in cooler climates where low temperatures and sometimes wet soil conditions currently delay oxidation of fresh residues and active SOM (Kirschbaum, 1995). SOM that has been stabilized through microbial processing and adsorption to clay and silt as MAOM is less vulnerable to rising temperatures than SOM that is physically protected with aggregates. Adapting soil microbiomes to function in warmer climates and to maximize MAOM formation will play a key role in climate resilience through soil health management.

Kirschbaum, M.U.F. 1995. *The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage*. Soil Biology and Biochemistry. 27(6): 753–760.

Organic Farming for Soil Biology: guidelines for optimizing practices and outcomes (Slides 43-45)

Slide 44 – *Four NRCS principles of soil health*

These principles provide a sound roadmap to soil biological health for all farming systems. They also reflect the NOP Practice Standards for organic farmers, especially the Soil Fertility and Crop Nutrient Practice Standard (section 205.2023) and the Crop Rotation Practice Standard (Section 205.205). It is important for organic farmers to remember that NOP-allowed pesticides and fungicides can exert chemical disturbances on soil life and other non-target organisms, and that they should be used sparingly and only when other control strategies are not sufficient to achieve adequate control.

Slide 45 – *Tips for enhancing soil biology in organic systems*

References

- Abdelrazek, Sahir. 2018. *Carrot Endophytes: Diversity, Ecology and Function*. PhD Thesis, Purdue University. <https://docs.lib.purdue.edu/dissertations/>.
- Abdelrazek, S., and L. A. Hoagland. 2017. *Potential functional role of carrot endophyte communities*. Tri-Societies Meetings, Tampa, FL, October, 2017.
- Amador, J. A., and J. H. Gorres. 2005. *Role of the anecic earthworm Lumbricus terrestris L. in the distribution of plant residue nitrogen in a corn (Zea mays)–soil system*. Applied Soil Ecology 30: 203-214.
- Ariena H. C. van Bruggen, Isolde M. Francis, and Randy Krag. 2015. *The vicious cycle of lettuce corky root disease: effects of farming system, nitrogen fertilizer and herbicide*. Plant and Soil 388 (1-2): 119-132.
- Atthowe, H., undated. *Weed Management, Reduced-tillage, and Soil Health: Weed Ecology in Biodesign Farm's Organic, Minimum-Till Vegetable Production System*. Final report, Organic Farming Research Foundation Grant 2007. <https://ofrf.org>.
- Baas, D. G., G. P. Robertson, S. R. Miller, N. and Millar, N. 2015. *Effects of Cover Crops on Nitrous Oxide Emissions, Nitrogen Availability, and Carbon Accumulation in Organic versus Conventionally Managed Systems*. Final report for ORG project 2011-04952.*
- Bakker, P. A. H. M., R. F. Doornbos, C. Zamioudis, R. L. Berendsen, and C. M. J. Pieterse. 2013. *Induced systemic resistance and the rhizosphere microbiome*. Plant Pathology Journal 29(2): 136-143.
- Barbercheck, M., I. Ahmad, and C. Voortman. 2018. *Managing a Beneficial Soil Fungus for Insect Control*. Extension bulletin. <https://extension.psu.edu/managing-a-beneficial-soil-fungus-for-insect-control>.
- Bhattacharyya, S. S., G. H. Ross, K. Furtok, H. M. N. Iqbal, and R. Parra-Saldivar. *Soil carbon sequestration – An interplay between soil microbial community and soil organic matter dynamics*. Science of the Total Environment 815 (April 2022). <https://doi.org/10.1016/j.scitotenv.2022.152928>.
- Bhowmik, A. A-M. Fortuna, L. J. Cihacek, A. Bary, P. M. Carr, and C. G. Cogger. 2017. *Potential carbon sequestration and nitrogen cycling in long-term organic management systems*. Renewable Agriculture and Food Systems, 32 (6): 498-510.
- Bhowmik, A., A. Fortuna, L. J. Cihacek, A. I. Bary, and C. G. Cogger. 2016. *Use of biological indicators of soil health to estimate reactive nitrogen dynamics in long-term organic vegetable and pasture systems*. Soil Biology and Biochemistry 103: 308-319.

Bowles, T. M., L. E. Jackson, M. Loeher, and T. R. Cavagnaro. 2017. *J. Applied Ecology* 54(6): 1785-1793. *Ecological intensification and arbuscular mycorrhizas: a meta-analysis of tillage and cover crop effects.*

Brennan, E. B., and V. Acosta-Martinez. 2017. *Cover cropping frequency is the main driver of soil microbial changes during six years of organic vegetable production.* *Soil Biology and Biochemistry* 109: 188-204.

Brown, G. 2018. *Dirt to Soil: One Family's Journey into Regenerative Agriculture.* Chelsea Green Publishing, White Junction, VT. 223 pp.

Button, E. S., J. Pett-Ridge, D. V. Murphy, Y. Kuzyakov, D. R. Chadwick, and D. L. Jones. 2022. *Deep-C storage: Biological, chemical and physical strategies to enhance carbon stocks in agricultural subsoils.* *Soil Biology and Biochemistry* Volume 170, July 2022, 108697.

Cavigelli, M. A., J. R. Teasdale, and J. T. Spargo. 2013. *Increasing Crop Rotation Diversity Improves Agronomic, Economic, and Environmental Performance of Organic Grain Cropping Systems at the USDA-ARS Beltsville Farming Systems Project.* *Crop Management* 12(1) Symposium Proceedings: USDA Organic Farming Systems Research Conference. <https://dl.sciencesocieties.org/publications/cm/tocs/12/1>.

Cobb, A. B., G. W. T. Wilson, C. L. Goad, S. R. Bean, R. C. Kaufman, T. J. Herald, and J. D. Wilson. 2016. *The role of arbuscular mycorrhizal fungi in grain production and nutrition of sorghum genotypes: Enhancing sustainability through plant-microbial partnership.* *Agriculture, Ecosystems, and Environment.* 233 (3): 432-440.

Cogger, C. G. M. Ostrom, K. Painter, A. Kennedy, A. Fortuna, R. Alldredge, A.; Bary, T. Miller, D. Collins, J. Goldberger, A. Antonelli, and B. Cha. 2013. *Designing Production Strategies for Stewardship and Profits On Fresh Market Organic Farms.* Final report for OREI project 2008-01247.*

Colla, G., M. Cardarelli, D. Egel, and L. Hoagland. 2017. *Using Biofungicides, Biostimulants and Biofertilizers to Boost Crop Productivity and help Manage Vegetable Diseases.* <https://articles.extension.org/pages/74056/using-biofungicides-biostimulants-and-biofertilizers-to-boost-crop-productivity-and-help-manage-vege>.

Davis, B. W., S. B. Mirsky, B. A. Needelman, M. A. Cavigelli, and S. A. Yarwood. 2019. *Nitrous oxide emissions increase exponentially with organic N rate from cover crops and applied poultry litter.* *Agriculture, Ecosystems and Environment* 272 (2019) 165–174.

Delate, K., C. Cambardella, and C. Chase. 2015. *Effects of cover crops, soil amendments, and reduced tillage on carbon sequestration and soil health in a long term vegetable system.* Final report for ORG project 2010-03956.*

Dick RP. 1992. *A review: long-term effects of agricultural systems on soil biochemical and microbial parameters.* *Agric Ecosyst Environ.* 1992; 40:25-36.

Douds, D. D. 2009. *Utilization of inoculum produced on-farm for production of AM fungus colonized pepper and tomato seedlings under conventional management*. *Biological Agriculture and Horticulture* 26: 353-364.

Drinkwater, L. E. 2011. *It's Elemental: How Legumes Bridge the Nitrogen Gap*. The Natural Farmer, Summer 2011, Special Supplement on Legumes as Cover Crops.

Druille M, Cabello MN, Omacini M, Golluscio RA. 2013. Glyphosate reduces spore viability and root colonization of arbuscular mycorrhizal fungi. *Applied Soil Ecology* 64:99–103; doi: <https://doi.org/10.1016/j.apsoil.2012.10.007>.

Dynarski, K. A., D. A., Bossio, and K. Scow. 2020. *Dynamic stability of soil carbon: reassessing the “permanence” of soil carbon sequestration*. *Frontiers in Environmental Science*. Vol 8 (November 2020). <https://doi.org/10.3389/fenvs.2020.514701>.

Eastburn, D. 2010. *Managing disease by managing soils*. <https://eorganic.org/node/2848>.

Egel., D., L. Hoagland, and A. K. Jaiswal. 2018. *Organic Tomato Foliar Pathogen IPM Webinar*. <https://eorganic.org/node/24154>.

Epstein, L. 2007. *The activity and suppression of soilborne pathogens and pests in organic vs conventional plots with conservation vs conventional tillage*. Proposal and final report for ORG project 2004-05151.*

Franzluebbers, A. J. 2018a. *Short-term C mineralization (aka the flush of CO₂) as an indicator of soil biological health*. *CAB Reviews* 2018 13, No. 017. doi: 10.1079/PAVSNR201813017.

Franzluebbers, A. J. 2018b. *Soil-Test Biological Activity with the Flush of CO₂: III. Corn Yield Responses to Applied Nitrogen*. *Soil Science Society of America Journal*, Volume 82, Issue 3, <https://doi.org/10.2136/sssaj2018.01.0029>.

Franzluebbers, A. J., S. Pehim-Limbu, and M. H. Poore. 2018. *Soil-Test Biological Activity with the Flush of CO₂: IV. Fall-Stockpiled Tall Fescue Yield Response to Applied Nitrogen*. *Agronomy Journal*, Volume 110, Issue 5, <https://doi.org/10.2134/agronj2018.03.0146>.

Goldstein, W. 2015. *Breeding corn for organic farmers with improved N efficiency/N fixation, and protein quality*. *Proceedings of the Organic Agriculture Research Symposium*. <https://eorganic.info/node/12972>.

Goldstein, W. 2016. *Partnerships between Maize and Bacteria for Nitrogen Efficiency and Nitrogen Fixation*. Bulletin 1. Mandaamin Institute, Elkhorn, Wisconsin, 49 pp. <http://www.mandaamin.org/about-nitrogen-fixing-corn>.

Grandy, S., and C. Kallenbach. 2015. *Microbes drive soil organic matter accumulation in organic cropping systems*. Recording from the Organic Agriculture Research Symposium, LaCrosse, WI February 25-26, 2015, <http://eorganic.info/node/12972>.

Gruber, P. 2017. Friendly fungi help farmers' cause. Lancaster Farming, February 17, 2017. https://www.lancasterfarming.com/farming/soil/friendly-fungi-help-farmers-cause/article_9c6611ae-8a25-522a-9ca6-d2f4bdc13d41.html.

Gunstone, T., T. Cornelisse, K. Klein, A. Dubey, and N. Donley. 2021. Pesticides and soil invertebrates: a hazard assessment. *Frontiers in Environmental Science*, Vol. 9. <https://doi.org/10.3389/fenvs.2021.643847>.

Hamel, C. 2004. *Impact of arbuscular mycorrhizal fungi on N and P cycling in the root zone*. *Can J Soil Sci.* 84(4):383-395.

Hiltpold, I., S. Toepfer, U. Kuhlmann, and T. Turlings. 2010. *How maize root volatiles affect the efficacy of entomopathogenic nematodes in controlling the western corn rootworm*. *Chemoecology* 20: 155 – 162.

Hoeksema, J. D., V. B. Chaudhary, C. A. Gehring, N. C. Johnson, J. Karst, R. T. Koide, A. Pringle, C. Zabinski, J. D. Bever, J. C. Moore, G. W. T. Wilson, J. N. Klironomos, and J. Umbanhowar. 2010. *A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi*. *Ecology Letters* 13: 394–407.

Hooks, C. R., K. H. Wang, G. Brust, and S. Mathew. 2015. *Using Winter Cover Crops to Enhance the Organic Vegetable Industry in the Mid-Atlantic Region*. Final report for OREI project 2010-01954.*

Hoorman, J. 2011. *The Role of Soil Protozoa and Nematodes*. Ohio State University Extension Fact Sheet SAG-15-11. 5 pp.

Howard, Sir Albert. 1947. *The Soil and Health: a Study of Organic Agriculture*. University Press of Kentucky (2006), 307 pp.

Hultengren, R., M. Glos, and M. Mazourek, 2016. *Breeding Research and Education Needs Assessment for Organic Vegetable Growers in the Northeast*. Organic Seed Alliance, <http://www.seedalliance.org/>.

Hurisso, T. T., S. W. Culman, W. R. Horwath, J. Wade, D. Cass, J. W. Beniston, t. M. Bowles, A. S. Grandy, A. J. Franzluebbers, M. E. Schipanski, S. T. Lucas, and C. M. Ugarte. 2016. *Comparison of Permanganate-Oxidizable Carbon and Mineralizable Carbon for Assessment of Organic Matter Stabilization and Mineralization*. *Soil Sci. Soc. Am. J.* 80 (5): 1352-1364.

Ingham, E. R., A. R. Moldenke, and C. A. Edwards. 2000. *Soil Biology Primer*. <https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/biology/>.

Jones, M. S., Z. Fu, J. P. Reganold, D. S. Carp, T. E. Besser, J.L. Tylianakis and W. E. Snyder. 2019. *Organic farming promotes biotic resistance to foodborne human pathogens*. *Journal of Applied Ecology* 56:1117–1127.

Kallenbach, Cynthia M., Frey, Serita D., & Grandy, A. Stuart. 2016. *Direct evidence for microbial-derived soil organic matter formation and its ecophysiological controls*. Nature Communications 7, Article number: 3630 <https://www.osti.gov/pages/servlets/purl/1363941>.

Khan, S. A., R. L. Mulvaney, T. R. Ellsworth, and C. W. Boast. 2007. *The myth of nitrogen fertilization for soil carbon sequestration*. J. Environ. Qual. 36:1821–1832.

Klein, K. 2019. Pesticides and Soil Health. Friends of the Earth, 9 pp.

Kleinhenz, M. 2018. *Assessing the Influence of Microbe-containing Crop Biostimulants on Vegetable Crops and Farms through On-station and On-farm Study*. Presentation at Annual Meetings of the American Society for Horticultural Science; Aug 1, 2018; Washington, D.C. Available from Dr. Kleinhenz, kleinhenz.1@osu.edu.

Kloot, Robin. 2018. *Using adaptive nutrient management to answer “how much fertilizer do you actually need?”* NRCS webinar May 8, 2018. Science and Technology Training Library, <http://www.conservationwebinars.net/listArchivedWebinars>.

Kuepper, G., and J. Schahczenski. 2020. *Reducing Tillage Intensity in Organic Production Systems*. ATTRA Bulletin, National Center for Appropriate Technology, 12 pp. <https://attra.ncat.org/product/reducing-tillage-intensity-in-organic-production-systems/>.

Lorenz, K., and R. Lal. 2016. *Environmental Impact of Organic Agriculture*. *Advances in Agronomy* 139: 99-152.

Lori, M., S. Symnaczik, P. MaEder, G. De Deyn, A. Gattinger. 2017. *Organic farming enhances soil microbial abundance and activity – A meta-analysis and meta-regression*. PLOS ONE | <https://doi.org/10.1371/journal.pone.0180442> July 12, 2017, 25 pp.

Moore-Kucera, J., A. N. Azarenko, L. Brucher, A. Chozinski, D. D. Myrold, and R. Ingham. 2008. *In Search of Key Soil Functions to Assess Soil Community Management for Sustainable Sweet Cherry Orchards*. HortScience 43:38 – 44.

Morrow, J. G., D. R. Huggins, L. A. Carpenter-Boogs, and J. P. Reganold. 2016. *Evaluating Measures to Assess Soil Health in Long-Term Agroecosystem Trials*. Soil Sci. Soc. Am. J. 80 (2): 450-462.

Morugán-Coronado, A., P. Pérez-Rodríguez, E. Insolia, D. Soto-Gómez, D. Fernández-Calvino, and R. Zornoza. 2022. *The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: A worldwide meta-analysis of agricultural sites*. Agriculture, Ecosystems, and Environment 329, Article 107867, May 2022.

Mulvaney, R. L., S. A. Khan, and T. R. Ellsworth. 2009. *Synthetic Nitrogen Fertilizers Deplete Soil Nitrogen: A Global Dilemma for Sustainable Cereal Production*. J. Environ. Qual. 38:2295–2314.

- Pelosi, C., Barot, S., Capowiez, Y., Hedde, M. and Vandenbulcke, F., 2014. *Pesticides and earthworms*. A review. *Agronomy for Sustainable Development*, 34(1), pp.199-228.
- Prescott, C. E., Yi. Rui, M. F. Cotrufo, and S. J. Grayston. 2021. *Managing plant surplus carbon to generate soil organic matter in regenerative agriculture*. *J. Soil & Water Conservation* 76(6): 99A-104A.
- Puissant, J., C. Villenave, C. Chauvin, C. Plassard, E. Blanchart, and J. Trap. 2021. *Quantification of the global impact of agricultural practices on soil nematodes: A meta-analysis*. *Soil Biology and Biochemistry* Volume 161, October 2021, 108383.
- Rillig, M.C. 2004. *Arbuscular mycorrhizae, glomalin, and soil aggregation*. *Can. J. Soil Sci.* 84(4): 355–363.
- Robb, D. and G. Zehnder. 2016. Weeds, nitrogen, and yield: measuring the effectiveness of an organic no-till system. Final report for Southern SARE project GS13-126. <https://projects.sare.org/project-reports/gs13-126/>.
- Schlatter, D., L. Kinkel, L. Thomashow, D. Weller, and T. Paulitz. 2017. *Disease-suppressive soils: new insights from the soil microbiome*. *Phytopathology* 107: 1284-1297.
- Schonbeck, M., D. Jerkins, and V. Lowell. 2019. *Soil Health and Organic Farming: Understanding and optimizing the community of soil life*. Organic Farming Research Foundation <https://ofrf.org/research/reports/>.
- Shade, J. 2021. Quote from Podcast 1 of *The Dirt on Organic Farming*, a 2021 podcast series hosted by Mallory Krieger and Nate Powell-Palm of the Organic Agronomy Training Service (OATS). <https://www.organicagronomy.org/the-dirt-on-organic-farming>.
- Simard, S. 2021 *Finding the Mother Tree: discovering the wisdom of the forest*. 337 pp. <https://suzannesimard.com/finding-the-mother-tree-book/>.
- Six, J., S.D. Frey, R.K. Thiet, and K.M. Batten. 2006. *Bacterial and Fungal Contributions to Carbon Sequestration in Agroecosystems*. *Soil Sci. Soc. Am. J.* 70(2): 555 – 569.
- Ugarte, C. M., and M. M. Wander. 2008. *Use of the Nematode Community Structure and Indicators of Biologically-based Fertility for the Assessment of Soils Under Organic Management*. *Midwest Organic Research Symposium, Research Summaries*, pp 30-31.
- Ugarte, C. M., E. R. Zaborski, and M. M. Wander. 2013. *Nematode indicators as integrative measures of soil condition in organic cropping systems*. *Soil Biology and Biochemistry* 64: 103-113.
- Vahter, T., S-K Sepp, A. Astover, A. Helm, T. Kikas, S. Liu, J. Oja, M. Öpik, P. Penu, M. Vasar, E. Veromann, M. Zobel, and I. Hiiesalu. 2022. *Landscapes, management practices and their*

interactions shape soil fungal diversity in arable fields – Evidence from a nationwide farmers' network. Soil Biology and Biochemistry, Volume 168, May 2022, 108652

Walder, F., M. W. Schmid, J. Riedo, A. Y. Valzano-Held, S. Banerjee, L. Büchi, T. D. Bucheli, and M. G.A.van der Heijden. 2022. *Soil microbiome signatures are associated with pesticide residues in arable landscapes*. Soil Biology and Biochemistry, Vol. 174, November, 2022.

Wander, M. M., S. J. Traina, B. R. Stinner, and S. E. Peters. 1994. *Organic and Conventional Management Effects on Biologically Active Soil Organic Matter Pools*. Soil Sci. Soc. Am. J. 58:1130-1139.

Wang, L. and M. Mazzola. 2019. *Interaction of brassicaceae seed meal soil amendment and apple rootstock genotype on microbiome structure and plant disease suppression*. Phytopathology 109: 607-614.

Wang, Z., J. Laudick, and M. Kleinhenz. 2016. *Getting the most from crop biostimulants and biofertilizers*. VegNet: the Vegetable and Fruit Crops Team Newsletter vol. 23, issue 12 (July 5), pp 4-5. <https://vegnet.osu.edu/newsletter>.

Wei, Z, E. Hoffland, M. Zhuang, P. Hellegers, and Z. Cui. 2021. *Organic inputs to reduce nitrogen export via leaching and runoff: A global meta-analysis*. Agriculture, Ecosystems, and Environment 291. <https://doi.org/10.1016/j.envpol.2021.118176>.

Weil, R. R., and N. C. Brady, 2017. *The Nature and Properties of Soils*, 15th Edition. Pearson, Boston. 1,086 pp.

Zuber S. M., and M. B. Villamil. 2016. *Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities*. Soil Biol Biochem. 97:176-187.

Zubieta, L. and L. A. Hoagland. 2017. *Effect of Domestication on Plant Biomass and Induced Systemic Resistance in Tomato (Solanum lycopersicum L.)*. Poster Number 1209, Tri-Societies Meetings, Tampa, FL, Oct 24, 2017.

* Project reports available at <https://nifa.usda.gov/data/data-gateway>.