**Understanding and Managing Soil Biology for Soil Health and Crop Production***Research-based Practical Guidance for Organic and Transitioning Farmers*

eOrganic Soil Health and Organic Farming Webinar Series

May 22, 2019

Developed and presented by Organic Farming Research Foundation, with funding from the Clarence Heller Foundation

*Presentation notes, additional information, and references to research literature on which webinar slides are based.*

Slide 1 – *title slide*.

Slide 2 – *Farmer research priorities*

A total of 1,403 respondents representing all four USDA regions (Northeast, North Central, South, and West) participated in OFRF’s 2015 survey to identify top research priorities. In addition, 21 listening sessions were held in conjunction with conferences across the US.

Soil health, quality, biology, and nutrient cycling were most often cited as a high research priority (74% of respondents). Farmers cited several aspects of the role of soil life in crop nutrition, health, and yield; and disease, pest, and weed problems as topics of interest.

Jerkins, D., and J. Ory. 2016. *National Organic Research Agenda. Outcomes and Recommendations from the 2015 National Organic Farmer Survey and Listening Sessions*. Organic Farming Research Foundation, <https://ofrf.org>.

Slide 3 – *Soil biology 101 subtitle slide*

Slide 4 – *Soil Food Web diagram from Soil Biology Primer*

This image was created by Dr. Elaine Ingham and colleagues 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, R. R., and N. C. Brady, 2017. *The Nature and Properties of Soils, 15th Edition*. Pearson, Boston. 1,086 pp.

Slide 5 – *Bacteria and archaea*

Soil prokaryotes – small, simple, single-celled organisms without a distinct nucleus – include a tremendous genetic and functional diversity of bacteria, and another group of microbes called archaea, which look like bacteria yet are no more related to true bacteria than ourselves!

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 and fine root sloughing (collectively called “rhizodeposition). They digest 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, lipids, 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 specialized roles such as fixing atmospheric N2 into plant-available form, oxidizing ammonium-N into nitrate-N, or living as gut symbionts in larger organisms helping them to digest the organic residues or prey they consume.

Many rhizosphere bacteria derive nourishment directly from plants. Most of these organisms are harmless or beneficial (plant growth promoting rhizobacteria or PGPR), while some deplete plant vigor to some degree (deleterious rhizobacteria or DRB) and a few are virulent pathogens.

Archaea comprise 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), sulfur oxidizers, ammonia oxiders (involved in nitrification) and others that convert 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 6 – *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.

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 many can tolerate drier or saline conditions, and help to sustain soil biological activity during drought and in arid climates.

One genus of actinobacteria, *Frankia*, forms N2-fixing nodules on the roots of alder and several others 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 may 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 7 – *Fungi*

Fungi are eukaryotic, with their DNA in distinct nuclei within each cell. Soil fungi are highly diverse, including saprotropic (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 of today’s ecosystems would simply cease to exist. 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 plant to occupy barren lands and to 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 cropland soils, fungi and bacteria play roughly equal roles in soil microbial biomass and function. About 80% of plant species on earth, and 70% of food and fiber crops, enter into symbiosis with arbuscular mycorrhizal fungi (AMF) and/or ectomycorrhizal fungi, and many depend on this mutualism to thrive, grow, and reproduce. Beneficial fungi of cropland also include natural enemies of plant pathogenic fungi and soil-dwelling pests; some of these fungi are formulated and marketed as bio-fungicides and bio-pesticides for organic farmers.

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>.

Slide 8 – *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. Soil protozoa feed mainly on bacteria, which contain higher concentrations of N and other nutrients than the protozoa need; the surplus is released into the soil, often near plant roots where bacterial populations are highest.

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

Slide 9 – *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. Entomopathogenic nematodes parasitize and kill larvae of several soil dwelling insect pests.

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

Note that the use of nematicides to deal with pest nematodes could 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 generally have high populations and diversity of nematodes.

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. CRIS Abstracts.\*

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. CRIS Abstracts.\*

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. CRIS Abstracts.\*

Moore-Kucera, J., A. N. Azerenko, L. Brutcher, 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.

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.

Slide 10 – *Micrr-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 decomposition by microbes. 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; and Epstein et al, 2017, cited above.

Slide 11 – *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, biostimulant, 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 mineralization and deep drainage of water through soil profile). In addition, when exotic earthworm species invade forest ecosystems, they can upset the indigenous soil biota and soil ecosystem on which the trees depend.

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.

Slide 12 – *Other soil macrofauna*

In the Pacific Northwest, organic vegetable farms had higher diversity of dung beetles and coprophagous (manure-consuming) microbes than conventional farms, and showed greater potential to attenuate populations of human foodborne pathogens in surface-deposited manure, thereby contributing to food safety in crop-livestock integrated systems.

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.

Slide 13 – *Subtitle slide – Soil life and soil functions*

Slide 14 – *Feed the Soil …*

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 agriculture since the dawn of the organic movement in the early 20th Century.

Other founding organic principles include meeting most nutrient needs from on farm sources through nutrient cycling, and composting residues to stabilize nutrients and organic matter.

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

Slide 15 – *Soil life processes all organic inputs*

Essentially all organic materials added to the soil – root exudates, plant residues, manure, etc – become food for soil organisms. Part of this organic input is converted to respiratory carbon dioxide (CO2), plant-available nitrogen (N) and other nutrients (*mineralization*), part becomes active soil organic matter (SOM) which undergoes further processing by the soil life, and part is converted into long-lasting SOM that is tightly bound to soil mineral particles (*stabilization*).

Both processes are essential to the health of agricultural and natural ecosystems, as plants depend on mineralization for nutrients, while stabilization sequesters carbon in the soil (climate stability), contributes to soil structure (tilth), and moisture and nutrient holding capacity. Thus, managing soil biota for long-term sustainability aims to sustain both processes.

An ingenious study by Kallenbach et al. (2016) has demonstrated the central role of soil life in processing organic inputs into SOM. Researchers created “mesocosms” of pure mineral sand + clay supplied with N and other mineral nutrients but devoid of organic matter, added a small inoculum of organisms from field soil, and “fed” the system with sugar, a simple phenolic compound called syringol, or a water extract of switchgrass (a complex mixture of soluble organic compounds). After 16 months, the initially dead-looking sand-clay mixture looked like topsoil (dark brown, well aggregated), and contained about 1.5 – 2.5% SOM whose chemical composition was highly complex (~80 compounds) and fairly similar to the SOM of field soil – *regardless of the form of organic carbon that the organisms received*.

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>.

Slide 16 – *Monitoring soil biological function*

Fairly simple and reliable laboratory protocols have been developed for estimating the two key functions of the soil life.

*Potentially mineralizable carbon* (PMC) is estimated as CO2 emitted during a four day incubation of moist soil at room temperature, and reflects the soil’s capacity to release plant-available nutrients.

*Permanganate oxidizable carbon* (POX-C) is an SOM fraction that reacts with a dilute (0.02 M) solution of the oxidizing agent potassium permanganate in a standard lab procedure. While POX-C is an active SOM fraction (microbial “food”), studies indicate that it is well correlated with microbially-mediated processes that build stable SOM.

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.

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.

Slide 17 – *A matter of balance*

When the soil microbiome (B) consumes fresh residues and root exudates, part of this organic input (OI) becomes new microbial biomass (Bn) and part is released as respiratory carbon dioxide (R) and plant-available nutrients. R reflects mineralization and Bn reflects the soil biota’s long term capacity to sustain both stabilization and mineralization. Stable SOM accrues as the soil microbiota “turns over,” leaving microbial residues and organic compounds that adsorb tightly to clay, silt, and other soil minerals, or become protected within aggregates.

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

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.

Slide 18 – *Building biomass and stable SOM*

Practices and inputs that enhance MGE and build stable SOM include diverse rotation, reduced or no tillage, and diverse inputs with balanced carbon:nitrogen (C:N) ratio, such as a mixed cover crop including cereal grains (high C) and legumes and/or crucifers (high N), 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).

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 the excess C.

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.

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>.

Cogger et al., 2013, cited earlier.

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. CRIS Abstracts\*

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>.

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.

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.

Slide 19 – *Promoting mineralization*

Tillage acts as a stimulant, accelerating soil respiration, releasing plant-available nutrients and consuming some active SOM. MBE (Bn/OI) tends to decline, qCO2 (R/B) may increase.

Cover crops, especially succulent legumes or crucifers, also promote the mineralization function over stabilization. Tilling in a high-N green manure stimulates the growth of soil bacteria and their immediate consumers, 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 MBE than microbiomes richer in fungi, these practices generally do not build much SOM, but can enhance nutrient availability to the current season’s crop.

Hurisso et al., 2016, cited above.

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

Slide 20 – *Stressed soil microbiome*

The qCO2 is generally considered an index of stress on the soil biota. Soil stressors 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 (absence of living roots, no daily rhizodeposition). In these conditions, the soil biota must devote a greater percent of their C intake to maintenance respiration (higher qCO2), leaving less available for microbial growth and SOM formation (lower MBE).

Farming systems that generate these stresses (e.g. conventional agriculture with tillage) also tend to provide less organic input than sustainable organic or conservation agriculture systems. As a result, microbial biomass and its capacity to build SOM or mineralize nutrients diminish over time. For example, orchard floor soils maintained in bare fallow by herbicides or tillage are highly stressed, showing two-fold higher qCO2 and 50% reduction in SOM compared to organic orchard soils maintained under living cover. Long term use of soluble NPK fertilizers tends to reduce microbial biomass, increase qCO2, deplete SOM, compromise the soil biota’s capacity to mineralize nutrients, and thereby increase the farming system’s dependence on fertilizer inputs.

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

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.

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.

Morrow et al., 2016, cited above.

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.

Zuber S. M., and M. B. Villamil. 2016, cited above.

Slide 21 – *Soil life, plant nutrients, and moisture*

The soil biota performs multiple functions upon which agricultural production and natural ecosystems depend. When decomposer organisms consume fresh organic residues such as animal dung, the initial nutrient immobilization against which 20th century agricultural professionals warned organic gardeners actually represents a vital ecosystem service: retaining nutrients that would otherwise be lost from the soil to damage water or air quality.

The next trophic level – protozoa and nematodes that graze on microbes – releases nutrients as plants need them. Mycorrhizal fungi and other plant symbionts also enhance plant nutrition.

Bacteria, fungi, plant roots, earthworms, ants, termites, and other macro-fauna work together in different ways to build and maintain soil aggregation and pore structure, prevent or relieve compaction, and thereby ensure sufficient drainage, aeration, moisture capacity, and favorable conditions for extensive root growth.

Finally, a diverse, balanced soil food web, together with living plant roots, protects water quality by holding and utilizing nutrients.

Slide 22 – *Two-way exchange*

Plant nutrition is a two way exchange, in which photosynthesis sustains soil life via rhizodeposition, and microbial activity delivers nutrients to the root zone. In addition to the “bread and butter” of sugars and amino acids, the roots of each plant species release specific chemical signals to stimulate and host those soil organisms most beneficial to that plant.

Weil and Brady, 2017, cited above.

Slice 23 – *Rhizosphere*

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

About 70% of crop plant species host 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 an inch or more beyond the root surface, thereby greatly expanding the effective volume of the root system. In addition, AMF mycelia can solubilize and absorb phosphorus (P) and other nutrients from soil minerals that uncolonized roots could not access directly. Enhanced water and nutrient uptake render mycorrhizal plants resilient to drought and low soluble nutrient levels. Meanwhile, 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 soil biota for nutrients in organic residues.

Another important plant nutrition pathway is via the second trophic level of the soil food web. As rhizodeposition 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.

All of these plant-microbe partnerships 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 minimize threats to water quality or climate – and sometimes low enough to trigger high fertilizer rates in standard soil test recommendations. When these nutrients are provided in soluble form, the plant may reduce its investment in the soil life; in the short run, this may enhance yield, but in the long run the multiple benefits of the root microbiome to soil, crop, and environmental health are diminished.

Slide 24 – *Four-way symbiosis*

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 feed seedlings via mycorrhizal networks, which may occupy acres and live for centuries; in this way seedlings can grow despite dense shade and eventually replace aging trees as the latter die and fall. 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 N and the fibrous and mycorrhizal root system of the grass efficiently absorbs P, the mycelial connection may facilitate an exchange of these two nutrients. The plants may invest 20 -30% of their photosynthetic product to their symbionts, yet the four-way partnership generally enhances the health and vigor of all four components. In legumes, AMF generally enhance N2 fixation by rhizobia symbiont.

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.

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

Rillig, M.C. 2004. *Arbuscular mycorrhizae, glomalin, and soil aggregation.* Can. J. Soil Sci. 84(4): 355–363.

Slide 25 – *Soil life and plant-available moisture*

For centuries, farmers have observed improved rain infiltration and moisture retention in healthy, living soils. The Rodale farming systems trial has shown improved drought resilience and yield stability in organic systems that also maintained higher SOM and microbial activity.

Rodale Institute, 2015. *Farming Systems Trial Brochure*, 2 pp. <http://rodaleinstitute.org/assets/FST-Brochure-2015.pdf>.

Slides 26 – 28 – *Soil life, pathogens, and pests; plant disease triangle, and how soil health practices can “break” it.*

Large populations of benign rhizosphere micro-organisms can outcompete pathogens and keep them from accessing plant roots (general suppression). In addition, parasitic fungi such as *Trichoderma* spp. attack a wide variety of soilborne fungal plant pathogens, and other microbes such as *Streptomyces* spp (actinobacteria) release antibiotics that suppress pathogen growth. The fungus *Coniothyrium minitans* specifically parasitizes the pathogen *Sclerotinia sclerotiorum*, which causes white mold disease in a wide range of vegetable and field crops. Several of these beneficial microbes are now marketed as biofungicides.

Another mechanism of disease suppression is Induced Systemic Resistance (ISR). Plants respond to a wide range of beneficial microbes in their rhizosphere by developing increased resistance, not only to soil-borne pathogens but also foliar pathogens such as tomato late blight (*Phytophthora infestans*) and carrot leaf blight (*Alternaria dauci*).

Soil dwelling insect pests can also fall prey to entomopathogenic nematodes such as *Heterorhabditis* and *Steinernema* (whose bacterial gut microflora digest the insect larva after the nematode enters it), and entomopathogenic fungi such as *Metarhizium* and *Beauvaria.* Strains of the two nematode genera and *Beauvaria* are marketed as biopesticides allowed in NOP certified organic produciton.

Some of these beneficial organisms show multiple modes of action. For example, parasitic *Trichoderma* and *Metarhizium* can also occur as root endophytes, where they elicit an ISR response and sometimes aid nutrient uptake. , Researchers at Pennsylvania State U have even documented a single mycelium of *Metarhizium* parasitizing an insect pest and partnering with crop roots, transferring detectable amounts of N from former to latter.

As noted earlier, dung beetle help eliminate livestock parasites, pests, and pathogens, and may reduce food safety risks in organic production.

Abdelrazek, Sahir. 2018. Carrot Endophytes: Diversity, Ecology and Function. PhD Thesis, Purdue University. <https://docs.lib.purdue.edu/dissertations/>.

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>.

Colla et al., 2017, cited earlier.

Eastburn, D. 2010. *Managing disease by managing soils.* <https://articles.extension.org/pages/18638/managing-disease-by-managing-soils>.

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>.

Jones, et al., 2019, cited earlier.

Mazzola, M., S. S. Hewavitharana, and S. L. Strauss. 2015. *Brassica seed meal soil amendments transform the rhizosphere microbiome and improve apple production through resistance to pathogen reinfestation.* Phytopathology 105: 460-469.

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.

Stone, A. 2014 *Using Contans (Coniothyrium minitans) for White Mold Management on Organic Farms*. <https://articles.extension.org/pages/69132/using-contans-coniothyrium-minitans-for-white-mold-management-on-organic-farms-webinar>.

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.

Slide 29 – *Subtitle slide – Organic practices for soil life*

Slide 30 – *NRCS principles of soil health*

Maximizing plant cover, biomass, and living roots in the soil profile (first two NRCS principles) ensures the food supply for the soil food web. When conditions are too hot, cold, or dry to maintain actively growing crops, coverage with plant residue, dormant vegetation, or organic mulch protects soil organisms from the extreme conditions. Sustainable intensification practices include cover crops planted after harvest or (even better) relay-planted into standing cash crop, intercropping, perennial sod or forage crops in the rotation, and maintaining orchard floor and alleys between other horticultural crop rows in living plant cover.

The third principle – diversified cropping system – builds species diversity and functional diversity in the soil biota, since each plant species harbors a specific suite of rhizosphere symbionts. Diversity increases the likelihood that most or all key soil life functions will be adequately covered, and decreases risks of crop disease. Adding just one or two new cover or cash crops to an existing low-diversity rotation can enhance microbial biomass and SOM, even if overall crop intensity (biomass, duration) is not increased. A simple corn-soybean rotation can degrade soil health even under organic management unless winter cover crops and/or perennial forage or sod crops are added.

The fourth principle – minimize soil disturbance – poses the greatest challenges to all farmers, since agriculture, especially annual crops, entails a major shift away from a region’s native forest, savanna, or prairie ecosystem. Farmers must impose some soil disturbance to maintain the agro-ecosystem: tillage, cultivation, fertilizers, and crop protection materials. Regular tillage and concentrated fertilizers tip the soil balance in favor of bacteria over fungi and can reduce SOM and MGE. Soil fumigants, soil applied fungicides, insecticides, nematicides, and even herbicides can knock-out key components of the soil biota for a period of time.

In an organic vegetable systems study in central California, growing winter cover crops each year in rotation with double cropped vegetables enhanced microbial biomass and total SOC, yet the frequent tillage caused a significant shift from fungi to bacteria over an 8-year period.

In at least one study (Druille et al., 2013), field soil treated with glyphosate at normal use rates showed significantly depressed mycorrhizal activity compared with untreated soil. In California, soluble N fertilizer and herbicide have been shown to reduce soil microbial diversity and increase corky root in lettuce, a disease that is less problematic in organic lettuce fields.

Invasive exotic plant species can alter indigenous soil microbiomes to allows the invasive species to gain an advantage over native plants. Garlic mustard (*Alliaria petiolata*) and diffuse knapweed (*Centaurea diffusa*) release root exudates toxic to the native soil biota, while other invasive species modify moisture relations, nutrient cycling, or soil biota to favor the invader.

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.

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.

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

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>.

Fauci, M. F., and R. P. Dick. 1994. *Soil Microbial Dynamics: Short- and Long-Term Effects of Inorganic and Organic Nitrogen* Soil Sci. Soc. Am. J. 58 (3): 801-806

Finney, D. M., J. S. Buyer, and J. P. Kaye. 2017. *Living cover crops have immediate impacts on soil microbial community structure and function.* J. soil & Water Conserv 72(4): 361-373.

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

McDaniel MD, L. K., Tiemann, and S. Grandy. 2014. *Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis.* Ecol Appl. 24(3):560-70.

Moncada, K., and C. Sheaffer, 2010. *Risk Management Guide for Organic Producers*. U. Minnesota. 300 pp. Chapter 13, Winter Cover Crops. http://organicriskmanagement.umn.edu/.

Ramirez, K.S., J.M. Craine, and N. Fierer. 2012. *Consistent effects of nitrogen amendments on soil microbial communities and processes across biomes*. Glob. Change Biol. 18(6): 1918–1927.

Wolfe, B. E., and J. N. Klironomos. 2005. *Breaking new ground: soil communities and exotic plant invasion.* BioScience 55(6): 477-487.

Slide 31 – *Two more principles for building soil food webs*

In management-intensive rotational grazing systems, a diverse mix of perennial grasses, legumes, and forbs provides soil organisms with a continuous supply of food. The shock of flash grazing causes the vegetation to slough some of its roots while the animals themselves add manure and trample tougher, less-palatable stems into the soil surface. This provides a feast for the soil microbiome, and the following rest period gives the sod time to recover fully so it can sustain the soil life over the long run. Similarly, rotational grazing of cover crops or a short (1-3 year) sod phase in a crop rotation can help restore and maintain cropland soil microbiomes.

Sir Albert Howard, one of the founders of the organic movement, stated the Law of Return for maintaining cropland soil fertility: both nutrients and organic matter must be continually replenished. While taking manure, crop residues, hay, and other biomass from one farm to make compost for use on another site can deplete the former to enrich the latter, there are literally millions of tons of organic residues going to waste in our society – including manure in lagoons of concentrated animal feeding operations (CAFO), as well as tree leaves, yard “waste” and food “waste” from towns and cities across the US. In a blog post, Dr. Girish Panicker (2017) states:

*“[A]ccording to EPA, we throw away 24 million tons of dried [tree] leaves into the landfills every year … This is the greatest gift of nature, which contains thousands of tons of macro and micro nutrients for the succeeding plants. It is the food of our Mother Earth. It can conserve soil and water. EPA states that Americans pay $65/ton to put it in the landfill.”*

The Natural Farmer, Winter 2014-15, 32 pp. Special supplement on grazing. Articles include Mob Grazing, Allen Savory’s Holistic Management system, and several farmer articles on organic dairy cattle and lamb grazing systems. <http://thenaturalfarmer.org/issue/winter-2014/>.

Panicker, G. K. 2017. October 9 response to September 28 blog post by National Sustainable Agriculture Coalition, *Conservation Groups Deliver Farm Bill Recommendations*, available at <http://sustainableagriculture.net/blog/conservation-consensus/>.

Slide 32 – *OFRF Soil Health and Organic Farming Guides*

The Soil Health and Organic Farming Guides published by Organic Farming Research Foundation and available for download free of charge, provide research based guidance on soil, crop, nutrient, weed, and water management for organic producers. The practices outlined here and in the corresponding eOrganic webinars archived on the eOrganic website can help producers develop, maintain, and protect a healthy, multi-functional soil biota for their farms.

Slide 33 – *Challenges in fine-tuning soil biology*

When it comes time to fine tune soil biology management for a specific farm’s region, climate, soil type and condition, crop mix, and production system, several challenges arise.

First, it is difficult to monitor what you cannot see directly – i.e., the soil microbiome. Field observations of abundance and activity of earthworms and other macrofauna, combined with soil condition (color, tilth, drainage, etc), and total SOM in a standard soil test can provide an overall index. Given the close linkage between soil life (abundance, activity, diversity) and soil health, a multi-factor assessment of soil health such as the Cornell Comprehensive Assessment of Soil health (CASH) and the various soil health scorecards and kits for in-field assessment may be valuable; however, they may not be practical for busy and cash-limited farmers.

Laboratory methods for assessing community structure of the soil microbiome including bacteria, archaea, fungi, protozoa, and nematodes are advancing rapidly, and the costs of genetic, fatty acid, and other biochemical analyses have plummeted to the extent that researchers use these methods routinely to evaluate the functional capacity and diversity of soil microbiomes in farming system trials. Some researchers even anticipate that these methods will eventually become available to farmers at cost similar to today’s standard soil tests.

The four-day soil respiration (or PMC), active organic matter (POX-C), and an improved method for total SOM may also become widely available in the near future. The USDA Natural Resources Conservation Service plans to publish a new Technical Guide on these three parameters as well as fatty acid analysis (microbial community structure), soil enzyme assays (C, N, P, and S cycling) and aggregation (beneficial effects of soil biota on tilth).

More research may be needed to develop meaningful interpretation before these methods can become part of the farmer’s soil assessment toolbox.

Second, the sheer complexity and fluidity of the soil biotic community makes it difficult to predict the impact of a given practice, input, or management change on soil health or crop yield.

Third, some caution is needed in categorizing a particular soil organism or functional group as “beneficial.” For example, while the European nightcrawler and other anecic earthworms (deep burrowing / surface casting) are highly beneficial to annual crop production, they can severely upset the soil ecology of native forests, and invasive exotic earthworms now threaten some boreal forests in the northernmost US. Forest trees depend on the accumulation of surface litter and the biotic community that thrives therein – which high earthworm populations can bury and destroy. This raises an interesting question: do we want a lot of anecic earthworms in woody perennial crops like berries, tree fruit, and vineyard – or would undisturbed surface-litter and its associated fungal-dominated soil biota sustain better production and soil health for these crops?

Similarly, while most crops benefit greatly from arbuscular mycorrhizal fungi, these same fungi can become mild parasites to brassica (cabbage), chenopod (spinach) and buckwheat family crops, which cannot form effective arbuscules for mutually beneficial nutrient trading. The multifunctional *Trichoderma* fungi that grow as beneficial endophytes in crop roots and parasitize fungal pathogens directly may also have antagonistic effects on some AMF species.

Finally, as the global climate warms and weather extremes intensify, soil microbiomes may undergo stresses and shifts that are difficult to predict.

Slide 34 – *Soil life challenges for organic farmers*

Tillage inevitably affects soil life, fragmenting fungal mycelia and damaging earthworms and other macro-fauna. However, not all tillage is alike. While the moldboard plow turns the house upside down and the rototiller can pulverize aggregates and mycelia, impacts can be significantly ameliorated by shallow, non-inversion, strip, or ridge tillage. Shallow (3-inch) tillage or chisel plow (non-inversion) improve microbial biomass and function compared to moldboard plow or disk. Ridge tillage works the ridge tops just before planting the crop, thereby stimulating nutrient release selectively within crop rows. After crop establishment, shallow between-row cultivation to take out weeds, rebuild ridges, and moves additional residue into the crop rows. This “soil functional zone management” enhances both microbial activity and POX-C on ridge tops, as well as improving overall SOM accrual across the field (Williams et al, 2017).

In organic vegetable production trials in Washington State, the spading machine (deep noninversion tillage, prepares seedbed in one pass) was found to prevent and relieve subsurface compaction, and is now the standard “full tillage” treatment for ongoing field trials.

The sweep plow undercutter, now gaining recognition as a soil- and moisture-conserving approach to primary tillage in lower-rainfall regions, undercuts weeds and cover crops at the root crown, leaving protective residues on the surface, and most of the soil profile undisturbed. Studies in Nebraska show less compaction and improved yields when this tool is used in lieu of the disk to terminate cover crops ahead of corn and soybean in Nebraska.

Organic production systems that rely on compost, poultry litter, or manure for organic matter and N tend to accrue surplus soil P, which in turn, can depress mycorrhizal activity. Very high levels of active SOM can also result in N mineralization in excess of crop needs, leading to nitrate leaching, denitrification, and reduced activity of N fixing microbes. As noted above, high levels of plant available N and P can reduce crop “investment” in the rhizosphere microbiome and may even reduce root biomass and depth. However, a little compost used with cover crops or rotational grazing can go a long way; its full benefits may be obtained at rates that do not build up excess nutrients or deter important rhizosphere organisms.

Cogger et al., cited above.

Hu, S., C. Reberg-Horton, M. Schroeder-Moreno, Y. Cardoza, J. Grossman, W. Robarge, and W. Eveman. 2016. *Assessing the Greenhouse Gas Mitigation Potential of Organic Systems in the Southeast.* Progress report for ORG project 2012-02978. CRIS Abstracts.\*

Reeve, J., and E. Creech. 2015. *Compost Carryover Effects on Soil Quality and Productivity in Organic Dryland Wheat*. <http://articles.extension.org/pages/73247/compost-carryover-effects-on-soil-quality-and-productivity-in-organic-dryland-wheat>.

Reinbott, T. 2015 .*Identification of factors affecting carbon sequestration and nitrous oxide emissions in three organic* *cropping systems*. Final report on ORG project 2011-04958. CRIS Abstracts.\*

Ryals, R., and W.L. Silver. 2013. *Effects of organic matter amendments on net primary productivity and greenhouse gas emissions in annual grasslands*. Ecol. Appl. 23(1): 46–59.

Sun H, P. Koal, D. Liu, G. Gerl, R. Schroll, A. Gattinger, R. G. Joergensen, and J. C. Munch. 2016. *Soil microbial community and microbial residues respond positively to minimum tillage under organic farming in Southern Germany*. Appl Soil Ecol. 108:16-24.

Van Geel, M., E. Verbruggen, M. De Beenhouwer, G. van Rennes, B. Lievens, and O. Honnay. 2017. *High soil phosphorus levels overrule the potential benefits of organic farming on arbuscular mycorrhizal diversity in northern vineyards*. Agriculture, Ecosystems, and Environment 248: 144-152.

Williams, A., A. S. Davis, A. Jilling, A. S. Grandy, R. T. Koide, D. A. Mortensen, R. G. Smith, S. S. Snapp, K. A. Spokas, A. C. Yannarell, and N. R. Jordan. 2017. *Reconciling opposing soil processes in row-crop agroecosystems via soil functional zone management*. Ag Eco Env 236: 99-107.

Wortman, S., C. Francis, R. Drijber, and J. Lindquist. 2016. *Cover Crop Mixtures: Effects of Diversity and Termination Method on Weeds, Soil, and Crop Yield*. Midwest Cover Crop Council, <http://mccc.msu.edu/wp-content/uploads/2016/12/NE_2016_Cover-Crop-Mixtures_-Effects-of-Diversity-and-Termination.pdf>.

Zuber S. M., and M. B. Villamil. 2016, cited above.

Slide 35 – *Have modern cultivars forgotten how to “talk” with soil life?*

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, natural enemies of pests and pathogens, and organisms that induce systemic resistance (ISR) to foliar and belowground pathogens. 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.

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.

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>.

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.

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/>

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.

Slide 36 – *Smorgasbord of microbial products*

Today’s organic soil amendment catalogs offer a dizzying array of microbial inoculants, microbial “foods,” and biostimulants claimed to restore soil life and soil function; improve crop nutrition, resilience, growth, and yield; or suppress disease directly or through ISR.

The slide shows only a short and incomplete listing of general classes of products.

Of those listed, rhizobia inoculants for legume seeds are the most “tried and true,” and widely used. Their use is strongly recommended when a legume is planted in a given soil for the first time in several years. Yet, efficacy of inoculants in improving N2 fixation can vary, and may be limited when soil soluble N is relatively abundant (the legume uses this N rather than investing in N fixing rhizobia), or when indigenous rhizobium strains outcompete the applied inoculant.

Ecto-mycorrhizal fungal inoculants are also recommended for certain woody perennial crops such as pecan, and can be highly effective in enhancing establishment and growth in nutritionally “lean” soils when plant and fungal species are correctly matched.

Research has shown significant reduction in disease from application of natural enemies of soilborne pathogens, such as *Coniothyrium minitans* and *Trichoderma* spp.

Research results with other microbial products have been mixed. For small scale intensive operations that do not have access to finished compost or worm castings, these products may help replenish the soil biota. However, their use may not be economically or logistically practical at larger scale, e.g. 100 acres or more.

Slide 37 – *Building the soil biotic community*

A biotic community is comprised of the organisms themselves, their food, water, and air supply; and habitat. The soil itself provides organisms; depleted soils may have lower diversity of organisms in dormant forms, but are almost never truly “dead.” Organic inputs that include readily digestible components – sugars, starches, proteins, lipids, and (for fungi) lignins and cellulose – comprise the food. Habitat is developed and maintained through soil aggregation and structure development, which creates the network of large to small pore spaces that different organisms inhabit. Good soil structure also maintains both water and air supplies.

Plant roots provide both food and habitat, and woody plant residues persist long enough to offer habitat for micro-arthropods and other larger soil organisms.

Soil conditioners such as biochar and humates primarily enhance habitat by stabilizing soil structure and SOM; compost tea acts primarily as an inoculant (organisms); and succulent green manures and fresh livestock manure provide readily-available microbial food. Thus, combining these inputs might build a more active, diverse, and balanced soil food web than any one input by itself. Several studies have demonstrated this synergism with cover crops plus compost.

Organic fertilizers and finished compost have contrasting impacts on the soil biota. Eleven years into the Washington State U organic vegetable systems trial, plots amended annually with a finished compost made from cattle manure, bedding and yard waste (moderate C:N ratio) showed 30% higher microbial respiration and accrued 60% higher POX-C and 45% total SOM than plots amended annually with pelleted poultry litter (low C:N ratio) at the same total N rate. Crop yields in the two systems were comparable.

In a California organic vegetable farming systems study, annual compost applications (~7 tons dry weight/ac-yr) contributed most of the total SOC accrual, while winter cover crops provided most of the boost in microbial biomass and activity, and greatly improved yields in a following lettuce crop through effective N cycling.

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.

Brennan et al., 2017, cited above.

Delate et al., 2015, cited earlier

Hooks et al., 2015, cited earlier.

Hurisso et al., 2016, cited earlier.

Tavantzis, S. M., R. P. Larkin, A. V. Alyokhin, M. S. Erich, and J. M. Jemison. 2012. *A Systems Approach to Optimize Organic Crop Production: Enhancing Soil Functionality and Plant Health to Suppress Plant Diseases and Pests.* Final report for ORG project 2007-01405. CRIS Abstracts.\*

Slide 38 – *Do we need to introduce microbes?*

Gabe Brown 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, reduced fertilizer and other inputs, integrated crop and livestock production, and implemented management-intensive rotational grazing. Over a 20 year period, SOM levels recovered from 2% to about 7%, compared to a “natural” level for the region of about 8% under native prairie.

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

Slide 39 – *Do commercial inoculants work?*

The great complexity of the soil ecosystem and the many factors impacting its function (from crop rotation and management history to soil type and climate) results in highly variable results from adding one or more newcomers to the existing soil biotic community. In healthy, fertile soil, the specific need (function or service) that the inoculant is intended to provide may already be met by existing soil biota (e.g., a strong AMF community) or management practices (e.g., sufficient NPK from inputs). Simnilarly, soils already rich in active and stable SOM are unlikely to show soil quality or crop yield responses to humates and other soil conditioners.

Mycorrhizal inoculants and other microbial biostimulant and biofertilizer products are most likely to benefit crop yields on soils of moderately low fertility – conditions in which plants are nutrient limited and the existing soil biota is below optimum in activity or diversity, yet in which soil conditions are reasonably favorable for the introduced microbes. *Extremely* degraded soils may hinder inoculum efficacy unless and until other restorative measures are also taken.

Inoculants can also fail if the existing soil biota outcompetes, preys on, parasitizes, or otherwise suppresses the added microbial species. Products applied to the bulk soil (e.g., spraying the entire field) may be prone to these factors, whereas products applied to a host crop (seed treatment, root dip, etc) may escape these hazards by establishing symbiosis with the crop.

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>.

Weil and Brady, 2017, cited above.

Slide 40 – *Do commercial inoculants work? Some research findings*

Researchers at Ohio State University worked with organic farmers to evaluate 13 different commercial microbial biostimulants and biofertilzers (not bio-fungicides or biopesticides). Most products contained several bacterial and/or fungal species (AMF and other) that research has shown play important roles in soil and plant health. Trials were conducted over two years at 19 farms and 2 research stations in seven states (IA, IL, MI, MO, OH, PA,TN). Surprisingly, none of the trials revealed significant positive effects of the inouclant on crop yields. This might reflect the already-fertile condition of organically managed soils in these studies.

In a meta-analysis of 134 studies around the world, test crops receiving AMF or ecto-mycorrhizal inoculants averaged 50% improvement in growth, biomass, or yield, though individual trials varied from 35% *loss* to more than doubling. P-limited crops showed the most positive responses, and inoculants worked better in the presence of a diverse soil biota than when applied alone to an otherwise sterile system in a greenhouse or growth chamber trial.

On a low fertility soil in Brazil, applying either the N2-fixing endophyte *Herbaspirillum seropedicae* or humic substances improved corn yield about 20%, and the two materials together acted synergistically, with a 65% yield increase. In severely saline soils in a cold temperate region of northern China, a *Trichoderma* inoculant ameliorated soil conditions, improved nutrient cycling, and nudged corn yields up 5 – 12%.

Canellas, L. P., D. M. Balmori, L. O. Médici, N. O. Aguiar, E. Campostrini, R. C. C. Rosa, A. R. Façanha, and F. L. Olivares. 2013. *A combination of humic substances and Herbaspirillum seropedicae inoculation enhances the growth of maize (Zea mays L*.). Plant and Soil 366 (1-2): 119-132.

Fu, J., Y. Xiao, Y. Wang, Z. Liu, and K. Yang. 2019. *Trichoderma affects the physiochemical characteristics and bacterial community composition of saline–alkaline maize rhizosphere soils in the cold-region of Heilongjiang Province*. Plant and Soil 436: (1-2):211-227.

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.

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](mailto:kleinhenz.1@osu.edu).

Slide 41 – *Tips for using microbial inoculants*

Clarifying goals and assessing existing soil condition can help determine whether existing soil resource and practices are meeting the goals, or whether an inoculant might be helpful.

The biggest risk with purchased soil inoculant products is the cost of the material and application – which can be substantial in multi-acre operations. On a healthy, well-managed soil, a purchased product may be an unneeded expense, yet it may be highly beneficial in soils of lower fertility, especially if combined with other practices such as cover cropping.

Some of the highly leached “red clay” soils and coastal plain sandy soils of the southeastern US (Ultisols) may be good candidates for purchased inoculants, especially AMF for most crops and ectomycorrhizal inoculants for woody perennial fruit and other horticultural crops. Be sure to match inoculant type with the crop – some ecto mycorrhizae are species specific; blueberries require a special ericoid mycorrhizal symbiont.

*Rhizobium* inoculants for legume seeds are advisable, especially if the field has not grown that legume in recent years. Legume inoculants are relatively “cheap insurance”, costing only a few dollars per acre. Be sure to use the correct inoculant type for the legume planted.

Obtain information on the product under consideration from impartial sources – experiences of other farmers who have used it, or field trials with the product or the organism(s) it contains by independent investigators.

Try it out on a small scale first, and do a comparison of crops grown with *versus* without the inoculant or other product. Repeat the trial for a couple of seasons, on a few different crops, and/or in fields with different soil types or conditions.

For organisms whose primary function is as a plant symbiont, endophyte, or rhizosphere organism (e.g., mycorrhizal fungi, rhizobia, plant growth promoting rhizobacteria, or microbes believed to induce systemic resistance to plant diseases), apply it directly to seeds or roots (dip root balls at planting, or root drench for established crop). If broadcast applied, it may become diluted or outcompeted by indigenous biota.

Slide 42 – *Encouraging mycorrhizal fungi*

Since mycorrhizal fungi are obligate plant symbionts, they can grow actively only in the presence of host plant species. They can persist as dormant spores when conditions do not permit active growth; however their numbers decline during prolonged fallow or prolonged periods in non-host crops such as brassicas, chenopods, amaranth, and buckwheat. Mycorrhizal activity can usually be restored with a grass-legume or multispecies cover crop. Crop diversity supports diversity of AMF species and strains, and can improve the chances of effective mycorrhizal colonization of subsequent crops. Grass or legume cover crops can enhance AMF populations and colonization of a following cash crop by up to 50 percent.

While all tillage can fragment mycelia and thus set back mycorrhizal activity, spores and viable mycelial fragments can persist and regenerate effective AMF for future crops, especially if tillage depth, intensity, and frequency are reduced. A meta-analysis of 54 studies from five continents indicated that ridge tillage or shallow tillage were nearly as effective as no-till improve AMF over moldboard plow (25, 28, and 30% increase, respectively).

NOP approved fungicides, including copper, sulfur, and possibly even biofungicides like *Trichoderma* may adversely impact AMF.

Dr. David Douds has developed a practical method for propagating a farm’s indigenous AMF populations. Starting with a few handfuls of the healthiest soil on the farm (from mature woodland, prairie, or the farm’s best fields), the mycorrhizal fungi therein can be propagated in container culture with a strong host species such as bahia grass, which is allowed to grow through the season, then winterkill (the mycorrhizal spores are winter hardy). The following spring, the growing medium with root residues can be used as a concentrated, multispecies inoculum to promote effective AMF colonization of strong host crop species such as tomato or pepper. By using indigenous AMF, this approach may yield a higher success rate and greater benefits to soil health and crop yield than a purchased inoculant.

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.*

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 .

Douds, D. D. 2015. *On-farm Production and Utilization of AM Fungus Inoculum*. <https://articles.extension.org/pages/18627/on-farm-production-and-utilization-of-am-fungus-inoculum>.

Hallema, M., C. Pekrun, H. Lambers, and E. Kandeler. 2019. Hidden miners – the roles of cover crops and soil microorganisms in phosphorus cycling through agroecosystems. Plant and Soil 434:7–45.

Hamel, 2004, cited above.

Rillig, 2004, cited above.

Slide 43 – *Managing crop diseases with soil biology*

A number of commercial biofungicides and ISR-inducers have been developed, based on sound science, including but not limited to the six fungal, actinomycete, and bacterial genera listed on the slide. When used on a susceptible pathogen in conjunction with sound crop rotation and soil health practices, many of these materials can be quite effective.

So-called “biofumigation” based on mustard seed meals, crucifer crop residues, and green manures may act by stimulating the growth of disease-suppressive soil biota rather than fumigant-like destruction of pathogens. For example, while mustard seed meals have outperformed conventional fumigants in suppressing orchard replant disease (caused by a complex of pathogens and pest nematodes), research showed that the direct fumigant effect of the seed meal lasts a few days at most, while disease control can last two *years* (compared to one year for conventional fumigant). The primary mode of action appears to be a proliferation of *Trichoderma* and other known disease antagonists. Similarly, incorporation of readily-degradable organic materials (green manures, rice bran, etc) has been found to stimulate antibiotic-producing strains of *Streptomyces*, which suppress plant pathogens.

Colla et al., 2017, cited above.

Mazzola, M. 2016. *Managing Resident Soil Biology for Tree Health.* Webinar, powerpoint slides available at: <http://tfrec.cahnrs.wsu.edu/organicag/wp-content/uploads/sites/9/2016/12/Organic-Soil-P1779.pdf>.

Mazzola, M., 2017. *Manipulation of the Soil Microbiome to Advance Orchard System Resilience.* Webinar, powerpoint slides available at:

<https://www.ars.usda.gov/ARSUserFiles/np305/GrapeandWine/2017%20Grape%20Research%20Workshop/15%20-%20Mazzola.pdf>

Mazzola, M., S. S. Hewavitharana, and S. L. Strauss. 2015. *Brassica seed meal soil amendments transform the rhizosphere microbiome and improve apple production through resistance to pathogen reinfestation.* Phytopathology 105: 460-469.

Stone, 2014, cited earlier.

Tomihama, T., Y. Nishi, K. Mori, T. Shirao, t. Iida, S. Uzuhashi, M. Ohkuma, and S. Ikeda. 2016. *Rice Bran Amendment Suppresses Potato Common Scab by Increasing Antagonistic Bacterial Community Levels in the Rhizosphere.* Phytopathology 106(7): 719-728.

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.

Wiggins, B. E., and L. L. Kinkel. 2005. *Green Manures and Crop Sequences Influence Potato Diseases and Pathogen Inhibitory Activity of Indigenous Streptomycetes.* Phytopathology 95(2):178-185.

Zubieta and Hoagland, 2017, cited earlier.

Slide 44 – *Anaerobic soil disinfestation (ASD)*

Anaerobic soil disinfestation is a process first developed and implemented by greenhouse produce growers in the Netherlands and in Japan. When Dr. Shennan adapted the concept to field production of strawberries in California, using rice bran at 5 – 9 tons/acre as the organic carbon source, ASD equaled or exceeded efficacy of conventional fumigation (methyl bromide) in terms of pathogen reduction and crop yields in several site-years of field trials. Two Webinars on eOrganic describing the technique and outcomes:

Shennan, C., and D. Butler. 2011. <http://articles.extension.org/pages/33656/a-novel-strategy-for-soil-borne-disease-management:-anaerobic-soil-disinfestation-asd-webinar>.

Shennan, C., and J. Muramoto. 2014. <http://articles.extension.org/pages/70271/anaerobic-soil-disinfestation-to-control-soil-borne-pathogens:-current-research-findings-and-on-farm>.

Slide 45 – *Summary: how to build a high-functioning soil food web*

Slides 46 and 47 – *Credits, questions*

\* 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: <http://cris.nifa.usda.gov/cgi-bin/starfinder/0?path=crisassist.txt&id=anon&pass=&OK=OK>.

Many final reports include references to research articles in refereed journals.