**Soil Biology for the Western Region***Organic Practices to Recruit and Nurture Beneficial Biota in the Soil*

eOrganic Soil Health and Organic Farming Webinar Series

June 12, 2019

Developed and presented by Organic Farming Research Foundation, with funding from the Western Region SARE program

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

*Slide 1 – Title slide*

*Slide 2 – Western region organic farmer research priorities*

A total of 555 respondents from the Western region participated in OFRF’s 2015 nationwide survey of organic farmers to identify top research priorities. In addition, six listening sessions took place in the West (four in CA, two in OR).

Farmers wanted more research on the roles of soil life in meeting challenges of organic production in the region, including water management and nutrient cycling in arid climates, and restoring soils “worn out” from conventional practices. They also want to know how to maintain good soil biology in organic systems with either routine full-field tillage or reduced tillage.

Farmers cited specific crop diseases in the region that need research attention, including several soilborne pathogens: fusarium wilt (*Fusarium oxysporum*), charcoal rot (*Macrophomina phaseolina*), *Verticillium* wilts, and *Phytophthora*.

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- Subtitle slide – Building soil biology in organic farming: the players*

*Slide 4 – The soil food web*

Beginning in the 1990s, Dr. Elaine Ingham and other soil biologists introduced the concept of the Soil Food Web to the agricultural community and the general public.

A food web consists of multiple trophic levels, beginning with the primary producers – living plants (by far the major component) and a few soil algae and chemo-autotrophic bacteria (e.g. nitrifiers). The next level consists of organisms that derive their nourishment directly from plant roots – including beneficial symbionts as well as pathogens and parasites – or from the residues of plant and animal life – decomposer bacteria and fungi. The latter immobilize (tie up) N and other nutrients, a fact that led 20th century agricultural professionals to warn that organic farming won’t work because the microbes will take all the nourishment in residues and starve the plants.

Understanding of the soil food web changed all that – we now know that the third trophic level – protozoa and bacterial- and fungal-feeding nematodes that eat the decomposer microbes do not need all of the N and other nutrients in their prey, so they give the surplus back to the soil in plant available form. In addition, plants give off root exudates to encourage bacteria and fungi to grow in their immediate vicinity – and that draws in the grazers (third trophic level) to release nutrient right in the root zone where and when plants need them.

Larger organisms of higher trophic levels accelerate the process of residue decomposition. These include shredders (mites, springtails), predators (some mites, larger nematodes, etc) and ecosystem engineers (earthworms, termites, ants, burrowing vertebrates).

In addition to recycling and releasing plant nutrients, the food web does the equally important job of converting much of the organic residue into soil organic matter, important for soil structure and long term soil health, as well as sequestering carbon in the soil.

The slide 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.

*Slide 5 – Soil microbiota*

Information in the next four 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.

The soil microflora include:

Rhizosphere (root zone) bacteria (A) and fungi live near actively growing roots and feed on root exudates and sloughed root hairs and epidermal cells (“rhizodeposition”).

Decomposer bacteria, filamentous actinobacteria (B), and fungi (C) live on fresh organic residues – plant litter, dung, insect and animal remains, etc. Bacteria consume readily-decomposable materials like sugars, proteins, amino acids, and organic acids, and reach their greatest numbers in fertile, nearly-neutral, periodically tilled soils amended with legume green manures, livestock manure, and other nutrient-rich residues. Fungi tolerate more acidic pH, can decompose more resistant materials like cellulose and lignin, and become dominant in undisturbed soils mulched with residues with relatively high carbon-to-nitrogen (C:N) ratio, such as chipped brush and tree leaves. Actinobacteria prefer near-neutral pH like bacteria, but can consume more decay-resistant materials like fungi. Some can tolerate dry or saline soil, and thus help sustain biological activity during drought and in semarid region soils.

Protozoa like ciliates (D), amoebas, and flagellates feed on bacteria, releasing plant-available nutrients in the process.

*Slide 6 – Root symbionts*

Plant roots directly support a range of important endophytic (within-root-tissue) symbionts, including but not limited to *Rhizobium* or *Bradyrhizobium* in legume root nodules (A), *Frankia* actinobacteria that fix N in root nodules of alder and several other families of trees and shrubs (not shown), ectomycorrhizal fungi on tree roots (B), and arbuscular mycorrhizal fungi or AMF (C) on the roots of most of the world’s plant species, including 70% of agricultural crops. Other endophytic symbionts include various bacteria (e.g., fluorescent *Pseudomonas*) and fungi (e.g., *Trichoderma, Metarhizium*). While all of these organisms live on plant photosynthetic product, they repay their hosts with N fixation (rhizobia, *Frankia*), enhanced uptake of nutrients and moisture (mycorrhizal fungi), enhanced crop resilience to stresses, and disease suppression (many organisms).

Other plant-dependent soil organisms include pathogenic fungi, bacteria, and actinobacteria; parasitic (root-feeding) nematodes; and larger soil pests such as corn rootworm. Healthy crops can tolerate a few of these “freeloaders”; higher numbers cause serious crop losses.

The soil biota includes natural enemies of the plant pathogens and pests, such as predatory and entomopathogenic nematodes and mites, and various parasitic fungi. For example the same *Metarhizium* and *Trichoderma* that enter plant root tissues as beneficial endophytes can also attack some fungal pathogens or pests directly. 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.

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, 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>.

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>.

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 7 – Soil 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.

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. Protozoa similarly contribute to nutrient cycling and release as they dine on bacteria. When this grazing activity is concentrated in the rhizosphere (where bacterial populations may be 10 to 100 fold higher than in bulk soil), it can contribute to tightly coupled (efficient) nutrient cycling.

Conversely, when the soil is amended with an abundance of N-rich organic residues (such as an all-legume green manure), the ensuing “bloom” of bacteria and bacterial-feeding nematodes 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.

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

Researchers use the structure of soil nematode communities to assess 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 and better stabilization of SOM and nutrients. Further research is needed to develop guidelines for interpretation and practical application of nematode community indices.

Healthy cropland and grassland soils with near-neutral pH generally have high populations and diversity of nematodes.

Chen, G., C. R. Hooks, M. Lekveishvili, K. H. Wang, K. H., N. Pradhan, S. Tubene, S., R. R. Weil, and R. Ogutu. 2015. *Cover Crop and Tillage Impact on Soil Quality, Greenhouse Gas Emission, Pests, and Economics of Fields Transitioning to Organic Farming.* Final report for project ORG 2011-04944. CRIS Abstracts.\*

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.\*

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

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 8 – Shredders and ecosystem engineers*

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.

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 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, which amounts 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 (by speeding mineralization and deep drainage of water through soil profile). In addition, when exotic earthworm species invade forest ecosystems, they can upset the particular soil biota and ecosystem on which the trees depend.

Dung beetles are nature’s pooper scoopers, and can play a major role in nutrient cycling and soil health in grazing lands and in crop-livestock integrated systems. In the Pacific Northwest, organic vegetable farms had higher diversity of dung beetles and coprophagous (manure-consuming) microbes than conventional farms, which showed potential for accelerating the attenuation of human foodborne pathogens in surface-deposited manure, thereby contributing to food safety in manure-fertilized and crop-livestock integrated systems.

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.

Cogger et al., 2013; Epstein et al, 2017, cited above.

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.

Weil and Brady, 2017, cited above.

*Slide 9- Subtitle slide – Building soil biology in organic farming: the processes*

*Slide 10 – Soil life, plant nutrients, and moisture*

As the soil life processes residues into SOM and plant nutrients, it performs essentially all of the functions of a healthy soil upon which agricultural production and natural ecosystems depend. In addition to conserving and delivering plant nutrients, soil organisms modulate soil physical properties. 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 holding capacity, and favorable conditions for extensive root growth. A diverse, balanced soil food web and plant roots work together to protect water quality and builds stable SOM.

*Slide 11 – Soil life processes all organic inputs*

Essentially all organic materials added to the soil – exudates and sloughing from living roots, plant residues, manure, etc – become food for soil organisms. Part of this organic input is respired and released as carbon dioxide and plant-available nitrogen (N) and other nutrients (process of *mineralization*), part is converted into 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 or otherwise protected from further decay (*stabilization*). Both processes are essential to the health of agricultural and natural ecosystems, and both are enhanced by management practices that build soil biodiversity and biological activity.

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 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 mixture of soluble organic compounds), along with Hoagland’s solution to provide NPK and other essential mineral nutrients. 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 complex (~80 compounds) and 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 12 – Monitoring soil biological function*

Simple, 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 itself part of the active SOM (microbial “food”), 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 13 – A matter of balance*

When the soil microbiome (B) processes 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 longer term capacity to sustain both stabilization and mineralization. Stable SOM develops as the soil microbiota “turns over” – grows and dies – leaving organic residues tightly bound to clay, silt, and other soil minerals.

Soil biologists have developed two parameters to describe the balance between these two vital processes: *microbial growth efficiency* (MGE) – the fraction of organic input that becomes new biomass (Bn / OI); and the *metabolic quotient* (qCO2), the ratio of respiration rate to existing biomass (R / B). These indices are calculated in terms of *carbon* – i.e. how much of the C in organic inputs 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 14 – Two-way exchange*

Plant nutrition is a two way exchange, in which photosynthesis provides nourishment for the soil life, in the form of rhizodeposition. In addition to the “bread and butter” of sugars and amino acids, the roots of each plant species secrete other substances that act as specific chemical signals to stimulate and host those soil organisms most beneficial to that plant. In turn, the resulting root zone microbiome facilitates uptake of the nutrients the plant needs to thrive.

*Slide 15 – Rhizosphere*

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

A significant 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). Fungal mycelia grow out into the soil an inch or further 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 access directly.

As noted earlier, protozoa and nematodes grazing on rhizosphere bacteria also deliver plant nutrients right to the roots. This process, together with mycorrhizae, promotes 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 risks to water quality or climate.

When ample NPK is applied in a readily plant-available form, the plant may reduce its investment in the soil life – why “waste” sugar on microbes if the soil is replete 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 environment are lost. Even NPK rates recommended on a standard soil test can reduce soil microbial activity in this way.

*Slide 16 – 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 can feed seedlings via mycorrhizal networks (some of 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 abundant N, and the large, fibrous, mycorrhizal root system of the grass absorbs P more efficiently, the mycelial connection may facilitate an exchange of these two nutrients and enhance vigor of all four components.

Other studies have shown the importance of AMF to N2 fixation efficacy in the legume-rhizobium symbiosis.

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.

Weil and Brady, 2017, cited earlier.

*Slide 17 – Soil life and plant available moisture*

*Slide 18 – Soil life, pathogens, and pests*

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.

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 production.

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 aid nutrient uptake.

As noted earlier, dung beetles 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/>.

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

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.

Zubieta, L. and L. A. Hoagland, 2017, cited earlier.

*Slide 19 – The plant disease triangle*

*Slide 20 – How a healthy soil biota can break the disease triangle*

*Slide 21 – Subtitle slide – Building soil biology in organic farming –the practices*

*Slide 22 – NRCS principles of soil health*

The four NRCS principles of soil health have been abundantly validated by research as guidelines for managing and optimizing soil biology in agricultural production.

Plant photosynthesis is the origin of essentially all organic carbon that soil organisms use to grow, multiply, build SOM, and perform their other agro-ecosystem services. Thus, *sustainable crop intensification* – maximizing annual plant biomass production and duration (days per year) of living root – is vital for soil life, and is covered by the first two Principles.

Sustainable intensification practices include cover cropping between production seasons, relay cover crop planting into standing cash crop, intercropping, perennial sod or forage crops in vegetable or field crop rotations, and maintaining living mulch in orchard and other perennial horticultural crops in living plant cover. When conditions are too hot, cold, or dry to maintain actively growing plant cover, keeping the soil surface covered with plant residue, dormant vegetation, or organic mulch will prevent erosion, slow SOM loss, and protect soil organisms from the extreme conditions.

The third principle – diversified cropping system – builds species and functional diversity in the soil food web, since each plant species harbors a specific suite of symbionts and rhizosphere organisms. Diversity increases the likelihood that most or all key soil life functions will be adequately covered, and decreases risks of crop disease. Multiple studies have shown significant benefits of adding just one or two new cover or cash crops to an existing low-diversity rotation such as corn-soybean, which can degrade soil health even under organic management unless winter cover crops, cereal grains and/or a perennial sod crop are added.

The fourth principle poses the greatest challenges to all farmers, since agriculture in any region, especially production of annual crops, entails a major shift away from the native forest, savanna, or prairie ecosystem, and requires some disturbance to maintain the agro-ecosystem: tillage, cultivation, fertilizers, and/or crop protection materials. Regular tillage tips the balance of the soil food web in favor of bacteria at the expense of fungi and tends to reduce SOM and MGE. Concentrated fertilizers favor “copiotrophs” (bacteria and other organisms that thrive in high-nutrient conditions and tend to burn up SOM) over “oligotrophs” (organisms that can live on slowly-decomposible, woody materials and tend to build SOM). Soil fumigants, soil applied fungicides, insecticides, nematicides, and even herbicides can knock-out key components of the soil biota, at least for a period of time.

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 risks of corky root in lettuce, which is significantly less prevalent in organic lettuce fields that do not use these inputs.

Finally, invasive exotic plant species can impact indigenous soil microbiomes in a way that allows the invasive species to gain even more advantage over native plants. Garlic mustard (*Alliaria petiolata*) and diffuse knapweed (*Centaurea diffusa*) release root exudates toxic to key members of the soil biota, while other invasive species modify nutrient cycling or soil moisture relations in ways that alter the soil food web in favor of the invasive plant.

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.

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>.

K. 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/.

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.

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 23 – Two more principles for building soil food webs*

In management-intensive rotational grazing systems, continuous cover with 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 some of the less-palatable (old, tough, carbon-rich) top-growth into the soil surface. This results in 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. Rotational grazing of cover crops or a short (1-3 year) sod phase in a crop rotation can help restore and maintain cropland soil food webs.

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 (CAFOs), 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.”*

**Grazing**. Special supplement to The Natural Farmer, Winter 2014-15, 32 pp.

<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 24 –Building 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 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 all 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 et al., 2016, cited earlier

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 25 – Promoting mineralization*

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

Cover crops, especially succulent legumes or crucifers, also promote mineralization over stabilization. Tilling in a high-N green manure, or adding concentrated organic fertilizers such as poultry litter, blood meal, and feather meal stimulates the growth of soil bacteria and bacterial-feeding nematodes. Because bacterial-dominated soil microbiomes generally have lower MGE than microbiomes richer in fungi, these practices may 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 26 – Stressed soil microbiome*

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 organic inputs). 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 MGE). These systems also provide less organic input than sustainable organic or conservation agriculture systems.

Because quantity and quality of organic inputs are inadequate to sustain substantial microbial biomass and growth, the soil biota’s capacity to mineralize N and other nutrients diminishes despite the large % of organic inputs respired (mineralized).

The qCO2 is generally considered an index of stress on the soil microbial community; for example, orchard floor soils maintained as bare fallow through 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. In addition, long term use of soluble NPK fertilizers tends to reduce microbial biomass, increase qCO2, deplete SOM, reduce N-mineralizing capacity and thereby increase the farm’s dependence on fertilizer N inputs.

Dick RP. 1992, cited earlier.

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 27 – Integrate complementary practices*

Understanding how different inputs and practices affect the soil biota can help farmers develop the best suite of practices to optimize the soil food web.

A biotic community is comprised of the organisms themselves, their food, water, and air supply; and habitat. The soil itself provides organisms, perhaps in dormant form when the soil is depleted. 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 make their home. Good soil structure also helps to maintain the water supply and at the same time provides for aeration.

In addition to providing the “daily bread” for soil life, living plant roots create a vital habitat for key members of the soil food web. Decay-resistant organic materials such as woody plant matter persist long enough to offer habitat for micro-arthropods and other larger soil organisms.

When selecting organic inputs and practices for building the soil community, keep in mind what each material offers most effectively. For example, 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 cover crops and manure provide 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 shown that cover crops plus compost or manure may build more active and total SOM, and support greater microbial activity and functional biodiversity than either practice by itself.

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 also proved essential for effective N cycling and for sustaining yields in the spring lettuce crop.

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.

Delate et al., 2015, cited earlier

Chen 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 28 – Soil life challenges for organic farmers*

Tillage can hurt soil life, especially fungi, micro-arthropods, earthworms, and other macro-fauna, but damage can be minimized. While the moldboard plow turns the house upside down and the rototiller on maximum PTO pulverizes aggregates and fungal mycelia, impacts can be ameliorated by using different implements, or simply reducing depth and PTO speed on the rototiller. Shallow (3-inch) tillage or chisel plow (non-inversion) improves microbial biomass and function compared to moldboard plow or disk. Ridge tillage works the ridge tops just before planting the crop, thereby promoting mineralization in the crop row. After crop establishment, shallow between-row cultivation to take out weeds and rebuild ridges moves additional residue into the crop rows. This “soil functional zone management” enhances microbial activity and POX-C on ridge tops, as well as total SOM accrual across the field (Williams et al, 2017).

In organic vegetable production trials in Washington State, the spading machine (deep noninversion tillage, incorporates cover crop and make a seedbed in one pass) was found to reduce subsurface compaction, and is now the standard “full till” treatment for ongoing trials.

The blade plow (sweep plow undercutter) severs weeds and cover crops just below the root crown, leaving protective residues on the surface, and most of the soil profile undisturbed. Dryland farmers in low-rainfall regions use the blade plow as a soil- and water-conserving primary tillage tool, and studies in Nebraska showed less compaction and improved soybean and corn yields when this tool was used in lieu of disk to terminate a preceding cover crop.

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 fungal activity. High rates of poultry litter or high-analysis compost can also result in high soluble N levels, nitrate leaching, denitrification, and reduced activity of N fixing and N cycling microbes.

However, a little compost goes a long way. When used in conjunction with cover crops or rotational grazing; its full benefits may be obtained at rates that do not build up excess nutrients or deter important rhizosphere organisms.

Today’s organic inputs catalogues include myriad microbial inoculants claimed to enhance crop nutrition and vigor, improve overall soil food web function, or suppress plant diseases. Research results have been mixed, even with organisms with known beneficial roles in soil and crop health. While the appropriate species of rhizobia applied to legume seeds is established practice, and the right mycorrhizal fungi applied to seeds or root balls of host crops at planting can be quite beneficial in some circumstances, many microbial preparations, especially when broadcast-applied to soil, often show little effect, especially on already-fertile, healthy soils.

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.\*

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).

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.

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>.

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

Plant genetics play a significant 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 elicit ISR. Reversing this trend through plant breeding and selection in and for organic systems has emerged as a plant breeding priority; 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 and Hoagland, 2017., cited above.

*Slide 30 – Encouraging mycorrhizal fungi*

Mycorrhizal fungi grow actively only in the presence of their host plants. They can persist as dormant spores, but their numbers decline during prolonged fallow or rotations dominated by non-host crops such as brassicas, chenopods, amaranth, and buckwheat

Crop diversity supports diversity of AMF species and strains, and can improve 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.

Tillage fragments mycelia and can set back mycorrhizal activity, yet spores and viable mycelial fragments can regenerate effective AMF for future crops, especially if gentler, non-inversion forms of tillage are used. A meta-analysis of 54 studies from five continents indicated that ridge tillage or shallow tillage were nearly as effective as no-till for improving AMF activity over moldboard plow (25, 28, and 30% higher, respectively)

NOP approved fungicides, including copper, sulfur, and possibly 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 of 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 in potting mix to grow starts of host crop species such as tomato or pepper. Indigenous AMF produced on-farm may be more effective than purchased inoculant.

Meta-analysis has shown purchased inoculants most effective on soils of moderately low fertility. Greatest benefits have been observed with ectomycorrhizal inoculants on woody perennial crops, when care is taken to match plant and fungal species.

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.

Kleinhenz, 2018, cited earlier.

Klironomos, and J. Umbanhowar. 2010. *A meta-analysis of context-dependency in plant response to inoculation with mycorrhizal fungi*. Ecology Letters 13: 394–407.

Rillig, 2004, cited above.

*Slide 31 – Subtitle slide – Building soil biological function in the Western region*

*Slide 32 – Maritime CA and the Pacific Northwest*

In the Mediterranean climates of California and the Pacific Northwest, crop production during spring through fall is normally followed by winter fallow. Since most of the region’s moisture comes during winter months, summer production relies on irrigation, while soils often become waterlogged and/or heavily leached during winter. Without living plant cover, the soil surface seals and much rainwater and nutrients are lost to runoff. The combination of poor aeration and lack of actively growing roots restricts soil biological activity and diversity, and compromises nutrient cycling, SOM stabilization, and soil aggregation. Wet soil conditions promote microbial denitrification, converting nitrate into the greenhouse gas nitrous oxide.

In maritime regions such as the Salinas Valley, cool season vegetables are often double cropped with considerable N inputs in both conventional and organic systems.

Field studies of organic broccoli production in CA and OR show best economic returns at about 220 lb N/ac from organic sources, a rate that can lead to major N losses to leaching (up to 180 lb/ac) and denitrification (up to 23 /ac) during the following winter. Planting strawberry after broccoli harvest did not recover the N since this crop’s main N demand takes place during April – July, after the end of the rainy season.

Collins, D. P. and A. Bary. 2017. *Optimizing nitrogen management on organic and biologically intensive farms.* Proceedings of the Special Symposium on Organic Agriculture Soil Health Research at the Tri-Societies Annual Meeting, Tampa, FL, October 22-25, 2017. <http://articles.extension.org/pages/74555/live-broadcast:-organic-soil-health-research-special-session-at-the-tri-societies-conference>.

Li, C., Salas, W. and Muramoto, J. 2009. *Process Based Models for Optimizing N Management in California Crop­ping Systems: Application of DNDC Model for nutrient management for organic broccoli production*. Confer­ence proceedings 2009 California Soil and Plant Conference, 92-98. Feb. 2009. <http://ucanr.edu/sites/calasa/files/319.pdf>.

*Slide 33 – Cover crop versus fallow field after winter rains*

A winter cover crop makes a tremendous difference to soil health in central California.

Dr. Kabir says: “I took these photos, other side of the County Road 98 near woodland, CA after a heavy rain fall event (about 2” of RF) with the same soil. As you can see, two fields opposite side of the road. The important difference is cover crop vs fallow. Cover crop field all rain water infiltrated but the fallow field soil is sealed off due to rain fall impact and remaining on the field and running off from the field.”

The soil biota under the cover crop is building SOM from root exudates while the stressed soil biota under water is converting SOM into greenhouse gases.

*Slide 34 – Organic vegetables + cover crop*

Dr. Eric Brennan of USDA Agricultural Research Service in the Salinas Valley has conducted an eight-year trial (Salinas Organic Cropping Systems Experiment), on a Chulalar loamy sand, which is well drained but with high bulk density restricting root growth at and below 30 inches. Each year, the rotation consisted of a double crop of spring lettuce followed by fall broccoli. The system sustained high lettuce yields (1000 boxes/ac, about 30 lb/box) *only when a winter cover crop was grown after the preceding broccoli harvest.* After winter fallow, lettuce either yielded just a few hundred boxes per acre, or failed completely. Cover crops of rye alone, mustard, or rye with vetch, fava, and pea were similarly effective, indicating that N recovery, not N fixation was the main benefit. Broccoli was fertilized with about 145 lb N/ac (organic sources), only about 25% of which was removed in harvest. The balance of this N was lost during winter fallow, while the cover crops retrieved it and made it available to the lettuce.

In a heavily fertilized (>400 lb N/ac) conventional vegetable double crop system on the same soil in the Salinas Valley, winter rains leached some 230 lb nitrate-N/ac from a bare fallow soil profile. November-planted cover crops of cereal rye or phacelia attained a moderate 3,200 lb/ac biomass at termination (March 20), and reduced N leaching by 65 - 70%, partly through N uptake and partly by reducing net downward movement of water (Wyland et al., 1996).

Brennan, E. 2018. *Lessons from long-term, cover crop research in the Salad Bowl of the World* – 10 minute youtube video, <https://www.youtube.com/watch?v=JurC4pJ7Lb4>

Brennan and Acosta-Martinez, 2017, cited earlier.

Wyland, L. J., L. E. Jackson, W. E. Chaney, K. Klonksi, S. T. Koike, and B. Kimple. 1996. *Winter cover crops in a vegetable cropping system: impacts on nitrate leaching, soil water, crop yield, pests and management costs.* Agriculture, Ecosystems and Environment 59: 1-17.

*Slide 35 – Salinas Organic Cropping Systems*

The Salinas Organic Cropping Systems (SOCS) trial compared five organic management systems for a lettuce-broccoli double crop over a six year period:

* Winter rye + legume cover crop every fourth winter
* Yard waste compost at 6.8 tons/ac-yr + rye-legume cover every fourth winter
* Compost + rye-legume cover every winter (cover crop mean 3.4 t/ac)
* Compost + rye cover every winter (cover crop mean 3.2 t/ac-yr)
* Compost + mustard cover every winter (cover crop mean 2.3 t/ac-yr)

Both compost and cover crop played important roles in sustaining microbial activity through the growing season. Compared to pre-experiment levels (October 2003), microbial biomass carbon (measured surface to 2.7 in) in October of the sixth year (2009) declined 25% in the first system (no compost, winter fallow three years out of four), increased about 50% with compost, and doubled or tripled with compost + winter cover crop each year. Thus, although the cover crop contributed only 25 -33% of total organic inputs in the annual cover crop systems, its living cover and root mass yielded the greatest boost for soil life.

Total soil organic carbon (= 0.5 X SOM) increased from 0.8% in the no-compost system to 1.1% with compost and 1.2% with compost + annual cover crop. Cover crop frequency had the greatest impact on microbial community structure (species composition) and cover crop species had a secondary impact.

All five treatments double cropped organic vegetables, and represented an increase in tillage and organic fertility inputs, compared to previous management of this field. This apparently resulted in a shift of the soil microbiota away from fungi, especially AMF, and toward bacteria, with the fungi:bacteria ratio (F:B) declining from about 1.4 to 1.0.

Brennan and Acosta-Martinez, 2017, cited above.

*Slide 36 – Balancing C and N in organic inputs*

Researchers at Washington State University compared the crop and soil impacts of two nutrient sources in a long-term organic vegetable systems trial in Puyallup (coastal region): on-farm mixed compost made from dairy manure, bedding, and yard waste (higher C:N) at rates of 6 to 8 tons/ac-yr, and poultry litter (low C:N) at 1.8 – 2.6 tons/ac-yr. Total N inputs were the same in the two treatments.

After 11 years, plots receiving the higher C:N mixed compost had better soil structure and 43% more total SOM than plots receiving poultry litter. Notably, compost-amended soil showed substantial increases in both microbial respiration (PMC, indicator of mineralization) and permanganate oxidizable organic carbon (POX-C, indicator of stabilization), as well as higher levels of enzyme activities involved in nutrient cycling and a more diverse nematode community. Higher levels of soluble soil N, nitrifying bacteria, and bacterial feeding nematodes were seen with poultry litter, while the larger microbial community of compost amended soil enhanced N cycling, maintaining sufficient N to crops yet immobilizing excess soluble N.

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. 2015., *Use of Biological Indicators of Soil Health to Estimate Reactive Nitrogen Dynamics in Long Term Organic Vegetable and Pasture Systems.* Soil Science Society of America Meeting, Nov 15-18, 2015, Minneapolis, MN, Poster No. 1205.

*Slide 37 – The universal nitrogen challenge*

Crops rely on the pool of plant-available N (PAN, consisting of nitrate and ammonium N), which can be replenished with fertilizers or via N mineralization from SOM. PAN from any source is subject to leaching and denitrification, and the associated environmental risks increase with the size of the PAN pool. Soil life mediates soil fertility in organic systems, and it can contribute to excess soluble N in response to excessive or unbalanced organic fertility inputs.

*Slide 38 – Delivering N where it is needed*

Can the “gatekeeper” of soil life deliver soluble N *directly* to plant roots as needed without flooding the bulk soil with soluble N? In nitrogen fixing legumes, the *Rhizobium* symbiosis performs this function. Research findings indicate that, under optimum conditions, the rhizosphere microbiomes of non-legumes can similarly deliver just the right amount of N to the plant, in a process called “tightly coupled N cycling.” In addition to AMF which improve uptake of all nutrients, some endophytic or rhizosphere N-fixing bacteria partner with non-legumes; for example, some warm season grasses, including pearl millet and traditional land races of field corn, support N fixing bacteria in their root zones, through which they can meet 10 to 50% of their N requirement.

*Slide 39 – Tightly coupled N cycling*

Researchers at UC Davis studied 13 organically managed tomato fields in central California, recording inputs and management practices, soil inorganic N, active and total SOM, microbial activity, and levels of microbial and plant root enzymes. They found three distinct patterns:

* Two N deficient fields had low SOM (~1.6%) and microbial biomass, and low nitrate-N levels through the season. Yield was reduced by poor timing of N release from fall-applied manure, combined with the soil’s limited capacity to mineralize N.
* Seven N saturated fields had two-fold higher microbial biomass, higher SOM (~2.4%), and fairly high nitrate-N levels. Tomato yield were high, near the county average for conventional tomato.
* Four fields showed tight N cycling: they had total microbial activity similar to the N saturated fields but higher SOM (~3.6%), and sustained yields similar to the N saturated fields despite season-long nitrate-N levels below 5 ppm, well below the threshold for tomato response to N fertilizer (16 ppm), and similar to levels in the deficient fields.

In the tight N cycling fields, crops received light applications of in-row soluble N as fish emulsion or Chilean sodium nitrate, while the whole field was amended with a yard waste compost with a moderate C:N ratio (15-18:1) and a slow release of N. These soils showed high levels of microbial enzymes involved in N cycling, and one plant root enzyme involved in N cycling and uptake was also elevated.

N saturated fields generally received more total organic N input, and from lower C:N sources such as guano, poultry litter fertilizer, and all-legume cover crops. While overall biological activity was similar to the tightly coupled fields, soil microbial enzyme activity associated with C cycling (SOM breakdown) was higher, and N cycling enzyme activity was lower, than in the tightly coupled fields. This difference may reflect the C-limited status of microbes in soils given low C:N organic amendments, versus balanced or N-limited microbial metabolism in tightly coupled fields that received a higher C:N compost as their main fertility input.

UC Davis researcher Louise Jackson states in her 2013 report: “Since genetic pathways regulating N uptake are highly conserved across plant species, studies on these N metabolism genes in a model plant such as tomato are highly relevant to other crops.”

Bowles, T. M., A. D. Hollander, K. Steenwerth, and L. E. Jackson. 2015. *Tightly-Coupled Plant-Soil Nitrogen Cycling: Comparison of Organic Farms across an Agricultural Landscape*. PLOS ONE peer-reviewed research article. <http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0131888>. Numerous other articles available at <http://ucanr.edu/sites/Jackson_Lab/>.

Jackson, L. 2013. *Researcher and Farmer Innovation to Increase Nutrient Cycling on Organic Farms.* Proposal and final report for OREI project 2009-01415. CRIS Abstracts.

Jackson, L. and T. Bowles. 2013. *Researcher and Farmer Innovation to Increase Nitrogen Cycling on Organic Farms* (Webinar). <http://articles.extension.org/pages/67391/researcher-and-farmer-innovation-to-increase-nitrogen-cycling-on-organic-farms-webinar>.

*Slide 40 – Managing for tightly coupled N cycling*

The UC Davis research team attributed the tightly coupled N cycling partly to existing soil conditions (soil type and past history that promoted soil health), and partly to current season management practices. Mycorrhizal fungi also enhance nutrient cycling and, in legumes N fixation by the *Rhizobium* 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. [www.nofa.org/tnf/Summer2011B.pdf](http://www.nofa.org/tnf/Summer2011B.pdf).

Hamel, 2004, cited above.

Rillig, 2004, cited above.

*Slide 41 – Dryland challenges*

In dry regions, cash crops and cover crops in the rotation vie with one another- and with weeds – for limited moisture. As a result, it is more difficult to grow a cover crop to sufficient biomass to support a vigorous soil microbiome. If the cover crop does attain high biomass, it may also consume so much moisture that subsequent grain yields are severely water-limited. Terminating the cover crop by tillage can further compromise benefits, as semiarid regions soils are especially prone to degradation. No-till termination is often complicated by perennial weeds. Yet, not growing a cover crop cuts off the food supply for soil life; reduces SOM, fertility, and moisture-holding capacity; and increases risks of wind erosion.

The traditional two-year dryland rotation of cereal grain / fallow is used to save up two years’ worth of moisture for the grain, but the prolonged fallow depletes SOM even in no-till systems. Diversifying the rotation by adding pulse, oilseed, and/or cover crops during the fallow year improves soil health, but care is needed in selecting the crop, planting and harvest / termination dates to ensure sufficient moisture for the following grain crop.

Winter-planted field peas have offered significant benefits (N, weed suppression, long term soil health) with minimal moisture-related drawbacks. Trials on 20 farms in eastern Washington (9 – 13 inches annual moisture) showed that cover crops hurt yields mainly by leaving insufficient moisture in the top 3-4 inches for wheat seed to germinate and emerge. Selecting and managing cover crops to avoid this depletion eliminated the yield tradeoff and sometimes resulted in a yield benefit from the cover crop.

Menalled F., C. Jones, D. Buschena, and P. Miller. 2012. *From Conventional to Organic*

*Cropping: What to Expect During the Transition Years*. Montana State University Extension MontGuide MT200901AG Reviewed 3/12. <https://store.msuextension.org/>.

Michel, L. 2018. *Meeting the Challenges of Soil Health in Dryland Wheat*. NRCS webinar October 9, 2018. Science and Technology Training Library, <http://www.conservationwebinars.net/listArchivedWebinars>.

Lehnhoff, E., Z. Miller, P. Miller, S. Johnson, T. Scott, P. Hatfield, and F. D. Menalled. 2017. *Organic Agriculture and the Quest for the Holy Grail in Water-Limited Ecosystems: Managing Weeds and Reducing Tillage Intensity*. A review article in *Agriculture* 2017, 7, 33; doi:10.3390/agriculture7040033 [www.mdpi.com/journal/agriculture](http://www.mdpi.com/journal/agriculture).

Miller, P. R.; D. E. Buschena, C. A. Jones, B. D. Maxwell, R. E. Engel, F. Menalled, and B. J. Jacobsen. 2009. *Organic Production in the Challenging Environment of the Northern Great Plains: from Transition to Sustainability.* Final report for ORG project 2005-04477. CRIS Abstracts.\*

White, C., Barbercheck, M., DuPont, T., Finney, D., Hamilton, A., Hartman, D., Hautau, M., Hinds, J., Hunter, M., Kaye, J., La Chance, J. 2016. *Making the Most of Mixtures: Considerations for Winter Cover Crops in Temperate Climates*. eOrganic, <http://articles.extension.org/pages/72973/making-the-most-of-mixtures:-considerations-for-winter-cover-crops-in-temperate-climates>.

*Slide 42 – Diverse rotation without fallow at Vilicus Farms, Havre, MT*

Doug and Anna Crabtree of Vilicus Farms (<https://www.vilicusfarms.com/>) in Hill County, Montana (average annual moisture 11 inches), manage over 7,000 acres of organic dryland crops. They have developed a complex crop rotation including 15 production crops (grains, oilseeds, pulses) and 10 cover crops, using the blade plow to terminate covers without disturbing the soil profile, leaving residues on the surface. The combination of integrated organic practices, annual cropping (no fallow), diverse rotation, intercropping, high biomass cover crops, and blade plow cover crop termination has resulted in gradually increasing SOM, climbing from 2.1% to about 2.7% over a 10 year period.

Shown on the slide clockwise from lower left: the farmers Doug and Anna Crabtree, a khorazan wheat / flax intercrop (both grains harvested together), sunflower, rye, black lentil, perennial prairie conservation strip.

*Slide 43 – Restoring indigenous organisms in dryland soil*

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, gradually reduced fertilizer and other inputs, 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.

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

*Slide 44 – Managing disease with soil biology*

A number of commercial products have been developed, based on well-researched examples of microbial pathogen antagonists and inducers of systemic resistance, including but not limited to the six genera listed on the slide. When directed at a susceptible pathogen and used in conjunction with sound crop rotation and soil health practices, many of these materials can be quite effective.

*Coniothyrium minitans* is a fungus that parasitizes sclerotia (dormant propagules) of the white mold pathogen, *Sclerotinia sclerotiorum*, a serious disease of soybean, dry bean, and many vegetable crops. Disease suppression has been significant and *C. minitans* is now marketed as a commercial biofungicide.

Clubroot is a particularly severe and difficult-to-control disease of cabbage family vegetable crops. The pathogen, *Plasmodiophora brassicae*, can persist for many years in the soil, and grows in acidic (pH <6.5) and high-moisture conditions. An integrated strategy of long (7 yr) rotation, maintaining near-neutral soil pH, and practices to optimize drainage and structure (cover crops, compost, reduced till) has successfully kept clubroot below economic thresholds.

Colla et al., 2017, cited above.

Heinrich, A., and A. Stone. 2017. *Integrated Clubroot Management Strategies for Brassica Crops*. eOrganic webinar, <https://articles.extension.org/pages/74054/integrated-clubroot-management-strategies-for-brassica-crops>.

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>

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.

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 45 – Walnut orchard in CA after rain: cover crop breaks disease triangle*

Cover cropping has vastly improved soil drainage after heavy winter rains in a Solano, CA walnut orchard. Risks of root rots and other soilborne diseases are likely reduced.

Dr. Kabir says: “I took these photograph in the same day close to each other in same soil type. Only difference is the cover crops. Poor soil structure which is associated with poor soil health causes the water not to infiltrate.”

*Slide 46 – Organic practices reduce lettuce corky root in central CA*

Organic production systems reduce incidence of many but not all plant diseases. In a comparison of several pairs of organic versus conventional vegetable farms in central CA, lettuce crop losses to corky root (caused by the bacterial pathogen *Rhizorhapis suberifaciens*) were substantially less in the organic systems. Disease incidence declined as total soil microbial activity increased. In conventional lettuce production, soluble N fertilizer and the herbicide Pronamide reduced microbial competition and antibiosis against the corky root pathogen.

In a multi-year survey of plant disease incidence in two long-term diversified organic vegetable farms – Persephone Farm in the Willamette Valley of Oregon and Phil Foster Ranches in Hollister, CA – many regionally-prevalent vegetable pathogens were absent or remained below economic thresholds. However, *Fusarium* wilt in cucurbits, *Verticillium* wilt in watermelon, and *Fusarium* basal rot in onion family caused serious and increasing problems. Thus, these two genera of plant pathogens are high research priorities for biological disease management in organic systems. The researchers speculated that, while soils become suppressive toward some pathogens, such as *Pythium* (damping off) within a few years after conversion to organic management, the process may take decades for stubborn pathogens like *Fusarium* and *Verticillium*.

Ariena et al., 2015, cited above.

O’Brien, D., A. Stone, P. Foster, and J. Falen. 2016. *Trends in soilborne diseases on two long-term organic vegetable farms in the West.* Presentation at Organic Agriculture Research Symposium, 2016.

*Slide 47 – Mustard seed meal vs orchard replant disease*

The term “biofumigation” has been used to describe the disease control efficacy of crucifer cover crops and crucifer crop residues, because the isothiocyanates released during their decay were thought to produce a soil fumigant approaching conventional fumigants in efficacy but not in risks to human health and environment. However, research by Dr. Mark Mazzola and others with USDA ARS has shown this term is a misnomer.

The orchard replant disease complex, caused by pathogenic fungi (*Rhizoctonia, Cylindrocarpon*), oomycetes (*Pythium*, *Phytophthora*), and the lesion nematode (*Pratylenchus penetrans*) imposes severe constraints on organic fruit production and renovation in the Pacific Northwest. Amending soil with mustard seed meals (residues left by oil extraction) at 3 tons/ac the autumn before tree planting suppressed the pathogen complex and improved tree survival and growth at least as effectively as conventional fumigation. Release of fungicidal isothiocyanates played a minor and short-lived role in disease suppression, as the allelochemicals dissipated within a few days after treatment, while suppression of *Pythium* and *Pratylenchus* lasted for several years after a single application (greatly facilitating orchard replanting), while in the conventional treatment (Telone C17 fumingant, active ingredients 1,3 dichloropropene and chloropicrin), pathogen numbers returned to pre-treatment levels by the second season after application. Tree growth and fruit yields during three years after treatment were generally: seed meal > Telone C17 > untreated control.

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

Growing certain cultivars of wheat, especially ‘Lewjain,’ in orchard soil prior to planting apple stock greatly reduced *Rhizoctonia* damage to apple roots by enhancing the growth of disease-suppressive strains of fluorescent *Pseudomonas* bacteria. In greenhouse trials, sterilization of soil after growing ‘Lewjain’ wheat or adding mustard seed meal eliminated the disease-suppressive effects, thus confirming a biological mechanism of disease suppression.

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 et al., 2015, cited earlier.

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.

Weerakoon, D. M. N., C. L.Reardon, T. C. Paulitz, A. D.Izzoa, and M.Mazzola. 2012. *Long-term suppression of Pythium abappressorium induced by Brassica juncea seed meal amendment is biologically mediated.* Soil Biology and Biochemistry 51: 44-52.

*Slide 48 – Anaerobic soil disinfestation.*

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.

Studies have shown that a major factor in the success of ASD is a lasting change in the soil microbiome that favors development of disease-suppressive bacteria, actinomycetes, and fungi. If finished compost is used in lieu of readily-decomposable organic residues, little change in soil microbiome and much less effective disease suppression results.

Mazzola, 2017, cited above.

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 49 – Biosolarization*

Biosolarization is another variant on these approaches, especially suited for hot, sunny climates such as the Imperial Valley of California and much of the southwestern US. In this technique, a high biomass, allelopathic cover crop like sorghum sudangrass is grown to high biomass and then tilled in; (or a readily decomposable organic residue such as rice hulls is incorporated), then the soil is watered to field capacity and covered with clear plastic for 4 – 6 weeks during hot, sunny conditions.

*Slide 50 – OFRF Soil Health 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 Organic Resource Area of the Extension can help producers develop, maintain, and protect a healthy, multi-functional soil food web for their farms. Guides are available at <http://ofrf.org>.

\* 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>.

Note that many of the final reports on the CRIS database include lists of publications in refereed journals that provide research findings in greater detail.