An Integrated Soil Health Framework for California

Soil Health Symposium Summary and Research Recommendations

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To identify new research directions and management practices that promote soil health, the California Department of Pesticide Regulation, in cooperation with the United States Department of Agriculture Natural Resources Conservation Service (NRCS), California Environmental Protection Agency, California Department of Food and Agriculture and the University of California Davis, sponsored a Soil Health Symposium on June 17, 2014, which included speakers, a panel discussion and participatory exercises. The symposium resulted from one of the recommendations made in the Nonfumigant Strawberry Production Working Group Action Plan, which examined strategies for development of strawberry pest management options that will reduce the need for fumigants. Over 100 representatives from some of California's most innovative farms, non-profit agencies, soil life scientists, biopesticide firms, and other interested stakeholders participated in the symposium. This document summarizes current knowledge of soil health, as well as topics discussed in the symposium and presents recommendations for research priorities to accelerate progress towards reduced reliance on soil fumigants in California.

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October 2014

Executive Summary

As the use of soil fumigants becomes more restrictive, the question of how to sustainably manage agroecosystems to increase soil health has become more important. The NRCS defines soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." Thus, the concept of soil health emphasizes soil organisms, whose biodiversity provides important ecosystem services like disease suppression, resilience to environmental stress and increased nutrient retention. However, scientific understanding of how these processes can be enhanced by manipulating soil biodiversity is still in its early stages.

As a leader in agricultural innovation and environmental stewardship, California is rapidly developing management practices that increase soil health. Well focused policy and research funding that increases scientific knowledge of soil health and soil biology can lead to the development of integrated pest management solutions that use less fumigants. At the soil health symposium, researchers, regulators, growers and industry representatives shared their insights and the latest scientific research on soil health and the best ways to move forward. This document summarizes current scientific understanding of soil health and makes recommendations for future research funding. To that end, nine research priorities are detailed in Table 1 with examples of efforts either currently underway or possible for the future.

Management strategies can shape soil communities either by introducing beneficial microorganisms or by stimulating native soil organisms. Such soil management actions may include reducing tillage, increasing plant diversity (for example through cover cropping or intercropping multiple crops together), amending soil with organic materials, and applying techniques such as steam, soil solarization and anaerobic soil disinfestation. On a longer time scale, crop plants could be bred to enhance beneficial interactions with soil organisms. Effective pest control will most likely be achieved through integrated strategies combining multiple approaches. Key focus areas include the need for programs that address the social and economic barriers that prevent the implementation of soil health strategies as well as diagnostic tools that asses soil pests and diseases.

Integrative soil health tests that combine biological, physical and chemical components will help government agencies formulate and evaluate sustainable land use policies and help growers evaluate the effects of soil management. Already existing soil health metrics could be adjusted and validated for use in California. Accompanied by relevant management recommend-ations, facilitating the availability of cost effective soil health testing could rapidly increase awareness and advancement of our ability to manage for soil health.

Problem Statement

For decades, California agriculture has relied heavily on fumigants for soil pest control. However, as uses of soil fumigants such as methyl bromide are eliminated and increasing buffer zones and other requirements are added for other fumigants, growers are searching for non-fumigant pest control alternatives. Unfortunately, many are frustrated to learn that research utilizing soil biology to suppress pests has not generally kept pace with fumigant research. Instead of relying on short term remedies, thoughtful investment in creating agricultural systems that sustainably manage soil may reduce pathogens and also fumigant needs. Advancing knowledge of soil health, which acknowledges the complex interactions of soil biota, offers promise to work towards this vision, reducing the risks associated with pesticide use while maintaining or increasing yields.

Background

Pre-fumigant pest control technologies relied heavily on resistant plants and cultural modifications, such as crop rotation, tillage, and hand weeding. While these were helpful in preventing pest outbreaks, increased use of soil fumigants since the 1950s provided more rapid, effective and inexpensive pest control, enabling California crop production to thrive economically and increase in scale. Methyl bromide was particularly useful in that a single treatment before planting could effectively control many types of soil borne pests, diseases, and weeds and thus increase both crop yields and quality. In the past several decades though, multiple fumigants have been withdrawn from the market amid concerns for human safety and water quality (for example, ethylene dibromide and dibromochloropropane), while those that remain are increasingly subject to regulations and other restrictions.

In 1999, a phase-out of methyl bromide began under the Montreal Protocol, an international treaty that limits the production of substances that deplete stratospheric ozone, commonly referred to as the ozone layer. While this treaty has allowed for quarantine/preshipment and critical use exemptions in many crops that do not have effective or affordable fumigant replacements, these exemptions decrease each year and will phase out entirely.

As the environmental effects of fumigants became known, agricultural researchers and industry began searching for fumigant alternatives. Initially, research focused on fumigants that do not deplete the ozone layer yet could effectively manage pests. These methyl bromide alternatives were still hazardous to human health, though, and drew criticism from environmental and farm worker groups. In the current regulatory and political climate of California, research, development, and production costs for new fumigants have become less likely to be recovered in profits. For example, methyl iodide, one of the most recently registered fumigants, was voluntarily withdrawn from the market by the manufacturer in 2012. Research on fumigant alternatives to methyl bromide continues, but no single chemical is emerging that provides similar broad spectrum control.

More recently, the dialog in California has shifted to moving beyond fumigants altogether. Unfortunately while research focused on developing new fumigants, little progress was made on how soil biology or modifications to farming practices could reduce pest pressure. In the current effort to identify non-fumigant control options, researchers are taking fresh looks at "old" technologies and designing new techniques. But, in reality, no single method is likely to control soil borne diseases and other pests as effectively as fumigants. The development of new integrated approaches emphasizing soil health offers the possibility of long-term sustainable pest control.

Within California and across the U.S., public interest in soil health is growing. The challenges of managing farm ecosystems for soil health have many parallels with human disease treatment. In both cases, treatments have traditionally focused on disease symptoms rather than ways to improve disease resistance. The use of fumigants could also be likened to the use of antibiotics, since both are non-specific and destroy microbes regardless of whether they are pathogenic or not. Like the communities of microorganisms which support human digestion (the gut microbiome), the soil around plants is surrounded by specific microbial communities (the root microbiome) which may either provide different limiting resources to plants, or act in concert to suppress disease. The discussion of how to manage for soil health comes as California agriculture faces challenges including drought, climate change, and soil degradation.

Decisive action and well-focused funding can take advantage of the surge of enthusiasm surrounding soil health to invest in creative new strategies for pest management based on soil ecology.

Overview of Current Knowledge of Soil Health

Soil health is determined by interactions between microbial communities, soil physical and chemical factors, and management decisions. This complexity differentiates it from air and water quality standards, which usually focus on maximum allowable concentrations of specific hazardous materials, and relate only to public health risk. The use of the term *soil health* began in the mid-1990s and gradually became distinct from *soil quality*, which historically described agricultural productivity or fertility (Singer et al. 2000). While soil quality focuses on soil's quantitative physical and chemical characteristics (Doran et al. 1996), soil health emphasizes the dynamic, living nature of soil (Van Bruggen and Semenov 2000), encompassing biological attributes such as biodiversity, food web structure and ecosystem functioning (Pankhurst et al. 1997). Since these attributes can be both categorically and numerically measured, and change over time, difficulties in defining soil health often arise (Karlan 2012). The NRCS concisely defines soil health as the "continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (NRCS-website).

Healthy ecosystems that function well involve the interaction of multiple soil organisms ranging in size from microscopic bacteria and fungi to comparatively large predatory nematodes (Figure 1). Biodiversity in soil communities may act as insurance, maintaining plant health through extreme environmental conditions such as drought (Wagg et al. 2011, Jorquera et al. 2012). Overall high microbial diversity is sometimes directly associated with root disease suppression (Nitta 1991; Workneh and van Bruggen, 1994) and increased nutrient and water use efficiencies (Wagg et al. 2014). However, terms such as high and low in this case are relative, since the minimum amount of biodiversity necessary to maintain plant health is often unknown. Often it is not the raw number of species that is important, but rather the functions certain species perform. Unfortunately, many groups of bacteria and fungi do not grow well in the laboratory and so we only know their identity via DNA sequencing, and nothing about their function. Although recent technological advances (such as lower costs of high throughput molecular sequencing) show promise, scientific understanding of how microbial diversity influences ecosystem functioning in agro ecosystems is still in its early stages (van der Heijden and Wagg 2013, Brussaard et al. 2007).

Pest suppression

While an integrated pest management framework has successfully managed aboveground pests by providing economic threshold values for action, adapting this approach to the soil has proven difficult since soil organisms are more complicated to quantify and vary widely with local conditions. The ecological principles of natural pest control in the soil are also less understood than in aboveground systems.

Research on naturally pest-suppressive soils can show which groups optimize disease control and what population levels are necessary to achieve protection. In suppressive soils, disease severity remains low, despite the presence of the pathogen, susceptible host plants, and conducive environmental conditions (Cook 1983). Suppressive soils have been discovered for many fungal, bacterial and nematode pests, but almost all soils possess some capability to suppress disease (Mazzola 2004). The suppressiveness of a soil can be categorized as either general or specific. General suppression relates to the amount of overall microbial activity residing in the soil and is generally thought to be due to competitive exclusion or trophic interactions. A potential pathogen is either starved of resources or rapidly consumed by other organisms, but no single group of organisms is likely responsible. In contrast, specific suppression acts against a specific pest and operates through biological mechanisms (Mazzola 2004).

Diagnostics

The practicalities of measuring soil health, with its emphasis on ecosystem functioning driven by soil organisms, presents several challenges, primary among them is what, exactly, should be measured. In comparison to traditional agricultural tests (for example a nitrogen-phosphorous-potassium panel), which offer static numbers and clear recommendations, the complexity and unit-less nature of a soil health score can appear vague. Nevertheless, integrative soil health tests are increasingly used (Idowu et al. 2009) and desperately needed to help government agencies formulate and evaluate sustainable land use-policies, as well as to allow growers to self-evaluate the outcomes of management decisions. Any measurement of soil health or soil quality will include two components, one which is inherent, and set by the physical and chemical properties which are constrained by the environment and another which can be affected by management decisions (Doran and Zeiss 2000). Soil health indices

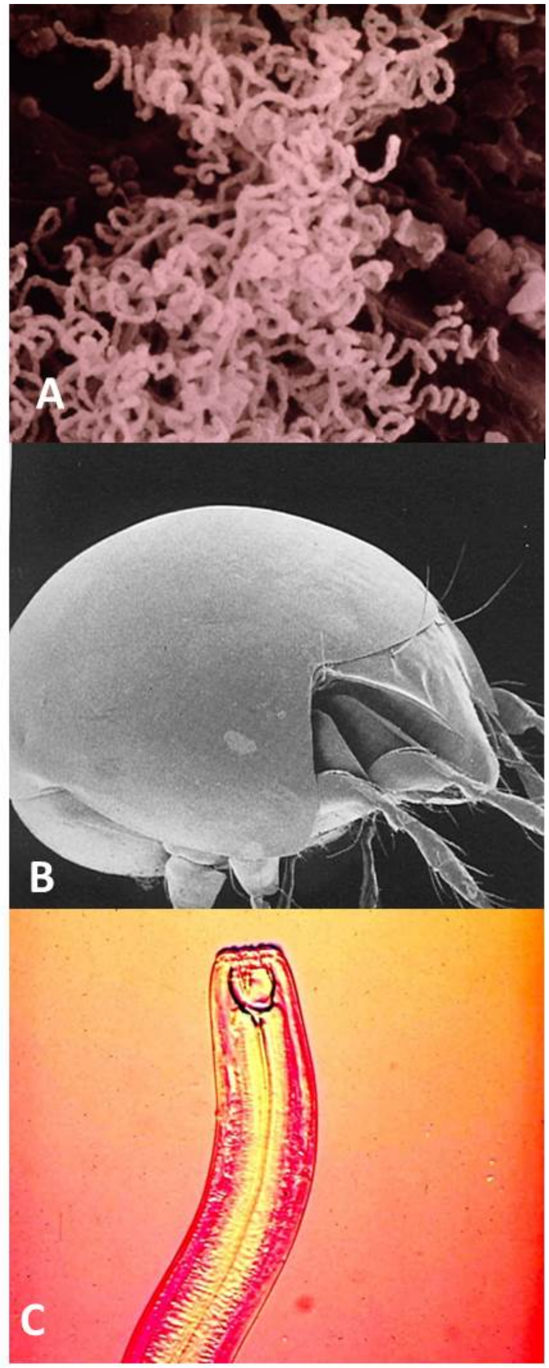

Figure 1. Examples of organisms that enhance soil health: A) Actinomycete bacteria which decompose organic matter into compost (0.0005 mm), B) Turtle mites (Orobatidae) which shred plant material into pieces, facilitating decomposition (0.05 mm), and C) Predatory nematodes (Monochidae) which regulate populations of pest nematodes (3 mm). (Images A and B courtesy of NRCS Soil Biology Primer and C courtesy of Society of Nematologists via Nemaplex).

and the resulting management recommendations will also be highly dependent on local soil conditions and cropping systems, making it necessary to have both a standardized approach and one that, at the same time, can be adapted locally.

In order to develop a measurement of soil health, a process of evaluation, or framework, can be followed (Kinyangi 2007). The first step in evaluating a soil health assessment is to select indicators for measurement. These indicators should meet several criteria in order to be useful (as outlined by Doran and Zeiss 2000). First, useful indicators will be sensitive to variations in management. They will also be well correlated with beneficial soil functions such as water storage, decomposition, nutrient transfer and pest suppression, which are often costly and difficult to measure directly. Indicators should also help explain why a soil is not functioning correctly, and what remedial action is required. They will be comprehensible and useful to land managers and, finally, easy and inexpensive to measure. After indicators are selected, a minimum data set should be collected, to assure that indicators are locally relevant and relate well to plant health (Arshad and Martin 2002). Based on this, an interpretation scheme and indices can be developed to provide understandable information upon which management decisions can be based. Lastly, the soil health assessments should be tested and validated on farms to evaluate the effects of management decisions (Andrews and Carroll 2001). Since the interaction between chemical, physical and biological components maintains soil health, a thorough evaluation of soil health would examine indicators from all these components. However the soil health tests currently available mostly focus on chemical and physical indicators, since these are generally straightforward to measure and interpret. Physical characteristics influence water and nutrient retention and include bulk density and water infiltration rate. Chemical indicators can provide information on plant available nutrients, and the amount of nitrates used in a system. These also include measurements of electrical conductivity, pH, and cation exchange capacity.

Biological indicators integrate chemical and physical measurements, and are more sensitive to management changes (Ritz et al. 2009), but are also more complicated to measure and interpret. For example, the living portion of organic matter, microbial biomass, is not often used in soil health tests because it lacks benchmark values and is cumbersome and time consuming (Dalal 1998). Instead, soil respiration is often used as an indicator of microbial activity and measured as the amount of carbon dioxide produced under laboratory conditions. Since soil microorganisms and fauna intimately relate to soil physical properties and immediately affect ecosystem processing, their presence, abundance, diversity, and food web structure has often been proposed as bioindicators of soil health (Nielsen and Winding 2002). Individual species may be used as indicators associated with healthy or unhealthy soil, for example keystone species, such as *Rhizobium*, which fix nitrogen for plants and are sensitive to agrochemicals (Visser and Parkinson 1992). Community composition of earthworms, collembola and predatory mites has also been measured (Pankhurst et al. 1997). Nematodes have been proposed as particularly good indicators of soil health (Kapp et al. 2013), since they are found in almost all soil, indicate functions performed by other organisms, and respond rapidly to changes in management. Clearly established nematode metrics exist that indicate ecosystem functions such as pest suppression and nutrient cycling (Ferris 2010). Drawbacks of biological indicators include the need for taxonomic knowledge of soil organisms, but at least for nematodes, this can be somewhat overcome by only identifying individuals to feeding group. As the concept of soil health becomes more holistic and common in the United States, direct measurements of soil microorganism communities will likely gain more popularity, as they have in Europe. For example, candidate biological indicators selected for national monitoring in Britain included soil respiration, enzyme profiles, and nematodes (Ritz et al. 2009). Successful soil health diagnostics for the future that include biological measurements will merge consistent results with cost effectiveness and ease of use.

Publically available soil health tests in the United States provide indices based on different suites of indicators. The Haney Soil Health Test, available through the USDA-ARS in Temple, TX, gives a soil health score in addition to measuring plant available nutrients. As an indicator of the food available to microbes, water extractable organic carbon and nitrogen are measured and soil respiration is used as an indicator of microbial activity. The score is calculated based on microbial activity, the food available to microbes, and the ratio of carbon and nitrogen in the sample. Recommendations provided to users include guidelines on cover crops and fertilizer use to achieve desired yield goals. NRCS also offers a free online soil quality test guide, which includes step by step instructions on how to build your own kit and measure many physical soil properties of soil health as well as soil respiration (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/health/assessment/?cid=nrcs142p2_053873).

The Cornell Soil Health Assessment, offered through the Cornell University Nutrient Analysis lab, provides indicators of many soil processes including disease pressure, biological activity and nutrient storage and release (http://soilhealth.cals.cornell.edu). Among the new biological measurements offered in the past year are soil respiration and soil proteins, which measure food available to microbes. Reports are provided on each indicator's significance, constraints to soil health, and management suggestions in the form of a Soil Health Management

Plan. The Cornell soil health test is also one of the only publically available tests to quantify the supressiveness of a soil to disease directly, providing a measurement of root pathogen pressure by screening green bean roots after four weeks growth in the soil sample for fungal pathogens such as *Fusarium*, *Pythium*, and *Rhizoctonia*. While the overall cost of the test package ($85) may be prohibitive for growers, individual analyses can be purchased for $12. For all of these tests, adjusting the soil health scores and management recommendations to local crops, soils and management practices, as well as on farm validation, will improve their relevance and accuracy for use in California.

Management

Microbial communities can be shaped by management strategies to favor plant health and reduce plant pathogens. Strategies to shape soil communities follow two approaches. The first is to introduce or inoculate with beneficial microorganisms. The second is to stimulate native soil organisms through soil management or cultivar selection. The main ways to shape soil microbial communities through management include manipulating tillage, crop rotation and organic matter inputs (Van Caprelle et al. 2012, Altieri 1999). While soil biodiversity in agroecosystems clearly responds to such changes in management, our understanding of how this biodiversity influences plant health is still in early stages. Those studies examining such mechanisms are often performed using simplified microbial communities under highly controlled conditions. These consistently suggest that increased microbial diversity provides important ecosystem services such as disease suppression, resilience to environmental stress and increased nutrient retention (Brussaard et al. 2007, van der Heijden et al. 2008, Berendsen et al. 2012, Wagg et al. 2014). The effects of individual strategies on microbial communities are outlined below. It is important to note, though, that successful strategies will likely combine multiple management tactics.

Soil Solarization, Steam and Anaerobic Soil Disinfestation

Soil solarization, steam and anaerobic soil disinfestation (ASD) have traditionally been thought to sterilize the soil by creating conditions inhospitable for microbes, making these strategies more like fumigation in many ways. For example, ASD deprives microbes of oxygen and generates toxic chemical compounds while soil solarization and steam elevate temperatures above those tolerated by many microbes. Recent research indicates, though, that at least for soil solarization and ASD, control may also be mediated through the microbial community (Mazzola et al. 2012, Simmons et al. 2014). For example, soil solarization alters bacterial communities (Simmons et al. 2014) while ASD enhances overall microbial activity as well as the abundance of specific fungal species (Shennan et al. 2013). In both cases, current research is examining how organic matter amendments can be combined with these techniques to achieve greater pest control (Hewavitharana et al. 2014, Shennan et al. 2013, Simmons et al. 2013).

Plant diversity

Crop rotation has traditionally been used to improve soil structure and starve out pests and diseases by depriving them of the main host plant. However, increasing plant diversity through cover crops, crop rotations, or intercropping can stimulate soil biodiversity by providing a variety of different food resources for beneficial microbes. Continuous soil cover with living plants also provides food for soil communities during time periods when the crop is not active. Additionally, plant diversity can be maintained by planting less used areas of the farm with native vegetation and preserving adjoining riparian zones. Recent research is examining manipulating cover crops to promote and maintain beneficial microbial communities (East 2013). To optimize management of plant diversity for soil health we need to know much more, though, about which planting mixtures and sequences select for beneficial microbial communities.

Tillage

Growers till soil to prepare seedbeds, kill weeds and reduce diseases. In addition to negative consequences such as destroying soil structure and reducing water infiltration, tillage disturbs soil microbial communities, either by killing them directly or by changing their habitat (Cavigelli et al. 2012). Larger organisms, which are often predators, are more likely to be affected (Wardle 1995). Tillage also favors bacteria and decreases fungi, which are important for maintaining soil structure, sequestering carbon and providing plant nutrients. While reduced-till systems favor increased soil biodiversity and the presence of more soil predators, weeds are often a problem. Mechanisms to reduce weeds, such as herbicide application, cause their own negative environmental effects. After no-till is established for several years however, herbicide costs may decrease as the system stabilizes, eventually becoming similar to that used in conventionally tilled systems (Pollock 2011). Research on the effects of no-till agriculture in cotton and tomato at the UC West Side Research and Extension Center has found that 15 years after sustained management of no till the soil stores up to 74% more carbon and 59% more soil nitrogen (http://casi.ucanr.edu/?blogpost=12608&blogasset=14128).

Organic amendments

Organic amendments include inputs ranging from biochar, or charcoal produced from plant matter, to animal manure and compost to biosolids obtained from treated wastewater. While organic amendments possess widely different characteristics, they generally enhance soil microbial biomass and activity by providing carbon in forms which are easy for microbes to digest (Janvier et al. 2007, Cavigelli et al. 2012). In some cases, organic amendments such as manure, compost, and cover crops can suppress plant diseases such as *Pythium*, *Phytophtora* and *Ralstonia solanacearum* (Garbeva et al. 2004). Amendments likely suppress pests by altering microbial communities, and enhancing overall microbial activity, but the mechanism of how this occurs remains unknown and results vary with both the amendment's formulation and the microbial community in question. The effects of organic amendments can be optimized through research examining their effects singly and in mixtures across different crops and soil types. Useful research will also characterize and monitor soil microbial communities associated with disease suppression after the application of amendments (Mazzola 2004).

Inoculation

Transferring microbes from one plant species to another can confer beneficial traits such as resistance to pests (Flor-Peregrin et al. 2014) and environmental stress (Coleman-Derr and Tringe 2014). The strategy of inoculating with beneficial microbes faces numerous hurdles including being able to achieve consistent results across plant species and soil types as well as difficulties in storage, registration and regulation (Mendes et al. 2013). Another problem is that many microbes cannot survive when introduced into a new environment and so are unable to control pathogens effectively (Mazzola 2004). These constraints can be somewhat mitigated by advancing knowledge of how plants and microbes communicate and how key beneficial organisms influence plant health and/or repel pathogens. Inoculating crops with an assemblage of complementary microorganisms will probably control diseases more effectively than inoculations with a single group. Demand is pushing researchers to develop methods of manipulating these compatible rhizosphere communities, or consortia. Consortia of microorganisms may also help restore diversity to depauperate communities, leaving fewer available resources for pathogens to become established (Bakker et al. 2012).

Breeding

Since root exudates can both attract disease agents and recruit disease-suppressive microbes, managing for soil health could include breeding crop plants for changes in root exudate chemistry. Breeding plants to work in concert with soil microbes could increase sustainability since such plants would require less nutrients (since microbes enable more efficient use of resources) and less pesticides. The question of how plants and microbes communicate chemically and what plant exudates are important in shaping the community has been examined for model plant species in the laboratory (Badri et al. 2009) but research remains sparse for agricultural crops. Recent advances in metabolomics (the study of plant metabolites such as sugars and fats), however, could assist in selecting plants that secrete chemical components that stimulate beneficial microbes.

While we know that existing crop cultivars differ in their associated microbial communities (Smith et al. 1999), breeding programs have rarely, if ever, taken an active approach to manipulate them. On the contrary, modern crop breeding may have inadvertently selected against traits that fed beneficial microbes and encouraged their establishment. The theory of plant-microbiome co-adaptation holds that crop plants grown close to areas where they were originally domesticated (the center of origin) had the opportunity to form close associations with microorganisms over long time periods. As these crop plants were brought into new locations, though, they encountered microbial communities to which they were not adapted. Signals which may have triggered a beneficial response in the native community would then go 'unheard' by microbes in the new cropping system (Bakker 2012). Such a mismatch between the root microbial community and the plant could create an opportunity for pathogen infection. Since pathogens compete with other microbes for food and physical space on the root, a tight association with beneficial microbes may leave little room for pathogens to establish (Bakker et al. 2012).

Future directions

In California, management practices for soil health are rapidly evolving. As a world leader in food production and innovative farming techniques, California's policy and research have far reaching influence. At the soil health symposium, researchers, regulators, growers and industry representatives shared the latest research and offered their insights, with the common goal of fostering California agroecosystems that are both profitable and sustainable. Soil health provides a framework to work together towards this vision, since effectively managing microbial communities will result in healthier plants that need fewer inputs of pesticides and fertilizer. Investment in future research to work in concert with soil organisms, rather than against them, will illuminate what management strategies best select for desirable microbial communities as well as how to optimize the functions they perform.

Research priorities gathered from the symposium, the scientific literature (Bakker et al. 2012) and the previous Nonfumigant Strawberry Working Group Action Plan (Gorder et al. 2013) are summarized in Table 1. Many were highlighted during an interactive exercise at the symposium in which participants allocated funding to those projects they found most promising to manage pests. One recurring theme that emerged from this exercise included the need for diagnostic tools that detect beneficial organisms and pathogens, as well as recommendations for management based on these diagnostics and other soil health indices. The current soil health tests available, though, do not measure organisms directly, and management recommendations require modification for local cropping systems. While some private industries do offer soil biology testing (such as Earthfort in Corvallis, OR), offering such tests through the university with supported experimental evidence could increase grower adoption of management practices that favor soil health. Universities such as UC Davis are particularly well positioned to offer soil health and soil biology testing, including microbial community and pest diagnostics. Rapid progress in soil health pest management could also come through fostering public private collaborations between growers, university researchers and industry to test new management practices, amendments or biological products. Increased availability of soil health testing will also enable growers to accurately monitor the extent of pest problems and the effects of management strategies, so that fumigants are only used when they are needed.

Another recurring theme was the social and economic barriers preventing the implementation of new management strategies. During the symposium it was brought up that growers often feel caught between economic constraints and regulation, and that many fumigant decisions are based largely on risk management. Additionally, growers may keep silent about pest problems due to concern about discrimination from packers and shippers. Presenting a viable way forward could change management practices quickly, for example through large on farm demonstration plots that incorporate outreach and education. Facilitating dialog and social engagement between growers, researchers and regulators will also enable successful pest management technologies to spread.

Managing for soil health will require more than just technological knowledge. Meaningful changes will combine multiple strategies and also adapt management practices to the specific needs of stakeholders. The multiple economic, environmental and social goals of interested parties must also be incorporated at the beginning when cropping systems are first designed (Chellemi 2009). This will require support at multiple cooperating levels including government agencies, research institutions, and commodity groups.

Table 1. Research Priorities (in no particular order)

1. **Develop diagnostic tools to monitor soil health for California soils and crops.**
   Example: Test existing soil health metrics and establish standardized testing centers through UCCE.

2. **Establish accurate economic thresholds for soil pests and pathogens**, since existing monitoring strategies for aboveground pests are not relevant to soils.
   Example: Establish public-private partnerships that test and commercialize affordable assays for diseases and nematodes.

3. **Develop a molecular database of microbial communities for specific crops**, including information on disease presence and management styles.
   Example: Expand on molecular databases for fumigated and unfumigated soil in multiple crops.

4. **Identify components of crop plant root exudates that shape microbial communities.**
   Example: Compare root metabolites, such as sugars and fats, with the microbes present.

5. **Identify microbes that influence plant health and evaluate their effects.**
   Example: Screen microbes for potential use in field trials or identify groups of compatible beneficial microbes.

6. **Develop integrated soil health management strategies that enhance populations of beneficial microbes.**
   Example: Use field trials to evaluate the effects of biologically integrated farming practices such as cover cropping, reduced tillage and organic matter inputs; showcase the most promising results through larger scale on-farm demonstrations.

7. **Prioritize beneficial interactions with microbes in crop breeding programs.**
   Example: Examine differences in root microbial communities across crop cultivars.

8. **Develop management decision making tools to choose practices that best support soil health for a given crop.**
   Example: Incorporate research results with existing soil, climate, and other data to develop belowground integrated pest management strategies.

9. **Facilitate dialog and social engagement between growers, researchers and regulating agencies.**
   Example: Develop online grower research networks to create safe spaces where growers can discuss their experiences of innovative practices.

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