Soil Health Paradigms and Implications for Disease Management*

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Abstract

Soil health has been defined as the capacity of soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health. Building and maintaining soil health are essential to agricultural sustainability and ecosystem function. Management practices that promote soil health, including the use of crop rotations, cover crops and green manures, organic amendments, and conservation tillage, also have generally positive effects on the management of soilborne diseases through a number of potential mechanisms, including increasing soil microbial biomass, activity, and diversity, resulting in greater biological suppression of pathogens and diseases. However, there also may be particular disease issues associated with some soil health management practices. In this review, research and progress made over the past twenty years regarding soil health, sustainability, and soil health management practices, with an emphasis on their implications for and effects on plant disease and disease management strategies, are summarized.

INTRODUCTION

Soil is a vital part of the natural environment. It is a dynamic living resource essential to the production of food and fiber as well as to global balance and ecosystem function, and as such, soil health is of concern to us all. The health of soils determines agricultural sustainability and environmental quality, and, as a result, greatly affects plant, animal, and human health as well (36). It has now been more than twenty years since the start of a major push by the soil science, agronomy, and sustainable agriculture communities toward increasing awareness and understanding of the importance of soil quality and soil health for a sustainable future. In the early to mid-1990s, numerous conferences, reports, and documents were published that focused on defining, assessing, and monitoring soil quality and soil health, emphasizing that soil was critically important not only for the production of food and fiber but also in ecosystem function and maintenance of local, regional, and global environmental quality (34, 36, 68, 112). Key to these concepts was the need to consider the multiple functions of soil and to fully integrate the physical, chemical, and biological attributes that define soil function (36). For agricultural systems in particular, reversal of years of degradation of soil productive capacity was needed, and assessment, monitoring, and management of soil health were crucial. This required moving away from the almost exclusive focus on a single soil function, crop production, and embracing the importance of all of the many functions of soil. Correspondingly, this entailed a shift away from an emphasis on chemical fertility and plant nutrition, which had been the norm in agricultural systems for the past several decades, to a greater adoption of indicators and analyses that included biological as well as physical and chemical attributes that would provide a more complete picture of soil health and function. Subsequently, additional emphasis has been placed on the development and implementation of soil management practices that promote soil health and sustainability. Inherent in the concept of soil health is that plant pathogens and diseases (especially soilborne diseases) remain low in healthy soils (61, 95, 96). Thus, management practices that promote soil health should also intuitively promote lower pathogen and disease levels. But is that always the case? And how effective are practices associated with soil health in managing or reducing plant diseases? In this review, I summarize the research and progress made over the past twenty years regarding soil health, sustainability, and soil management practices, with an emphasis on their implications for and effects on plant disease and disease management strategies.

SOIL HEALTH

Definition and Characteristics

Soil health has been defined in various ways over the years but can generally be summed up as the continued capacity of soil to function as a vital living system to sustain biological productivity, maintain environmental quality, and promote plant, animal, and human health (36, 37). This definition evolved from the soil quality concepts and discussions of the 1990s (34, 36, 68). Although these concepts had been around for a long time, renewed interest in the development and implementation of the importance of soil health for a sustainable future was begun in earnest during this decade. After decades of focusing primarily on fertility aspects of soil as a physical medium for plant growth, degradation of agricultural soils was acknowledged as a major constraint to continued productivity and sustainability (34, 36).

Although the terms soil quality and soil health are often used interchangeably, and certainly developed from the same overall concepts, there are differences between the two. Overall, soil quality refers to a particular soil's fitness for a specific use, whereas soil health generally refers to broader aspects and multiple soil functions and draws particular emphasis on soil as an integrated, dynamic, living system (35, 36, 71). Corresponding with that emphasis is more of a focus on soil biology. The biological components of soil, including bacteria, actinomycetes, fungi, algae, protozoa, nematodes, mites, insects, earthworms, and larger soil-dwelling animals, as well as plant roots and underground plant parts, all interact in what is collectively referred to as the soil-food web, and are all critical components to soil health. They affect soil structure, erosion, and water availability, are crucial to decomposition, nutrient cycling, breakdown of toxins, and suppression of pests, and are responsible for a large proportion of the world's genetic diversity (105, 111). The biological component of soils and its importance to soil health have been neglected in the past, partly because they were difficult to measure or assess but also because its full importance was not recognized. Recent advancements in molecular characterization techniques [such as high-throughput sequencing, terminal restriction fragment length polymorphisms (T-RFLP), automated ribosomic intergenic spacer analysis (ARISA), denaturing gradient gel electrophoresis (DGGE), DNA probes, etc.] have enabled the realization of much more specific and detailed information on the structure of, function of, and changes in soil microbiology (40, 99, 137, 143, 148).

Soil health is also an appropriate term to use because it addresses not only the concept of soil as a living system but also the aspect that it incorporates all facets of the physical, chemical, and biological attributes of soil into one holistic system in which all its functions are important. Overall, there are several critical functions that soils are primarily involved in, and all are important in soil health. These include the ecological functions of biomass production (for food, fiber, and energy), nutrient cycling, filtering and buffering, and water storage and availability. Soils also serve as a biological habitat and a source of biodiversity. These are all in addition to the human activity–related functions of serving as a source of raw materials, physical medium and support for buildings, structures, etc., and preserving our cultural and archaeological heritage (14, 36).

Because it represents complex interactions among the components, there is no one ideal version of a healthy soil. Also, because each soil has limitations determined by soil type and climate, and soils can be very different, there is no one criterion that defines a healthy soil. However, there are several attributes that are characteristic of a healthy soil. These include such things as: (*a*) high levels of organic matter, which stabilizes soil structure, provides energy and nutrients, and increases soil fertility and water relations; (*b*) high tilth (loose, friable structure), which supports crop establishment and root and plant growth, and aids in the movement of air and water; (*c*) high water-holding capacity and drainage, which results in water storage and supply and prevents waterlogging and nutrient leaching; (*d*) an adequate and accessible supply of the nutrients needed for optimal plant growth and the maintenance of balanced nutrient cycling (however, excess nutrients can lead to toxicity, leaching, run-off, and pollution); (*e*) sufficient depth for root growth and to compensate for weather fluctuations and to avoid drought and flooding stresses; (*f*) large and diverse populations of beneficial soil organisms, needed for nutrient cycling, decomposition, soil structure, and suppression of pathogens and pests; and (*g*) low populations of plant pathogens and pests, for lower disease and plant stress levels. In addition, healthy soils should be (*h*) resistant to degradation (able to withstand adverse events such as erosion, excess rainfall, drought, etc.) and (*i*) resilient in their ability to recover from unfavorable conditions and stresses (52, 95, 96). Soils that are not healthy are not functioning at their normal capacity, have properties that limit crop productivity, sustainability, and environmental quality, and are constrained by problems such as erosion, compaction, poor structure, poor water and nutrient retention, and high disease, weed, and pest problems.

Assessment and Indicators

Because soil health, much like human health, represents the culmination of many individual networks, factors, responses, and interactions, there is no one measurement that can be used to assess overall health. Just as there are many different key measurements, such as temperature, blood pressure, pulse rate, blood chemistry, etc., that a medical doctor uses as indicators to get a sense of a person's overall health, there are also many different attributes that need to be monitored to assess the relative health of soils. Thus, once the basic characteristics of soil health were established, the next step was to identify the most important, useful, and reliable indicators of soil health that could be readily measured. These indicators are needed to assess parameters from all aspects of soil quality, incorporating the physical, chemical, and biological components. From early on, basic sets of indicators and minimum data sets were proposed for assessing and monitoring soil health, and for which standardized methodologies and procedures would be used. The attributes are representative of important soil quality functions and are sensitive to management and changes detected in relatively short time periods. Measurement methodologies for these attributes should be accessible and readily available to most people (34–36). However, in practice, various and different sets of attributes have been used by researchers and farmers as means to assess soil health, making standardization and uniformity difficult. The most commonly used and accepted indicators include such physical attributes as texture, rooting depth, bulk density, infiltration, aggregate stability, and water-holding capacity; such chemical attributes as total (or particulate) organic matter (or total organic C and N), pH, electrical conductivity, and extractable N, P, and K; and such general biological attributes as microbial biomass C and N, potentially mineralizable N, soil respiration, and earthworm populations (35, 36, 52, 144). Many researchers have focused specifically on identifying other appropriate biological indicators of soil health, including such factors as populations of specific groups or types of microorganisms, microbial community structure and activity, soil enzyme activities, soil biodiversity, and populations of soil micro- and macrofauna (97, 105, 111, 146).

Over the years, these and other attributes have been combined in various ways to establish particular soil health assessment programs. The Soil Quality Test Kit and use of soil quality scorecards were developed by the USDA-NRCS Soil Quality Institute in the late 1990s and was one of the first such programs (144). The kits and methodologies were designed to be able to be used on-site by conservationists, growers, and soil and crop consultants for a field assessment of soil quality. Later, USDA-NRCS incorporated the Soil Conditioning Index (SCI), which is based on soil organic matter/organic carbon levels, into their conservation and environmental policies and programs (145). Although this index is limited because it is based on a single factor, organic matter content has been considered the best single factor for assessment because of the many different physical, chemical, and biological properties and processes it influences. The Soil Management Assessment Framework (SMAF) is a measurement-based approach tool that interprets soil physical, chemical, and biological data and can be used for evaluating all types of cropping systems and management goals (4). A similar indexing approach is provided by the Agroecosystem Performance Assessment Tool (AEPAT), which is a computer program designed to assess agronomic and environmental performance of soil and crop management practices (89). More recently, a simplified version of the SMAF approach is used in the Cornell Soil Health Assessment program, in which standardized assessments of soil physical, chemical, and biological indicators are interpreted, and are accessible, useful, consistent, and economical for farmers and land managers to use to make soil management decisions (52). Of particular note from a plant pathology perspective, the Cornell Soil Health Assessment program includes a root health rating as part of the biological parameters measured and is one of the few soil health assessment programs to include a direct measure of plant disease response in their soil assessments (52). These and other assessment approaches focus on dynamic soil quality, which is affected and determined by recent crop and soil management practices, as opposed to inherent soil quality, which reflects the inherent characteristics of the soil (soil-forming processes, base materials, etc.) and is much more resistant to change (66, 68). Numerous researchers have addressed how to best utilize, analyze, and implement these assessment and analysis tools for practical soil health assessments (43, 60, 66, 69).

SOIL HEALTH MANAGEMENT

Overall Strategies

In addition to establishing overall soil health characteristics, assessments and indicators can be used to identify specific areas and parameters that need to be improved. There are several general strategies to keep in mind when making management decisions to achieve improved soil health. These include managing organic matter, minimizing disturbances, diversifying soil biota, maintaining living plants, and maintaining soil cover as much as possible (95, 96). These core strategies have been the focus of soil health management initiatives outlined by USDA-NRCS (**http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/mgnt/**). In addition, to enhance sustainability, strategies can also be geared toward balancing production and environmental quality and making better use of renewable versus nonrenewable resources (36, 37).

Manage organic matter. Soil organic matter, one of the primary indicators of soil health, is fundamental to the long-term sustainability of agroecosystems and global biogeochemical cycles. Managing for soil health (and improved soil function) is largely a matter of maintaining a suitable habitat for the multitude of organisms that make up the soil biology. Organic matter is the primary food source for soil microorganisms, and soil organic matter has such a profound effect on numerous soil physical, chemical, and biological properties that organic matter management is crucial in maintaining soil health. In addition to providing nutrients and energy for the soil biota, organic matter stabilizes soil structure and water relations (used here to refer to all aspects of water infiltration, storage, availability, etc.) and increases soil fertility (96). Conserving and/or maintaining existing organic matter levels is just the start, as in most cases regular additions of organic matter are necessary to replenish soil resources and improve soil health. Organic matter can be added through crop residues, rotations, and cover crops, as well as via off-field sources of organic amendments such as compost, manures, and mulches. Conservation of organic matter can be improved by minimizing tillage, maintaining active crop growth (shorter fallow periods), controlling erosion, and controlling field traffic as well as by retention of plant residues. Increasing organic matter content can increase plant nutrient availability, provide a favorable physical condition for plant growth, increase soil buffering capacity, stimulate root development, increase biological diversity, and facilitate nutrient cycling (96).

Minimize disturbances. Soil disturbance, which can be caused by physical, chemical, or biological activities, disrupts soil organisms and biological processes, and diminishes the habitat for soil organisms, thus diminishing the function of the soil biology. Physical disturbances include tillage and compaction as well as loss of topsoil through erosion. Thus, reduced, minimum, or no-till operations are preferred, and it is important to minimize or control field traffic and reduce erosion (96, 133). Chemical disturbances can be reduced through elimination or reduction of broad-spectrum pesticides or other harsh chemical inputs. Overgrazing is an example of a potential biological disturbance that reduces root mass, increases run-off, and increases soil temperature.

Diversify soil biota. An active and diverse soil biology is necessary for effective decomposition, nutrient cycling, good soil structure, and suppression of pathogens and diseases. Diverse soil microbiology is promoted by a diversity of plants and plant types grown, with different plants releasing different sets of carbohydrates and organic compounds and interacting with different assemblages of microorganisms (47, 109). This can be accomplished with diverse rotations, cover crops, and organic matter amendments. In addition, in some cases, biological amendments can also be added to augment or stimulate specific groups of beneficial organisms (77).

Maintain living plants. Living plants provide the most readily available food source for soil microbes, because plants maintain a rhizosphere, an area of concentrated microbial activity, which is the most active part of the soil ecosystem (most readily available food and peak nutrient and water cycling). Thus, growing plants throughout the year (long-season crops or multiple short-season crops, rotations, cover crops) helps the soil-food web and helps cycle the nutrients that plants need to grow (95, 96).

Maintain soil cover. Soil cover reduces erosion, conserves moisture, reduces temperature, intercepts rainfall, suppresses weed growth, and provides habitat for soil organisms. Soil cover can be provided by rotations, cover crops, stubble or residue during crop growth periods, and residue or mulches between cropping periods.

Conservation agriculture is a term used to describe a system or approach to agriculture, promoted by the Food and Agriculture Organization of the United Nations (FAO), that incorporates soil health management strategies, and focuses primarily on the three principles of (*a*) minimal soil disturbance, (*b*) permanent soil cover (mulch), and (*c*) diversified crop rotations, for a more sustainable means of global food production (55, 62, 70).

Management Practices

Crop rotation. Crop rotations provide numerous benefits to crop production and soil quality, and serve multiple functions. They can help conserve, maintain, or replenish soil resources, including organic matter, nitrogen and other nutrient inputs, and physical and chemical properties (8, 67, 95, 96, 111). Crop rotations have been associated with increased soil fertility, increased soil tilth and aggregate stability, improved soil water management, and reduced erosion (8, 51). Crop rotations also are associated with increasing soil microbial biomass and activity, and can also lead to increased microbial diversity due to the presence of different types of plant species being present and active in the soil (47, 109, 152). Crop rotations that maximize diversity and different types of plant and root systems (mixing legumes, cereals, solanaceous, cucurbits, brassica, etc.) may maximally influence soil microbial communities.

Cover crops and green manures. A cover crop is defined as a crop grown primarily to cover the soil in order to protect it from soil erosion and nutrient losses between periods of crop production (124). Benefits and uses of cover crops, including reduction of water runoff and soil erosion, addition of organic matter, improved soil structure and tilth, addition and recycling of nitrogen, greater soil productivity, and weed, pest, and disease control, have been documented and summarized in numerous reviews, general references, and practical guides (45, 54, 96, 124, 128, 142). Cover crops also add to crop diversity, and there also may be advantages to increasing crop diversity further by using multispecies cover crop mixtures instead of single species (138, 156). Use of hairy vetch or rye/vetch cover crops in vegetable production systems has been shown to increase organic matter content, aggregate stability (ability to resist disintegration), porosity, and available water, and reduce soil bulk density and penetration resistance, as well as suppress weeds (139, 151). High residue fall and winter cover crops have been shown to be important for adding C, retaining plant-available N, increasing fertilizer efficiency, and improving soil physical properties (59), and the use of winter and summer cover crops also minimized erosion, increased nutrient cycling, and reduced N leaching. Cover crops also use soil water, however, which may be a problem when water is particularly limited (128).

Green manuring refers specifically to the incorporation of fresh plant material for the purpose of soil enrichment. Thus, green manure crops are grown solely to be incorporated into soil as organic matter while still fresh and green. Green manuring generally results in larger organic matter inputs than traditional crop rotations or cover crops, producing improvements in soil fertility and structure (3, 51, 92, 142) as well as significant changes in soil microbial community characteristics (28, 131). Green manures are traditionally used for their nutritional and fertility benefits, particularly the addition of C (organic matter) and N to soil (12, 26, 44). Green manures result in increased microbial biomass and activity but also change microbial communities in ways that are distinctly different from other types of organic matter amendments, such as manure or sawdust (42).

Organic amendments. The direct addition of organic matter to soil through organic amendments, such as composts, animal manures, or organic mulches, has many practical uses and advantages for improving soil quality, affecting many parameters and improving biological, chemical, and physical properties. Organic amendments have been associated with changes in soil aeration, structure, drainage, water-holding capacity, nutrient availability, and microbial ecology, resulting in reduced erosion, improved water retention, and enhanced soil biodiversity (3, 7, 28, 37, 51, 120, 121, 131, 140, 142). Compost amendments, in particular, have been shown to be related to an increase in microbial biomass and microbial activity, a change in community structure and composition, and enhancements of specific groups of organisms (18, 33, 113, 114, 123, 143). Manure applications have been used to increase organic matter, aggregation, soil organic carbon, soil respiration, and infiltration and other water transmission properties, as well as decrease bulk density and increase soil microbial biomass and activity (11, 41). Mulching has been shown to improve bulk density, porosity, K saturation, aggregate stability, and soil water content (13, 49, 65, 159).

Conservation tillage. Extensive tillage increases erosion, disrupts biological processes, causes water loss, and reduces soil aggregation, resulting in crusting, soil compaction, and loss of organic matter (133). Conservation tillage is a system of cultivation that leaves at least 30% of the soil surface covered by residue between crop harvests and planting (105). As such, conservation tillage encompasses no-till operations, in which the soil is left undisturbed, and minimum- or reduced-till operations, in which the number or intensity of tillage operations is reduced so as to maintain residue cover. Implementation of reduced and/or no-till systems has a long history of documented effects on soil properties, including improvements in various physical soil properties, such as available water capacity, infiltration, porosity, aggregate stability, penetration resistance, and bulk density (6, 59, 63, 65, 90, 129, 151). Changes to chemical properties often include decreases in pH, variable changes to cation exchange capacity (CEC), and increases in nutrient availability, and effects on biological properties may include increases in organic matter (and soil organic carbon [SOC]), microbial biomass, and microbial diversity (38, 110, 155).

SOIL HEALTH AND DISEASE MANAGEMENT

By definition, healthy soils have low disease levels, but what aspects of soil health are related to low pathogen populations and/or low disease development? What effects do specific management practices intended to improve soil health have on soilborne pathogens and disease development? Are soil health management practices sufficient to control soil diseases, or are additional specific disease management practices needed? And what about foliar diseases? Can soil health management practices have any effect on pathogens and diseases that are not soilborne but result from airborne and/or aboveground inoculum introduction and dispersal? How can soil health and disease management best be optimized? These are all questions that need to be more closely investigated.

In general, most practices that maintain or improve soil health also have a positive effect on reducing soilborne plant diseases through a number of potential mechanisms of action. These beneficial effects of soil health management practices on plant diseases have been widely documented and are the subject of previous reviews (1, 7, 29, 48). In their review of management practices and soilborne diseases, Abawi & Widmer (1) concluded that soilborne diseases are most severe when soil conditions are poor as a result of inadequate drainage, poor soil structure, low organic matter, low soil fertility, and high soil compaction, and that soil health management practices can improve these conditions, as well as increase the diversity of soil biota, resulting in improved soil health and reduced disease. Most importantly, management practices associated with soil health (crop rotations, cover crops, conservation tillage, organic amendments, etc.) all tend to increase microbial biomass and activity, and often biodiversity as well, resulting in conditions favorable for the development of general disease suppression (18, 24, 109, 110, 152). General disease suppression refers to suppression related to the nonspecific increase in overall size and activity of the microbial community, resulting in increased competition and interactions reducing the ability of soilborne pathogens to grow and infect plants. This may or may not result in an actual reduction in pathogen populations, but reduces the disease-causing activity of the pathogen. In addition, some practices may stimulate or enhance particular organisms or groups that result in specific disease suppression, which is suppression due to the activities of specific antagonistic organisms that directly interact with and interfere with pathogen populations and/or their disease-causing activity (61).

For ease of presentation, the effects of each major type of soil health management practice on plant disease management are dealt with separately, followed by the circumstances and challenges surrounding assessments of combinations and interactions of multiple practices and integrated systems.

Organic Amendments

The use of organic amendments (such as compost, manure, and mulch) to reduce or suppress plant pathogens and diseases is well-documented and has been the subject of several previous reviews (7, 19, 106, 107, 149). Composted materials, in particular, have often been associated with reductions in soilborne diseases in a wide variety of different crops and for many different pathosystems, including diseases such as damping-off and root rots (*Pythium ultimum*, *Rhizoctonia solani*, *Rosellinia necatrix*, *Phytophthora* spp., etc.), wilts (*Fusarium oxysporum*, *Verticillium dahliae*), and others (*Sclerotinia* spp., *Streptomyces* spp., etc.) (5, 17, 19, 53, 56, 57, 106, 157). Although compost amendments are generally associated with reductions in soilborne diseases, results can be quite variable, and dependent on many factors (16, 107). Termorshuizen et al. (141) evaluated a wide range of composts against a range of pathogens and diseases with a consortium of researchers from several countries, and of the 120 bioassays using 18 composts and 7 pathosystems, just over half (54%) resulted in significant disease suppression, whereas 43% showed no effect and only 3% resulted in increased disease, with effects varying for different pathogens. In another survey of studies involving the use of organic amendments, compost was found to be the overall most suppressive form of amendment, with 55% of the cases showing effective disease control (17). However, disease control of *Rhizoctonia* was the most difficult of the fungal pathogens monitored, with compost reducing *Rhizoctonia* disease in only 32% of the studies, while having no effect or increasing disease in 68% of the cases (17). The most important factors appear to be the compost materials, age, maturity, and quality (57). Thus, the type and characteristics of the compost are of primary importance in determining whether the compost will be suppressive or not, but although much has been written on the subject regarding the important characteristics (16, 56, 57, 107, 141), much variability still exists, and a better understanding of compost microbial ecology and just what characteristics make a compost suppressive are needed (5, 53). In a series of trials in potato cropping systems in Maine, composted dairy manure and some other compost amendments consistently increased crop yield and positively impacted many soil parameters, including increased microbial populations and activity and distinctive changes in microbial community characteristics, but did not result in suppression of diseases caused by *R. solani* and *Streptomyces scabies*, and in some cases increased disease relative to unamended soils (9, 83, 85, 86). Although they can be highly beneficial, any compost should be tested on a small scale prior to being used for intended disease-suppressive performance on a large scale.

Noncomposted manures or other organic amendments have also been shown to reduce soilborne diseases in some cases, but again results can be inconsistent, with reports of both successes and failures in reducing disease problems (91). In a survey of hundreds of studies involving organic amendments, Bononami et al. (17) reported that organic wastes, which included uncomposted manures and industrial by-products (such as fish and bone meal, paper mill residues, etc.), resulted in disease suppression in more than 50% of the trials and in increased disease in <12% of trials.

The quantity and quality of the organic matter inputs affect both the physicochemical properties of the soil and the biotic factors associated with soil microbiology, including microbial biomass, diversity, community structure, and biochemical activities. Although some abiotic factors have been associated with disease suppression in some systems, soil microbiology is consistently related to disease suppression, either through general suppression due to an increase in overall microbial biomass and activity, specific suppression related to specific organisms or groups of organisms, or, as is often the case, a combination of both. Although several studies have attempted to identify the key factors in organic amendments responsible for disease suppression, due to the complex interactions and variations among soils, microbiology, and pathosystems involved, no specific parameter has been observed to be related to suppression in all cases (16, 106). However, disease suppression is often related to overall increases in soil microbial biomass and activity, which create a competitive environment deleterious to the pathogen (16, 19). In some cases, suppression is related to microbial diversity or to the presence or increase of specific organisms or groups of organisms. Supporting this, in most all cases the suppression is of biological origin, as suppressiveness is lost when composts are sterilized (16, 19).

In addition, there has been evidence that organic amendments may also in some cases effect disease suppression through the mechanism of induction of resistance in the host plant, which is brought about through an increase or stimulation in rhizobacteria capable of inducing resistance of the crop plants to soilborne pathogens (132, 158). However, there are also examples of specific types of interactions between organic amendments and soil properties wherein disease suppression occurs only under specific conditions. In a series of experiments in which various manures and organic wastes were found to be highly suppressive to Verticillium wilt, disease control was not consistent from site to site (87, 88). Further investigation determined that different mechanisms of action were operating under different conditions, wherein high nitrogenous amendments suppressed pathogens by the formation of ammonia or nitrous acid, and such conversions were dependent on pH and organic matter content of the soils; also, the use of liquid swine manure reduced disease because of the formation of volatile fatty acids but only in acidic soils (87, 88). These examples indicate some of the complex interactions among organic amendments and disease suppression as well as the need to fully understand the mechanisms of action, the requirements, and the limitations.

Biological amendments are another type of type of organic amendment and consist of direct additions of propagules or biomass of specific beneficial organisms or mixtures of organisms. These include such things as commercial biocontrol agents, microbial inoculants, mycorrhizae, and compost teas, and can also be used to introduce, augment, or stimulate soil populations of beneficial microorganisms and may enhance the development of microbial disease suppression. In particular, the augmentation of composts with biocontrol or disease-suppressive microorganisms has been successful in improving disease control in some cases (39, 57, 58, 107, 117). In addition to the use of established biocontrol agents and organisms, which has been shown to be effective in the reduction of soilborne diseases in many systems, the introduction/augmentation of microorganisms to soil through the use of other types of microbial inoculants has also been successful in reducing disease in some situations. Compost teas, which are water-based compost extracts that can be prepared or brewed under either aerobic or nonaerated conditions, contain high populations of a diverse mix of microorganisms and have been suggested to have disease-suppressive qualities (126, 130). Although the efficacy of compost teas sprayed on plants for the direct control of foliar diseases may be questionable (lack of reliable documentation), the use of compost tea as a means to introduce/augment potentially beneficial microoorganisms in soil has much potential (77, 130). In a series of studies, biological amendments, including commercial biocontrol agents, microbial inoculants, mycorrhizae, and an aerobic compost tea (ACT), successfully delivered microorganisms into soil, altering microbial populations and activity consistent with the particular types of organisms added and significantly modifying soil microbial community characteristics in additional ways (beyond the specific organisms added) (77). In field trials in different potato rotations, biological amendments (an aerated compost tea and a microbial mix of various beneficial organisms) reduced soilborne disease and improved yield in some rotations, but not others. Specifically, biological amendments were successful in a rotation that was more favorable to soil health (grain rotation with ryegrass cover crop), less successful in less desirable rotations, and not at all successful in continuous potato (lack of rotation) (77). These results indicate that certain rotations were better able to support the added beneficial organisms from biological amendments and enable more effective biological control than others. Establishment and persistence of amendment effects may depend on many factors, but an effective and supportive crop rotation is apparently important.

Crop Rotation

Although crop rotations provide multiple benefits for soil health, of most importance is their role in disease management, as crop rotations are essential to maintain crop productivity and reduce the buildup of soilborne plant pathogens and diseases, which can devastate crops grown in multiple consecutive years (30, 74). However, there can be substantial differences among types of rotation crops in their ability to reduce disease development. In general, crop rotations can reduce soilborne pathogens by any (or all) of three general mechanisms: (*a*) by serving to interrupt or break the host-pathogen cycle of inoculum production, growth, or survival; (*b*) by altering the soil's physical, chemical, or biological characteristics, making the soil environment less conducive for pathogen development or survival (often by stimulating microbial activity and diversity or the growth of plant-beneficial microbes); and (*c*) by direct inhibition of pathogens, either through production of inhibitory or toxic compounds in the roots or plant residues or by stimulating specific microbial antagonists that directly suppress pathogen inoculum (80). Any crop species that is not a host to the same pathogens as the primary crop can be useful as a rotation crop using the first mechanism. However, a serious limitation to this mechanism is that most soilborne pathogens can survive many years in the absence of a host, longer than is feasible for most rotations. Thus, for crop rotations to be more effective as a disease management tool, the second and third mechanisms (which involve the active suppression, reduction, or destruction of pathogen propagules, survival, and disease-causing activity) must be more fully explored and exploited.

Crops and rotations that play an active role in reducing diseases can be referred to as disease suppressive. Grass and forage crops with extensive root systems grown as rotation or cover crops are known to increase microbial populations, activity, and diversity, and may also suppress diseases (7, 47, 48, 75). For example, crops in the Brassicaceae family, which include broccoli, turnip, radish, canola, rapeseed, and mustards, as well as sorghum-sudangrass and some other plant groups, produce compounds that break down to produce volatile toxins that can suppress soilborne pathogens and diseases as part of a process referred to as biofumigation (98, 125). These plants also have unique effects on soil microbial communities that may be related to disease suppression (27, 79, 80, 100), and use of these plants as rotation, cover, or green manure crops has been observed to reduce soilborne diseases in a variety of cropping systems (85). In long-term studies in Maine, canola and rapeseed used in two-year rotations with potato resulted in reductions of soilborne diseases caused by *R. solani* and *S. scabies* relative to other rotation crops (80).

Additional benefits of crop rotation can be achieved by increasing the diversity of rotation crops as much as possible. Use of a diverse mix of different types of rotation crops results in increases in microbial biomass, activity, and biodiversity, and has been associated with further reductions in soilborne diseases (74, 118). With crop rotations, generally the longer amount of time and the more types of crops used between occurrences of the primary host crop, the better it is for disease management (i.e., three- or four-year rotations are known to provide better disease control than two-year rotations, etc.) (30, 74, 115, 116). With longer rotations, the crop sequence, i.e., which crops follow which, also becomes important, as no crops with similar pathogen or pest problems should follow each other in a rotation (82).

Another way crop rotations can be used for disease management involves the manipulation of soil microbial communities. Plants are a primary driver of changes in soil microbial communities, and recent studies have documented the effects of crop rotations on microbial communities (76, 82, 94, 150). Because crop rotations, cover crops, and green manures can dramatically affect soil microbial communities (25, 47, 109, 134, 148), the use of specific crops for their effects on soil microbial communities and the development of disease-suppressive soils is a viable approach to disease management, sometimes referred to as active management of soil microorganisms (47, 61, 99, 122, 152). The goal of this approach is to manipulate, alter, or augment the microbial characteristics of the soil through various management practices that increase soil microbial activity, diversity, populations of plant-beneficial organisms, and antagonism toward pathogens, resulting in disease suppression. In potato field trials, crop rotations resulted in larger and more lasting effects on soil microbial community characteristics than direct introduction/augmentation of microorganisms (77). However, much more information is needed regarding the specific effects of particular crops and their relationship to disease suppression before widespread recommendations for disease management through active management of soil microbial communities can be realized.

Cover Crops and Green Manures

Cover crops are generally chosen based primarily on what they are most needed for, such as N addition, organic matter biomass, erosion control, etc., but regardless of their primary purpose, cover crops can also provide some degree of supplemental disease control as well, as long as the crop chosen is not host to the same pathogens as the main crop. As with standard crop rotations, cover crops also add crop diversity, which can help stimulate and diversify soil microbial biomass and potentially result in some disease suppression. The effects of cover crops and green manures on plant diseases have been discussed in several general reviews (1, 7, 26, 46) and a more detailed analysis of green manures and plant disease management has recently been published (78). Cover crops function in a similar way to regular rotation crops regarding their effects on soil microbial biomass, activity, diversity, and potential for disease suppression. In general, use of the crops as green manures has greater effects on all soil health parameters than cover crops, and has greater potential for reducing soilborne diseases, because of the much higher levels of fresh organic matter added as well as their greater extent of effects on soil microbiology (24, 26, 44, 50). Green manure crops have a long history of providing disease suppression for soilborne plant pathogens of potato and various other crop plants. In particular, use of disease-suppressive biofumigation crops, such as *Brassica* spp. and sudangrass, has been effective in reducing soilborne pathogens and diseases (78), weeds (20, 21), and nematodes (22, 23, 98, 102–104), as well as in improving soil characteristics and crop yield (83, 101). These types of biofumigation crops have become the preferred green manures for their potential disease-suppressive characteristics. Biofumigation potential of different *Brassica* crops and cultivars can vary widely based on the levels and types of glucosinolates produced, with oriental or Indian mustard (*Brassica juncea*) generally having among the highest biofumigation potential, and crops such as rapeseed and canola (*Brassica napus*) having substantially lower levels (72, 98). *Brassica* green manures have been used to reduce soilborne potato diseases caused by the pathogens *V. dahliae*, *R. solani*, *S. scabies*, *F. oxysporum*, and others at numerous locations, with disease reductions ranging from 20% to 80% (31, 32, 84, 85, 154). Although biofumigation is the presumed mechanism of action for these crops, further research has indicated that additional mechanisms, including specific changes in soil microbial communities not related to levels of glucosinolate or other toxic metabolites, are also important in the reduction of soilborne diseases by *Brassica* crops, particularly for the control of *Rhizoctonia* (27, 31, 32, 79, 85, 100). In addition, non-*Brassica* (and nonbiofumigant) crops, such as barley, buckwheat, winter pea, rye, ryegrass, and oats, have also been effective as green manures for reducing a number of soilborne diseases, with mechanisms of action attributed to increased microbial biomass and activity, changes in soil microbial community characteristics, and specific effects on populations of antagonistic microorganisms (32, 108, 153, 154). *Brassica* and other green manures have also been used to control Verticillium wilt on several other crops, including cauliflower, strawberry, and tomato, Phytophthora blight on squash and pepper plants, and root rot of peas (64, 127, 135, 136, 153).

In a recent study in Maine (81) assessing several cover crops (sudangrass, rapeseed, mustard blend, soybean, and barley underseeded with red clover) managed in various ways (with increasing levels of biomass incorporation: as a cover crop, a harvested crop with residues not incorporated, a harvested crop with residues incorporated, or as a green manure), all crops managed as green manures produced lower soilborne disease and higher yield than any other management practice. However, crops harvested with residue incorporated also reduced disease but to a lesser extent. Overall, the biofumigation crops (mustard, rapeseed, and sudangrass) resulted in the lowest disease levels. The combination of mustard blend managed as green manure was the overall best for crop production, reducing black scurf by 54% and increasing yield by 25% relative to a soybean cover crop. These results indicated the importance of incorporation of fresh biomass (regardless of whether it was classified as a disease-suppressive crop or not), in that a variety of different crops all performed best (from a disease reduction standpoint) as green manures versus cover crops, yet the disease-suppressive crops produced the best overall results. These results also indicated that significant disease reduction could be observed even when the biofumigation crops were not fully incorporated as a green manure (81).

However, as with crop rotations and organic amendments, green manures are not always effective at reducing disease. In a recent survey summarizing numerous field trials of various *Brassica* green manures in potato rotations in Maine, effective disease reduction was observed in 70%, 41%, and 46% of the trials for black scurf, common scab, and powdery scab, respectively, and yield was increased in 51% of the trials (78).

Conservation Tillage

Conservation tillage can have varying effects on soilborne pathogens and diseases, with either increases or decreases observed, depending on the type of pathogen and conditions. The impact of conservation tillage on soilborne diseases has been previously reviewed (7, 15), most recently by Page et al. (110). Because of the positive effects on soil health due to reduced tillage, particularly reduction of erosion and increases in soil organic matter, microbial biomass, and diversity, some soilborne diseases are expected to decrease with conservation tillage over time as a result of healthier crops and disease suppression by a larger, more diverse microbial community. This has been observed for some root rots and *Rhizoctonia* diseases (110).

Pathogens that are able to survive in crop residues for extended periods may increase and become more of a problem under conservation tillage systems because of the retention of residues on the soil surface during periods when host crop tissue was normally not present under conventional tillage. The burial and subsequent decomposition of crop residues in traditional tillage systems also tended to reduce pathogen populations. In addition, reduced soil disturbance, increased soil moisture, and lower soil temperatures may create a more favorable soil environment for some plant pathogens and encourage disease persistence. Some pathogens (primarily of wheat, barley, and other grains) observed to increase under conservation tillage include *Gaemannomyces graminis* (take-all), *Fusarium pseudograminearum* (head blight, scab, or crown rot), *Pyrenophora tritici-repentis* (tan spot), *Pythium* spp. (Pythium root rot), *R. solani* (root rot), *Rhynchosporium secalis*, and *Stagnospora avenae* (leaf blotch) (110). Most of the disease problems associated with reduced tillage have occurred mainly in grain monocultures, where there are no crop rotations and the pathogens are able to survive in residues to infect the next crop. Because of this, the primary means to address this issue is through the implementation of appropriate crop rotations, which breaks the host-pathogen cycle and reduces disease. In systems where effective crop rotations were used, increases in these pathogens were generally not observed.

Combinations and Interactions Among Multiple Management Practices

Ideally, for optimal effects on soil health and sustainability, all the soil health management practices should be used together to some degree. Yet, care must be taken that combined practices are compatible, will be complementary, and do not interfere with each other. However, most studies, in order to be able to accurately assess the effects of a given practice, deal mainly with one or two factors at a time. Impacts of each type of practice give a good indication of the effects and changes observed with soil health management practices, but these types of studies cannot provide information on how multiple practices will all interact and respond in conjunction with each other as a complete system. Although there are many studies that assess two different soil management practices, such as tillage and rotation, or tillage and cover crops, there are relatively few studies that combine three or more of the soil health management practices and also assess plant diseases. In many cases, the combined effects appear to be additive and/or complementary, but there are also cases in which combining multiple practices provides no additional benefit or may even be counterproductive. For example, several studies that combine multiple soil health management practices have been conducted in potato cropping systems. A long-term study that combined multiple management practices into potato cropping systems that utilized disease-suppressive rotations, diverse cover crops and green manures, compost amendments, and reduced tillage demonstrated that low soilborne disease levels and high yield could be maintained with the disease-suppressive system and that a composted dairy manure amendment increased yield and water availability but did not suppress disease (83). In a separate study assessing the impact of a *Brassica* green manure rotation and compost amendments, compost increased yield under both organic and conventional conditions but did not reduce disease, whereas the green manure reduced disease but had only marginal effects on yield; yet the combination of the two practices resulted in both disease reduction and yield increases, for complementary effects (9). In a long-term potato rotation study, *Brassica* rotation crops reduced soilborne diseases better than others (reduction of 20% to 40%), and when combined with a fall cover crop (winter rye), an additional (8% to 13%) reduction in disease severity was achieved, resulting in a combined reduction of 30% to 50% (80). When it comes to disease management, a particular soil health management practice may have a small but significant effect on pathogens or disease, but by combining multiple compatible practices, several incremental increases in disease management can result in substantial control of multiple soilborne diseases.

Studies that make comparisons between organic agriculture, which consists primarily of these types of soil health–building practices, and conventional agriculture systems can also give an overall picture of how multiple soil management practices can work together to realize goals of soil health and sustainability. In general, these organic sites have demonstrated consistently higher soil health ratings and assessments, higher microbial activity, and corresponding lower disease pressure (9, 10, 73, 93, 119, 137, 147). However, although these comparisons are useful, there are also some very distinct differences between organic and conventional systems that are separate from these soil health management practices, such as pesticide usage and the possibility of very different soil types, backgrounds, histories, etc. at different sites. Such all-inclusive studies can indicate overall effects from many different factors together, but it is difficult to determine what specific factors may be responsible for the many changes observed or just how these different factors are interacting. Overall, much more research is still needed to better determine the mechanisms of action involved, the interactions among the various practices and their effects, and how to best incorporate the management practices into cohesive systems that will not only improve overall soil health and sustainability but also ensure effective management of plant diseases.

Efficacy of Soil Health Management Practices for Plant Disease Management

It is clear that soil health in general and soil health management practices in particular can have very positive effects on management of soilborne diseases. However, these practices are not sufficient to completely control or eliminate most plant disease problems. There is no evidence that indicates that total disease control is likely or even possible. Just as the attainment of perfect soil health is not possible, neither is the possibility of reaching a state in which disease management is absolute. Most of the available literature indicates that soil health management practices may help reduce most soilborne diseases by anywhere from 20% to 80%, but rarely are there any reports of the complete control of a pathogen. And in some cases, as was learned with the lessons of conservation tillage, even when one disease problem is more or less controlled by a management practice, there are usually other new or emerging disease problems just waiting to exploit the new or altered conditions brought about by the management changes, so that another different disease problem may emerge.

And what about foliar pathogens and diseases? There has been very little mention of these here. Not surprisingly, most of the direct effects of soil health management practices are on soilborne pathogens and diseases. Pathogens that spend at least some of their life cycle in, on, or around the soil, even if they are predominantly foliar pathogens, can be affected by soil management practices and reduced to some degree. It is primarily airborne pathogens, such as rusts and mildews, which move in from outside the field itself, sometimes over long distances, that are not directly affected by soil management practices. And, as already mentioned, some leaf spots and other pathogens that can reside in surface residues may be increased with conservation tillage. However, even diseases caused by these types of pathogens may be reduced through soil management practices under the right circumstances. One of the mechanisms of action for disease suppression by many rhizobacteria, as well as fungi, is induced resistance in the host plant, wherein induction of systemic resistance to a variety of pathogens is activated. Healthy soils would be expected to have larger more robust populations of beneficial root-colonizing microorganisms and thus may result in a greater occurrence of induced resistance to foliar as well as soilborne diseases. Several compost amendments that are suppressive to disease have also been shown to induce resistance to various diseases, including foliar diseases such as Botrytis rot, anthracnose, angular leaf spot, and other foliar leaf spots on tomato, cucumber, bean, and others, through activation of plant defense responses (2, 132, 158, 160). It has also been argued that plants grown in healthier soils are more resilient, receive better nutrition, and produce better defense responses, and are thus less susceptible to infection by pathogens in general. However, the frequency and/or extent of efficacy of management of foliar disease through natural or induced resistance mechanisms as a result of soil health management practices are not known. Overall, alternative and/or additional control measures for outbreaks of foliar pathogens would be needed even if all soil health management practices were implemented as fully as possible.

CONCLUSIONS

Implementation of the concepts of soil health and soil health management into agricultural production, which has been ongoing for the past twenty years, and will continue to be the direction of the future, is essential for sustainable crop production and maintaining environmental quality. On some levels, conventional agriculture has come a long way in that time, with the widespread adoption of conservation tillage and crop rotations in many production systems. However, in other ways, progress has been very slow, with many aspects of crop production still mired in unhealthy soil practices and a reluctance to adopt more aggressive soil health management practices, such as diversified cover crops and green manures, and organic amendments. Thus, much more needs to be done to continue to move agriculture to greater soil health and a more sustainable future. For our part, as researchers, there is still much more that needs to be determined regarding understanding the complex interactions among practices and soil properties and their ultimate effects and consequences, as well as providing clear answers for how to best implement the appropriate soil health management practices for each production system for maximum benefit and productivity.

Overall, management practices that promote soil health will also generally improve disease management. All of the major soil health–building practices, such as use of crop rotations, cover crops and green manures, organic amendments, and conservation tillage, contribute to building active, diverse, disease-suppressive soil microbial communities, and when used appropriately, provide the potential for an effective and sustainable disease management system. All these practices have been shown to effectively reduce most of the major soilborne diseases within their respective agroecosystems in at least some situations. However, some of these changes take considerable time to develop and stabilize, and some diseases, and different disease problems, may emerge during transition stages. In addition, there also exist a lot of variability and uncertainty associated with the different types and qualities of materials used, their interactions, and combinations of other factors, making the extent of disease management uncertain. Much care and attention must be given to determining the right mixture of practices that work best for specific systems. Even when the soil health management practices are working and progressing as they should, disease management will not be complete, and additional control measures will be needed. Make no mistake, soil health management practices provide probably the best overall approach for managing soilborne, and even some foliar diseases, and should be the core of a good disease management program. But there will always be a need for additional control measures as well as the need to respond quickly to an emerging threat, whether it is through pesticides, natural products, additional cultural practices, or biological control, in order to provide sufficient disease management for optimal crop production.

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LITERATURE CITED

1. Abawi GS, Widmer TL. 2000. Impact of soil health practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Appl. Soil Ecol.* 15:37–47
2. Abbasi PA, Al-Dahmani J, Sahin F, Hoitink HAJ, Miller SA. 2002. Effect of compost amendments on disease severity and yield of tomato in conventional and organic production systems. *Plant Dis.* 86:156–61
3. Abdallahi MM, N'Dayegamiye A. 2000. Effects of green manures on soil physical and biological properties and on wheat yields and N uptake. *Can. J. Soil Sci.* 80:81–89
4. Andrews SS, Karlen DL, Cambardella CA. 2004. The soil management assessment framework: a quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.* 68:1945–62
5. Aviles M, Borrero C, Trillas MI. 2011. Review on compost as an inducer of disease suppression in plants grown in soilless culture. *Dyn. Soil Dyn. Plant* 5:1–11
6. Aziz I, Mahmood T, Islam KR. 2013. Effect of long-term no-till and conventional tillage practices on soil quality. *Soil Tillage Res.* 131:28–35
7. Bailey KL, Lazarovits G. 2003. Suppressing soil-borne diseases with residue management and organic amendments. *Soil Tillage Res.* 72:169–80
8. Ball BC, Bingham I, Rees RM, Watson CA. 2005. The role of crop rotations in determining soil structure and crop growth conditions. *Can. J. Plant Sci.* 85:557–77
9. Bernard E, Larkin RP, Tavantzis S, Erich MS, Alyokhin A, Gross S. 2014. Rapeseed rotation, compost, and biocontrol amendments reduce soilborne diseases and increase tuber yield in organic and conventional potato production systems. *Plant Soil* 374:611–27
10. Bernard E, Larkin RP, Tavantzis SM, Erich MS, Alyokhin A, et al. 2012. Compost, rapeseed rotation, and biocontrol agents significantly impact soil microbial communities in organic and conventional potato production systems. *Appl. Soil Ecol.* 52:29–41
11. Bhattacharyya R, Chandra S, Singh RD, Kundu S, Srivasta AK, Gupta HS. 2007. Long-term farmyard manure application effects on properties of a silty clay loam soil under irrigated wheat-soybean rotation. *Soil Tillage Res.* 94:386–96
12. Biederbeck VO, Campbell CA, Rasiah V, Zentner RP, Wen G. 1998. Soil quality attributes as influenced by annual legumes used as green manures. *Soil Biol. Biochem.* 30:1177–85
13. Blanco-Canqui H, Lal R. 2007. Impacts of long-term wheat straw management on soil hydraulic properties under no-tillage. *Soil Sci. Soc. Am. J.* 71:1166–73
14. Blum WEH. 2005. Functions of soil for society and the environment. *Rev. Environ. Sci. Bio/Technol.* 4:75–79

15. Bockus WW, Shroyer JP. 1998. The impact of reduced tillage on soilborne pathogens. *Annu. Rev. Phytopathol.* 36:485–500
16. Bonanomi G, Antignani V, Capodilupo M, Scala F. 2010. Identifying the characteristics of organic amendments that suppress soilborne plant diseases. *Soil Biol. Biochem.* 42:136–44
17. Bonanomi G, Antignani V, Pane C, Scala F. 2007. Suppression of soilborne fungal diseases with organic amendments. *J. Plant Pathol.* 89:311–24
18. Bonilla N, Cazorla FM, Martinez-Alonso M, Hermoso JM, Gonzalez-Fernandez J, et al. 2012. Organic amendments and land management affect bacterial community composition, diversity and biomass in avocado crop soils. *Plant Soil* 357:215–26
19. Bonilla N, Gutierrez-Barranquero JA, de Vicente A, Cazorla FM. 2012. Enhancing soil quality and plant health through suppressive organic amendments. *Diversity* 4:475–91
20. Boydston RA, Hang HA. 1995. Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*). *Weed Technol.* 9:669–75
21. Brown PD, Morra MJ. 1995. Glucosinolate-containing plant tissues as bioherbicides. *J. Agric. Food Chem.* 43:3070–74
22. Brown PD, Morra MJ. 1997. Control of soilborne plant pests using glucosinolate-containing plants. *Adv. Agron.* 61:167–231
23. Buskov S, Serra B, Rosa E, Sorensen H, Sorensen JC. 2002. Effects of intact glucosinolates and products produced from glucosinolates in myrosinase-catalyzed hydrolysis on the potato cyst nematode (*Globodera rostichiensis*). *J. Agric. Food Chem.* 50:690–95
24. Chander K, Goyal S, Mundra MC, Kapoor KK. 1997. Organic matter, microbial biomass and enzymatic activity of soils under different crop rotations in the tropics. *Biol. Fertil. Soils* 24:306–10
25. Chaparro JM, Sheflin AM, Manter DK, Vivanco JM. 2012. Manipulating the soil microbiome to increase soil health and plant fertility. *Biol. Fertil. Soils* 48:489–99
26. Cherr CJ, Scholberg JMS, McSorley R. 2006. Green manure approaches to crop production: a synthesis. *Agron. J.* 98:302–19
27. Cohen MF, Mazzola M, Yamasaki H. 2005. *Brassica napus* seed meal soil amendment modifies microbial community structure, nitric oxide production and incidence of *Rhizoctonia* root rot. *Soil Biol. Biochem.* 37:1215–27
28. Collins HP, Alva AK, Boydston RA, Cochran RL, Hamm PB, et al. 2006. Soil microbial, fungal, and nematode responses to soil fumigation and cover crops under potato production. *Biol. Fertil. Soils* 42:247–57
29. Conway KE. 1996. An overview of the influence of sustainable agricultural systems on plant diseases. *Crop Prot.* 15:223–28
30. Cook RJ. 2000. Advances in plant health management in the twentieth century. *Annu. Rev. Phytopathol.* 38:95–116
31. Davis JR, Huisman OC, Westermann DT, Everson DO, Schneider A, Sorensen LH. 2004. Some unique benefits with sudangrass for improved U.S. #1 yields and size of Russet Burbank potato. *Am. J. Potato Res.* 81:403–13
32. Davis JR, Huisman OC, Westermann DT, Hafez SL, Everson DO, et al. 1996. Effects of green manures on Verticillium wilt of potato. *Phytopathology* 86:444–53
33. D'Hose T, Cougnon M, De Vliegher A, Vandecasteele B, Viaene N, et al. 2014. The positive relationship between soil quality and crop production: a case study on the effect of farm compost application. *Appl. Soil Ecol.* 75:189–98
34. Doran JW, Parkin TB. 1994. Defining and assessing soil quality. In *Defining Soil Quality for a Sustainable Environment*, ed. JW Doran, DC Coleman, DF Bezdicek, BA Stewart, pp. 3–21. Madison, WI: Soil Sci. Soc. Am.
35. Doran JW, Saffley M. 1997. Defining and assessing soil health and sustainable productivity. In *Biological Indicators of Soil Health*, ed. C Pankhurst, BM Doube, VVSR Gupta, pp. 1–28. Wallingford, UK: CABI
36. Doran JW, Sarrantonio M, Leibig M. 1996. Soil health and sustainability. In *Advances in Agronomy*, ed. DL Sparks, pp. 1–54. San Diego, CA: Academic
37. Doran JW, Zeiss MR. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Appl. Soil Ecol.* 15:3–11

38. Dorr de Quadros P, Kateryna Z, Davis-Richardson A, Fagen JR, Drew J, et al. 2012. The effect of tillage system and crop rotation on soil microbial diversity and composition in a subtropical acrisol. *Diversity* 4:375–95
39. Dukare AS, Chaudhary V, Singh RD, Saxena AK, Prasanna R, et al. 2011. Evaluating microbe-amended composts as biocontrol agents in tomato. *Crop Prot.* 30:436–42
40. Edel-Hermann V, Dreumont C, Perez-Piqueres A, Steinberg C. 2004. Terminal restriction fragment length polymorphism analysis of ribosomal RNA genes to assess changes in fungal community structure in soils. *FEMS Micobiol. Ecol.* 47:397–404
41. Edmeades DC. 2003. The long-term effects of manures and fertilizers on soil productivity and quality: a review. *Nutr. Cycl. Agroecosyst.* 66:165–80
42. Elfstrand S, Hedlund K, Mårtensson A. 2007. Soil enzyme activities, microbial community composition and function after 47 years of continuous green manuring. *Appl. Soil Ecol.* 35:610–21
43. Erkossa T, Itanna F, Stahr K. 2007. Indexing soil quality: a new paradigm in soil science research. *Aust. J. Soil Res.* 45:129–37
44. Fageria NK. 2007. Green manuring in crop production. *J. Plant Nutr.* 30:691–719
45. Fageria NK, Baligar VC, Bailey BA. 2005. Role of cover crops in improving soil and row crop productivity. *Commun. Soil Sci. Plant Anal.* 36:2733–57
46. Gamliel A, Austerweil M, Kritzman G. 2000. Non-chemical approach to soilborne pest management: organic amendments. *Crop Prot.* 19:847–53
47. Garbeva P, van Veen JA, van Elsas JD. 2004. Microbial diversity in soil: selection of microbial populations by plant and soil type and implications for disease suppressiveness. *Annu. Rev. Phytopathol.* 42:243–70
48. Ghorbani R, Wilockson S, Koocheki A, Leifert C. 2008. Soil management for sustainable crop disease control: a review. *Environ. Chem. Lett.* 6:149–62
49. Glab T, Kulig B. 2008. Effect of mulch and tillage system on soil porosity under wheat (*Triticum aestivum*). *Soil Tillage Res.* 99:169–78
50. Goyal S, Chandler K, Mundra MC, Kapoor KK. 1999. Influence of inorganic fertilizers and organic amendments on soil organic matter and soil microbial properties under tropical conditions. *Biol. Fertil. Soils* 29:196–200
51. Grandy AS, Porter GA, Erich MS. 2002. Organic amendment and rotation crop effects on the recovery of soil organic matter and aggregation in potato cropping systems. *Soil Sci. Soc. Am. J.* 66:1311–19
52. Gugino BK, Idowu OJ, Schindelbeck RR, van Es HM, Wolfe DW, et al. 2009. *Cornell Soil Health Assessment Training Manual.* Geneva, NY: Cornell University. 2nd ed.
53. Hadar Y, Papadopoulou KK. 2012. Suppressive composts: microbial ecology links between abiotic environments and healthy plants. *Annu. Rev. Phytopathol.* 50:133–53
54. Hartwig NL, Ammon HU. 2002. Cover crops and living mulches. *Weed Sci.* 50:688–99
55. Hobbs PR, Sayre K, Gupta R. 2008. The role of conservation agriculture in sustainable agriculture. *Philos. Trans. R. Soc. B* 363:543–55
56. Hoitink HAJ, Boehm MJ. 1999. Biocontrol within the context of soil microbial communities: a substrate-dependent phenomenon. *Annu. Rev. Phytopathol.* 37:427–46
57. Hoitink HAJ, Stone AG, Han DY. 1997. Suppression of plant diseases by compost. *Hortic. Sci.* 32:184–87
58. Horst LE, Madden LV, Hoitink HAJ, McMahon RW, Locke J, Krause CR. 2005. Suppression of Botrytis blight of begonia by *Trichoderma hamatum* 382 in peat and compost-amended potting mixes. *Plant Dis.* 89:1195–200
59. Hubbard RK, Strickland RC, Phatak S. 2013. Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the coastal plain of southeastern USA. *Soil Tillage Res.* 126:276–83
60. Idowu OJ, van Es HM, Abawi GS, Wolfe DW, Schindelbeck RR, et al. 2009. Use of an integrative soil health test for evaluation of soil management impacts. *Renew. Agric. Food Syst.* 24:214–22
61. Janvier C, Villeneuve F, Alabouvette A, Edel-Hermann V, Mateille T, Steinberg C. 2007. Soil health through soil disease suppression: which strategy from descriptors to indicators? *Soil Biol. Biochem.* 39:1–23
62. Jat RA, Sahrawat KL, Kassam AH, Friedrich T. 2013. Conservation agriculture for sustainable and resilient agriculture: global status, prospects and challenges. In *Conservation Agriculture: Global Prospects and Challenges*, ed. RA Jat, KL Sahrawat, AH Kassam, pp. 1–25. Oxfordshire, UK: CABI

63. Jemai I, Aissa NB, Ben-Guirat S, Ben-Hammouda M, Gallali T. 2013. Impact of three and seven years of no-tillage on the soil water storage, in the plant zone, under a dry subhumid Tunisian climate. *Soil Tillage Res.* 126:26–33
64. Ji P, Kone D, Yin JF, Jackson KL, Csinos AS. 2012. Soil amendments with *Brassica* cover crops for management of Phytophthora blight on squash. *Pest Manag. Sci.* 68:639–44
65. Kahlon MS, Lal R, Varughese MA. 2013. Twenty-two years of tillage and mulch impact on physical characteristics. *Soil Tillage Res.* 125:151–58
66. Karlen DL, Andrews SS, Wienhold BJ, Zobeck TM. 2008. Soil quality assessments: past, present and future. *J. Integr. Biosci.* 6:3–14
67. Karlen DL, Hurley EG, Andrews SS, Cambardella CA, Meek DW, et al. 2006. Crop rotation effects on soil quality at three northern corn/soybean belt locations. *Agron. J.* 98:484–95
68. Karlen DL, Mausbach MJ, Doran JW, Cline RG, Harris RF, Schuman GE. 1997. Soil quality: a concept, definition, and framework for evaluation. *Soil Sci. Soc. Am. J.* 61:4–10
69. Karlen DL, Wienhold BJ, Kang S, Zobeck TM, Andrews SS. 2011. Indices for soil management decisions. In *Soil Management: Building a Stable Base for Agriculture*, ed. JL Hatfield, TJ Sauer, pp. 39–51. Madison, WI: Am. Soc. Agron. Soil Sci. Soc. Am.
70. Kassam AH, Friedrich T, Shaxson F, Pretty J. 2009. The spread of conservation agriculture: justification, sustainability and uptake. *Int. J. Agric. Sustain.* 7:292–320
71. Kibblewhite MG, Ritz K, Swift MJ. 2008. Soil health in agricultural systems. *Philos. Trans. R. Soc. B* 363:685–701
72. Kirkegaard JA, Sarwar M. 1998. Biofumigation potential of brassicas. I. Variation in glucosinolate profiles of diverse field-grown brassicas. *Plant Soil* 201:71–89
73. Kremen C, Miles C. 2012. Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* 17:40
74. Krupinsky JM, Bailey KL, McMullen MM, Gossen BD, Turkington TK. 2002. Managing plant disease risk in diversified cropping systems. *Agron. J.* 94:198–209
75. Ladygina N, Hedlund K. 2010. Plant species influence microbial diversity and carbon allocation in the rhizosphere. *Soil Biol. Biochem.* 42:162–68
76. Larkin RP. 2003. Characterization of soil microbial communities under different potato cropping systems by microbial population dynamics, substrate utilization, and fatty acid profiles. *Soil Biol. Biochem.* 35:1451–66
77. Larkin RP. 2008. Relative effects of biological amendments and crop rotations on soil microbial communities and soilborne diseases of potato. *Soil Biol. Biochem.* 40:1341–51
78. Larkin RP. 2013. Green manures and plant disease management. *CAB Rev.* 8(037):1–10
79. Larkin RP, Griffin TS. 2007. Control of soilborne diseases of potato using *Brassica* green manures. *Crop Prot.* 26:1067–77
80. Larkin RP, Griffin TS, Honeycutt CW. 2010. Rotation and cover crop effects on soilborne potato diseases, tuber yield, and soil microbial communities. *Plant Dis.* 94:1491–502
81. Larkin RP, Halloran JM. 2014. Management effects of disease-suppressive rotation crops on potato yield and soilborne disease and their economic implications in potato production. *Am. J. Potato Res.* 91:429–39
82. Larkin RP, Honeycutt CW. 2006. Effects of different 3-year cropping systems on soil microbial communities and *Rhizoctonia* diseases of potato. *Phytopathology* 96:68–79
83. Larkin RP, Honeycutt CW, Griffin TS, Olanya OM, Halloran JM, He Z. 2011. Effects of different potato cropping system approaches and water management on soilborne diseases and soil microbial communities. *Phytopathology* 101:58–67
84. Larkin RP, Honeycutt CW, Olanya OM. 2011. Management of Verticillium wilt of potato with disease-suppressive green manures and as affected by previous cropping history. *Plant Dis.* 95:568–76
85. Larkin RP, Honeycutt CW, Olanya OM, Halloran JM, He Z. 2012. Impacts of crop rotation and irrigation on soilborne diseases and soil microbial communities. In *Sustainable Potato Production: Global Case Studies*, ed. Z He, RP Larkin, CW Honeycutt, pp. 23–41. Amsterdam: Springer
86. Larkin RP, Tavantzis S. 2013. Use of biocontrol organisms and compost amendments for improved control of soilborne diseases and increased potato production. *Am. J. Potato Res.* 90:261–70

87. Lazarovits G. 2001. Management of soil-borne plant pathogens with organic amendments: a disease control strategy salvaged from the past. *Can. J. Plant Pathol.* 23:1–7
88. Lazarovits G, Subbarao K. 2010. Challenges in controlling Verticillium wilt by the use of nonchemical methods. In *Recent Developments in Management of Plant Diseases*, ed. U Gisi, I Chet, L Gullino, pp. 247–64. Dordrecht, Neth.: Springer
89. Leibig MA, Miller ME, Varvel GE, Doran JW, Hanson JD. 2004. AEPAT: a computer program to assess agronomic and environmental performance of management practices in long-term agroecosystem experiments. *Agron. J.* 96:109–15
90. Li YX, Tullberg JN, Freebairn DM, McLaughlin NB, Li HW. 2008. Effects of tillage and traffic on crop production in dryland farming systems: I. Evaluation of PERFECT soil-crop simulation model. *Soil Tillage Res.* 100:15–24
91. Litterick AM, Harrier L, Wallace P, Watson CA, Wood M. 2004. The role of uncomposted materials, composts, manures, and compost extracts in reducing pest and disease incidence and severity in sustainable temperate agricultural and horticultural crop production: a review. *Crit. Rev. Plant Sci.* 23:453–79
92. Little SA, Hocking PJ, Greene RSB. 2004. A preliminary study of the role of cover crops in improving soil fertility and yield for potato production. *Commun. Soil Sci. Plant Anal.* 35:471–94
93. Liu B, Tu C, Hu S, Ristaino JB, Gumpertz M. 2007. Effect of organic, sustainable, and conventional management strategies in grower fields on physical, chemical, and biological factors and the incidence of southern blight. *Appl. Soil Ecol.* 37:202–14
94. Lupawayi NZ, Rice WA, Clayton GW. 1998. Soil microbial diversity and community structure under wheat as influenced by tillage and crop rotation. *Soil Biol. Biochem.* 30:1733–41
95. Magdoff F. 2001. Concepts, components, and strategies of soil health in agroecosystems. *J. Nematol.* 33:169–72
96. Magdoff F, van Es H. 2009. *Building Soils for Better Crops.* Waldorf, MD: Sustain. Agric. Res. Educ. 3rd ed.
97. Martinez-Salgado M, Gutier-Romero V, Jannsens M, Ortega-Blu R. 2010. Biological soil quality indicators: a review. In *Current Research Technology and Education Topics in Applied Microbiology and Microbial Biotechnology*, ed. A Mendez-Vilas, pp. 319–28. Badojoz, Spain: Formatex
98. Matthiessen JN, Kirkegaard JA. 2006. Biofumigation and enhanced biodegradation: opportunity and challenge in soilborne pest and disease management. *Crit. Rev. Plant Sci.* 25:235–65
99. Mazzola M. 2004. Assessment and management of soil microbial community structure for disease suppression. *Annu. Rev. Phytopathol.* 42:35–59
100. Mazzola M, Granatstein DM, Elfving DC, Mullinix K. 2001. Suppression of specific apple root pathogens by *Brassica napus* seed meal amendment regardless of glucosinolate content. *Phytopathology* 91:673–79
101. McGuire AM. 2003. Mustard green manures replace fumigant and improve infiltration in potato cropping system. *Crop Manag.* doi:10.1094/CM-2003-0822-01-RS
102. Mojtahedi H, Santo GS, Ingham RE. 1993. Suppression of *Meloidogyne chitwoodi* with sudangrass cultivars as green manure. *J. Nematol.* 25:303–11
103. Mojtahedi H, Santo GS, Wilson JH. 1993. Managing *Meloidogyne chitwoodii* on potato with rapeseed as green manure. *Plant Dis.* 77:42–46
104. Muelchen AM, Rand RA, Parke JL. 1990. Evaluation of crucifer green manures for controlling Aphanomyces root rot of peas. *Plant Dis.* 74:651–54
105. Njira KOW, Nabwami J. 2013. Soil management practices that improve soil health: elucidating their implications on biological indicators. *J. Anim. Plant Sci.* 18:2750–60
106. Noble R. 2011. Risks and benefits of soil amendment with composts in relation to plant pathogens. *Aust. Plant Pathol.* 40:157–67
107. Noble R, Coventry E. 2005. Suppression of soil-borne plant diseases with composts: a review. *Biocontrol Sci. Technol.* 15:3–20
108. Ochiai N, Crowe FJ, Dick RP, Powelson ML. 2007. Effects of green manure type and amendment rate on Verticillium wilt severity and yield of russet Burbank potato. *Plant Dis.* 91:400–6
109. O'Donnell AG, Seasman M, MacRae A, Waite I, Davies JT. 2001. Plants and fertilisers as drivers of change in microbial community structure and function in soils. *Plant Soil* 232:135–45

110. Page K, Dang Y, Dalal R. 2013. Impacts of conservation tillage on soil quality, including soil-borne diseases, with a focus on semi-arid grain cropping systems. *Aust. Plant Pathol.* 42:363–77

111. Pankhurst CE, Doube BM, Gupta VVSR. 1997. *Biological Indicators of Soil Health*. Wallingford, UK: CABI

112. Papendick RI, Parr JF. 1992. Soil quality: the key to a sustainable agriculture. *Am. J. Altern. Agric.* 7:2–3

113. Peacock AD, Mullen MD, Ringelberg DB, Tyler DD, Hedrick DB, et al. 2001. Soil microbial community responses to dairy manure or ammonium nitrate applications. *Soil Biol. Biochem.* 33:1011–19

114. Perez-Piqueres A, Edel-Hermann V, Alabouvette V, Steinberg C. 2006. Response of soil microbial communities to compost amendments. *Soil Biol. Biochem.* 38:460–70

115. Peters RD, Sturz AV, Carter MR, Sanderson JB. 2003. Developing disease-suppressive soils through crop rotation and tillage management practices. *Soil Tillage Res.* 72:181–92

116. Peters RD, Sturz AV, Carter MR, Sanderson JB. 2004. Influence of crop rotation and conservation tillage practices on the severity of soil-borne potato diseases in temperate humid agriculture. *Can. J. Soil Sci.* 84:397–402

117. Pugliese M, Liu B, Gullino ML, Garabaldi A. 2011. Microbial enrichment of compost with biological control agents to enhance suppressiveness to four soil-borne diseases in greenhouse. *J. Plant Dis. Prot.* 118:45–50

118. Ratnadass A, Fernandes P, Avelino J, Habib R. 2012. Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. *Agron. Sustain. Dev.* 32:273–303

119. Reilly K, Cullen E, Lola-Luz T, Stone D, Valverde J, et al. 2013. Effect of organic, conventional and mixed cultivation practices on soil microbial community structure and nematode abundance in a cultivated onion crop. *J. Sci. Food Agric.* 93:3700–9

120. Ros M, Klammer S, Knapp B, Aichberger K, Insam H. 2006. Long-term effects of compost amendment of soil on functional and structural diversity and microbial activity. *Soil Use Manag.* 22:209–18

121. Ros M, Pascual JA, Garcia C, Hernandez MT, Insam H. 2006. Hydrolase activities, microbial biomass and bacterial community in a soil after long-term amendment with different composts. *Soil Biol. Biochem.* 38:3443–52

122. Ryan PR, Dessaux Y, Thomashow LS, Weller DM. 2009. Rhizosphere engineering and management for sustainable agriculture. *Plant Soil* 321:363–83

123. Saison C, Degrange V, Oliver R, Millard P, Commeaux C, et al. 2006. Alteration and resilience of the soil microbial community following compost amendment: effects of compost level and compost-borne microbial community. *Environ. Microbiol.* 8:247–57

124. Sarrantonio M, Gallandt E. 2003. The role of cover crops in North American cropping systems. *J. Crop Prod.* 8:53–74

125. Sarwar M, Kirkegaard JA, Wong PTW, Desmarchelier JM. 1998. Biofumigation potential of brassicas. III. In vitro toxicity of isothiocyanates to soil-borne fungal pathogens. *Plant Soil* 210:103–12

126. Schuerell SJ, Mahaffee WF. 2002. Compost tea: principles and prospects for disease control. *Compost Sci. Util.* 10:313–38

127. Shetty KG, Subbarao KV, Huisman OC, Hubbard JC. 2000. Mechanism of broccoli-mediated Verticillium wilt reduction in cauliflower. *Phytopathology* 90:305–10

128. Snapp SS, Swinton SM, Labarta R, Mutch D, Black JR, et al. 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. *Agron. J.* 97:322–32

129. So HB, Grabski HB, Desborough P. 2009. The impact of 14 years of conventional tillage and no-till cultivation on the physical properties and crop yields of a loam soil at Grafton NSW, Australia. *Soil Tillage Res.* 104:180–84

130. St. Martin CCG, Brathwaite RAI. 2012. Compost and compost teas: principles and prospects as substrates and soil-borne disease management strategies in soil-less vegetable production. *Biol. Agric. Hortic.* 28:1–33

131. Stark C, Condron LM, Stewart A, Di HJ, O'Callaghan M. 2007. Influence of organic and mineral amendments on microbial soil properties and processes. *Appl. Soil Ecol.* 35:79–93

132. Stone AG, Vallad GE, Cooperbrand LR, Rotenberg D, Darby HM, et al. 2003. Effect of organic amendments on soilborne and foliar diseases in field-grown snap bean and cucumber. *Plant Dis.* 87:1037–42

133. Stubbs TL, Kennedy AC, Schillinger WF. 2004. Soil ecosystem changes during the transition to no-till cropping. *J. Crop Improv.* 11:105–35
134. Sturz AV, Christie BR. 2003. Beneficial microbial allelopathies in the root zone: the management of soil quality and plant disease with rhizobacteria. *Soil Tillage Res.* 72:107–23
135. Subbarao KV, Hubbard JC, Koike ST. 1999. Evaluation of broccoli residue incorporation into field soil for Verticillium wilt control in cauliflower. *Plant Dis.* 83:124–29
136. Subbarao KV, Kabir Z, Martin FN, Koike ST. 2007. Management of soilborne diseases in strawberry using vegetable rotations. *Plant Dis.* 91:964–72
137. Sugiyama A, Vivanco JM, Jayanty SS, Manter DK. 2010. Pyrosequencing assessment of soil microbial communities in organic and conventional potato farms. *Plant Dis.* 94:1329–35
138. Teasdale JR, Abdul-Baki AA. 1998. Comparison of mixtures versus monocultures of cover crops for fresh-market tomato production with and without herbicide. *Hortic. Sci.* 33:1163–66
139. Teasdale JR, Abdul-Baki AA. 2007. *Sustainable production of fresh-market tomatoes and other vegetables with cover crop mulches.* USDA-ARS Farmer's Bull. US Dep. Agric. Agric Res. Serv., Washington DC
140. Termorshuizen AJ, Moolenaar SW, Veeken AHM, Blok WJ. 2004. The value of compost. *Rev. Environ. Sci. Biotechnol.* 3:343–47
141. Termorshuizen AJ, van Rijn E, van der Gaag DJ, Alabouvette C, Chen Y, et al. 2006. Suppressiveness of 18 composts against 7 pathosystems: variability in pathogen response. *Soil Biol. Biochem.* 38:2461–77
142. Thorup-Kristensen K, Magid J, Jensen LS. 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. *Adv. Agron.* 79:227–302
143. Tiquia SM, Lloyd J, Herms DA, Hoitink HAJ, Michel FC Jr. 2002. Effects of mulching and fertilization on soil nutrients, microbial activity and rhizosphere bacterial community structure determined by analysis of TRFLPs of PCR-amplified 16S rRNA genes. *Appl. Soil Ecol.* 21:31–48
144. USDA-NRCS. 2001. *Soil Quality Test Kit Guide*. Washington, DC: USDA-NRCS. **http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050956.pdf**
145. USDA-NRCS. 2003. *Interpreting the Soil Conditioning Index; A Tool For Measuring Soil Organic Matter Trends*. Washington, DC: USDA-NRCS. **http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053273.pdf**
146. Van Bruggen AHC, Semenov AM. 2000. In search of biological indicators for soil health and disease suppression. *Appl. Soil Ecol.* 15:13–24
147. Van Bruggen AHC, Termorshuizen AJ. 2003. Integrated approaches to root disease management in organic farming systems. *Aust. Plant Pathol.* 32:141–56
148. Van Elsas JD, Costa R. 2007. Molecular assessment of soil microbial communities with potential for plant disease suppression. In *Biotechnology and Plant Disease Management*, ed. ZK Punja, SH Boer, H Sanfacon, pp. 498–517. King's Lynn, UK: CABI
149. Van Elsas JD, Postma J. 2007. Suppression of soil-borne phytopathogens by compost. In *Compost Science and Technology*, ed. LF Diaz, M de Bertoldi, W Bidlingmaier, E Stentiford, pp. 201–4. Amsterdam: Elsevier
150. Vepsalainen M, Erkomaa K, Kukkonen S, Vestberg M, Wallenius K, Niemi RM. 2004. The impact of crop plant cultivation and peat amendment on soil microbial activity and structure. *Plant Soil* 264:273
151. Villamil MB, Bolero GA, Darmody RG, Simmons FW, Bullock DG. 2006. No-till corn/soybean systems include winter cover crops: effects on soil properties. *Soil Sci. Soc. Am. J.* 70:1936–44
152. Welbaum GE, Sturz AV, Dong Z, Nowak J. 2004. Managing soil microorganisms to improve productivity of agro-ecosystems. *Crit. Rev. Plant Sci.* 23:175–93
153. Wiggins BE, Kinkel LL. 2005. Green manures and crop sequences influence alfalfa root rot and pathogen inhibitory activity among soil-borne streptomycetes. *Plant Soil* 268:271–83
154. Wiggins BE, Kinkel LL. 2005. Green manures and crop sequences influence potato diseases and pathogen inhibitory activity of indigenous streptomycetes. *Phytopathology* 95:178–85
155. Willekens W, Vandecasteele B, Buchan D, De Neve S. 2014. Soil quality is positively affected by reduced tillage and compost in an intensive vegetable cropping system. *Appl. Soil Ecol.* 82:61–71
156. Wortman SE, Francis CA, Bernard ML, Drijber RA, Lindquist JL. 2012. Optimizing cover crop benefits with diverse mixtures and an alternative termination method. *Agron. J.* 104:1425–35

157. Yogev A, Raviv M, Hadar Y, Cohen R, Katan J. 2006. Plant waste–based composts suppressive to diseases caused by pathogenic *Fusarium oxysporum*. *Eur. J. Plant Pathol.* 116:267–78
158. Yogev A, Raviv M, Hadar Y, Cohen R, Wolf S, et al. 2010. Induced resistance as a putative component of compost suppressiveness. *Biol. Control* 54:46–51
159. Zhang GS, Chan KY, Li GD, Huang GB. 2008. Effect of straw and plastic film management under contrasting tillage practices on the physical properties of an erodible loess soil. *Soil Tillage Res.* 98:113–19
160. Zhang W, Dick WA, Hoitink HAJ. 1996. Compost-induced systemic acquired resistance in cucumber to Pythium root rot and anthracnose. *Phytopathology* 86:1066–70