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Integrated Soil Health Management for Plant Health and One Health: Lessons From Histories of Soil-borne Disease Management in California Strawberries and Arthropod Pest Management

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Many soil health assessment methods are being developed. However, they often lack assessment of soil-borne diseases. To better address management strategies for soil-borne disease and overall soil and plant health, the concept of Integrated Soil Health Management (ISHM) is explored. Applying the concept of Integrated Pest Management and an agroecological transdisciplinary approach, ISHM offers a framework under which a structure for developing and implementing biointensive soil health management strategies for a particular agroecosystem is defined. As a case study, a history of soil-borne disease management in California strawberries is reviewed and contrasted with a history of arthropod pest management to illustrate challenges associated with soil-borne disease management and the future directions of soil health research and soil-borne disease management. ISHM system consists of comprehensive soil health diagnostics, farmers' location-specific knowledge and adaptability, a suite of soil health management practices, and decision support tools. As we better understand plant-soil-microorganism interactions, including the mechanisms of soil suppressiveness, a range of diagnostic methodologies and indicators and their action thresholds may be developed. These knowledge-intensive and location-specific management systems require transdisciplinary approaches and social learning to be co-developed with stakeholders. The ISHM framework supports research into the broader implications of soil health such as the "One health" concept, which connects soil health to the health of plants, animals, humans, and ecosystems and research on microbiome and nutrient cycling that may better explain these interdependencies.

Keywords: soil health assessment, soil-borne disease management, integrated pest management, non-fumigant alternatives, soil suppressiveness, agroecology, soil-plant-microbe interactions, organic farming

INTRODUCTION

The concept of soil health recognizes soil as a living ecosystem with one of the greatest diversities on the earth. These organisms interact with each other, plants, and the complex abiotic environment (Wall et al., 2012; Orgiazzi et al., 2016; USDA-NRCS, 2021). Healthy soil can provide multiple ecosystem services such as food and fiber production, water quality and supply, pest and disease suppression, atmospheric composition, and climate regulation, and biodiversity conservation (Kibblewhite et al., 2008; Lehman et al., 2015; Bünemann et al., 2018).

Many laboratory-based soil health assessment methods and indicators have also been proposed and developed (Andrews et al., 2004; Moebius-Clune et al., 2016; Stott, 2019; Norris et al., 2020). These typically analyze chemical (pH, electrical conductivity, available nutrients contents, soil organic carbon, labile carbon, potentially mineralizable nitrogen, protein nitrogen, etc.), physical (water-stable aggregates, slake test, bulk density, etc.), and biological (various enzyme activities, respiration, microbial biomass, phospholipid fatty acid, etc.) properties. Yet, they often lack the assessment of soil-borne diseases. According to the Web of Science database, 3,120 papers were published on the topic "soil health" between 2000 and 2020. Among these, only 4.7% included topics of "soil-borne (or soilborne) pathogen," "soil-borne (or soilborne) disease," "suppressive," "suppressiveness," "suppressive soil," or "plant health."

Soil-borne diseases by fungal or bacterial pathogens and nematodes cause severe damage in agricultural production worldwide (Strange and Scott, 2005) and soil health assessment without assessing soil-borne diseases can be misleading. Healthy soil, defined using common soil health indicators, can produce unhealthy low-yield crops due to soil-borne diseases (Lazicki and Geisseler, 2021). To ensure healthy crop production, the inclusion of a soil-borne disease management perspective in soil health assessments is critical (van Bruggen and Semenov, 2000; Janvier et al., 2007; Larkin, 2015; Hodson and Lewis, 2016; van Bruggen and Finckh, 2016). However, many pathogens are plant-specific and effective management requires development of crop-, agroecosystem-, or location-specific soil health assessment and management strategies (Miner et al., 2020). While fumigants are widely used to control soil-borne diseases, the negative environmental and human health impacts are spurring development of non-fumigant alternatives for cropping systems worldwide (Labarada, 2008; Porter et al., 2010; López-Aranda et al., 2016; Daugovish et al., 2021).

Agroecology is the integrative study of the food system, encompassing ecological, economic, and social dimensions (Francis et al., 2003; Center for Agroecology, 2021). To create ecologically sound, economically viable, and socially just food systems, agroecology embraces science, practices, and social movements (Gliessman, 2018; Wezel et al., 2020) using transdisciplinary participatory approaches (Méndez et al., 2013). Transdisciplinary approaches value different types of knowledge systems including western scientific, indigenous, and farmer-generated practical knowledge on specific locations (Mendez et al., 2016:5) and co-production of knowledge by stakeholders and experts to realize more just food systems (Anderson et al., 2021).

Though first proposed to connect health between animals, humans, and the environment (Karesh et al., 2012; Wolf, 2015), a novel concept of "One Health" connects soil, plant, animal, human, and ecosystem health through the cycling of diverse microbiomes (Keith et al., 2016; van Bruggen et al., 2019; Altier and Abreo, 2020).

The concept of Integrated Soil Health Management (ISHM) can address management strategies for soil-borne disease and overall soil health. Melakeberhan (2010) used the term "agro-biologically, economically, and ecologically ISHM" that ties nematology and cross-disciplinary gaps for developing agrobiologically sustainable soil health management practices. Manter et al. (2018) argued the importance of underlying soil biology for soil conservation and regeneration. They have proposed a 5-step ISHM approach (knowledge, initial assessment, threshold for action, management, and reassessment) based on the adaptive management framework. However, there has been no examination of ISHM in the context of soil-borne disease management.

Applying the concepts of Integrated Pest Management (IPM) (Cook, 2000) and agroecological transdisciplinary and participatory approaches (Mendez et al., 2016; Anderson et al., 2021), we argue that ISHM and its four components, including farmer's location-specific knowledge and adaptability (**Figure 1**), offer a framework for developing and implementing a comprehensive site-specific biointensive soil health and soil-borne disease management strategy.

We begin with a brief case study review of the history of soil-borne disease management in California strawberries. Then, we contrast this with a history of arthropod pest management to illustrate the unique challenges associated with soil-borne disease management and future directions of soil health research. Lastly, we discuss the ISHM system and its relationship with One Health.

CASE STUDY: HISTORY OF SOIL-BORNE DISEASE MANAGEMENT IN CALIFORNIA STRAWBERRY

California produces ∼90% of strawberries in the US. In 2019, 1.0 million tons of fruits, valued at 2.2 billion dollars, were produced from 14,326 hectares of strawberry fields in the state (California Department of Food and Agriculture, 2021). The large-scale monocultural production of this lucrative crop has evolved dependent on the core technology of pre-plant soil fumigation (Guthman, 2019). Since the 1960s, chemical fumigation using methyl bromide mixed with chloropicrin, was the primary tool to control soil-borne diseases and weeds in California strawberries (Wilhelm et al., 1961; Holmes et al., 2020). Later, methyl bromide was identified as a significant stratospheric ozone-depleting compound by the Montreal Protocol (Ozone Secretariat Team, UNEP, 2020) and was phased out for strawberry production in 2016.

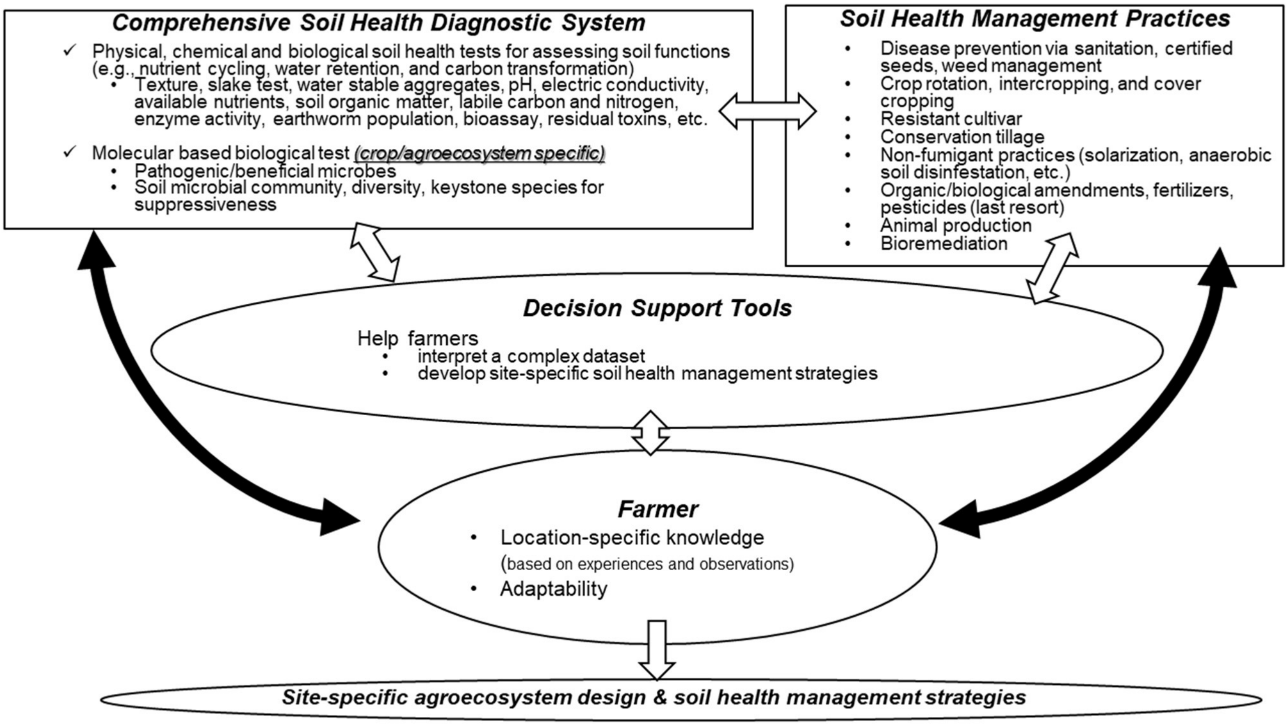

FIGURE 1 | The structure of the integrated soil health management (ISHM) system consists of farmers location-specific knowledge and adaptability, comprehensive soil health diagnostics, a suite of soil health management practices, and decision support tools (optional). Studies on relationships between varying soil health management practices and disease/pest suppression, nutrient uptake, and plant growth will help improve the diagnostic methods and develop actionable thresholds in diagnostics. Rectangular shapes and oval shapes indicate hardware/physical elements and software/intellectual elements of the system, respectively. Roles of decision support tools can be substituted or enhanced by agricultural professionals, consultants, and/or farmer-to-farmer networks (social learning).

In response, growers increased the use of alternative fumigants, such as chloropicrin and 1,3-dichloropropene, but they lacked effectiveness over the methyl bromide/chloropicrin mixture (Holmes et al., 2020).

The use of fumigants is highly regulated due to their toxicity and high application rates (California Department of Pesticide Regulation (CDPR), 2020) and negative impacts of fumigants on soil health (Dangi et al., 2017) and human health (Gemmill et al., 2013) have been reported. CDPR has documented hundreds of acute illnesses due to accidental exposure for both agricultural workers and populations adjacent to fumigated fields since 2003 (California Department of Pesticide Regulation (CDPR), 2013).

The California Strawberry Commission (CSC) initiated the "Farming without Fumigants" initiative in 2007 (Shennan et al., 2008). Non-fumigant approaches such as anaerobic soil disinfestation (ASD) (Shennan et al., 2018; Muramoto et al., 2020; Rosskopf et al., 2020), crop rotation with disease suppressive crops (Subbarao et al., 2007), use of host plant resistance (Guthman, 2019; Holmes et al., 2020), integration of these techniques (Shennan et al., 2020; Zavatta et al., 2021), substrate production (Thomas et al., 2014), and steaming with a mobile machine (Fennimore and Goodhue, 2016; Xu et al., 2017) have been examined. Overall, however, the adoption of non-fumigant approaches at conventional strawberry fields is yet limited.

Organic strawberry production may have the highest levels of adoption of fumigant alternatives. The acreage of organic strawberries has been gradually increasing since the 1980s (Gliessman and Muramoto, 2010) reaching 1,982 hectares, 13% of total strawberry acreage in California in 2021(California Department of Food and Agriculture (CDFA), 2021). Although typical organic yield is about 60% of the conventional counterpart (Bolda et al., 2016, 2019) disease suppressive strategies such as crop rotation with broccoli, host plant resistance, and ASD, alone or in combination, have supported the growth in organic strawberry acreage.

The recent development of rapid and accurate molecular diagnostic techniques is gradually making "scouting" of soil-borne pathogens a reality. For major lethal soil-borne pathogens in California strawberries, molecular approaches for *Verticillium dahliae* in plants (Dan et al., 2001) and soil (Bilodeau et al., 2012), *Fusarium oxysporum* f. sp. *fragariae* in plants (Burkhardt et al., 2019), and *Macrophomina phaseolina* in plant and soil (Burkhardt et al., 2018) have been established.

Recently, Lazcano et al. (2021) found that the rhizosphere microbiome plays a role in the resistance to soil-borne pathogens. Strong genotype by environment interactions observed suggests that soil health may also play a role in establishing beneficial plant-microbial interactions.

LESSONS FROM A HISTORY OF ARTHROPOD PEST MANAGEMENT

A history of arthropod pest management may offer some lessons for the future of soil-borne disease and soil health management. Between the 1940s and 1960s, broad-spectrum, highly toxic insecticides were widely used in arthropod pest management (Carson, 1962) following the motto, "the only good bug is a dead bug." (Warner, 2007: 141). In the late 1960s to early 1970s, due to "(insecticide) resistance, resurgence of primary pests, upsurges of secondary pests, and overall environmental contamination (Kogan, 1998: 245)," the concept of IPM was developed (Council on Environmental Quality, 1972) recognizing "there are good bugs (beneficial) as well as bad bugs (pests)." In the IPM system, transitioning to biointensive (National Research Council, 1996) or prevention-based IPM (Jacobsen, 1997) as well as redesigning of cropping systems (Hill, 1998) aimed at fostering plant and insect community and population dynamics that self-regulated pest presence and damage. More recently, the extinction of some arthropod species (Kiritani, 2000) and the decline of honeybee colonies (vanEngelsdorp et al., 2009; Ratnieks and Carreck, 2010) has raised awareness of the benefits of arthropod biodiversity and pollinators leading to the realization that "without bugs, we might all be dead." (Worrall, 2017). In biological control, social learning among farmers, rather than top-down extension, became more critical to implementing and disseminating knowledge-intensive approaches (Fakih et al., 2003; Warner, 2007).

In contrast, for soil-borne disease management in California strawberries, relatively broad-spectrum fumigants are still in use, and the IPM approach (Katan, 2014) is just beginning. The slow transition is partially due to the unique challenges associated with soil-borne disease management. For example, compared to arthropod pests, soil-borne pathogens are microscopic and require specific processes for identification that are still in the nascent stages of development and utilization. Identification and scouting are typically the first step of the IPM approach (Kogan, 1998). Unlike arthropod pest management, there are effectively no post-symptomatic treatments for soil-borne diseases. Instead, currently available treatments are all pre-plant treatments and the availability of non-fumigant alternatives is limited. The complexity and heterogeneity of soil ecosystems, the diversity of soil organisms, and the lack of basic understanding of plant-soil-microbiome interactions have limited a quicker transition to non-fumigant-based IPM approaches (Bardgett and van der Putten, 2014; Mazzola and Freilich, 2017; Thomashow et al., 2019). Further, risks due to the substantial financial investment required in wholesale marketing of high-value horticultural crops hinder the adoption of less proven non-fumigant soil-borne disease management approaches (Chellemi and Porter, 2001; Guthman, 2020).

However, advances in molecular techniques, computational power, and statistics over the last 20 years have rapidly increased our knowledge of soil-plant microbiomes and their functions. Similar to the "discovery" of "good bugs" in arthropod management, we are now understanding the importance of beneficial (Mendes et al., 2013), commensal (Teixeira et al., 2019), and core microbes (Banerjee et al., 2018; Toju et al., 2018). Mechanisms of suppressive soil conditions are a highly active area of research (Schlatter et al., 2017; Duran et al., 2021; Samaddar et al., 2021). To understand plant-soil microbe interactions as a part of the plant defense system, concepts of soil (Lapsansky et al., 2016) and plant memory (Kong et al., 2019), and plant (Han, 2019; Teixeira et al., 2019) and rhizosphere immunity (Wei et al., 2020) have been proposed. As we better understand the soil biome's life cycles, structures, and functions and their relationships with plant health, indicators and thresholds of beneficial soil microbes and soil microbial communities may be developed for specific crops or agroecosystems (Blundell et al., 2020).

European Union (EU) has one of the world's most stringent fumigant regulations and is leading in the development of the IPM approach for soil-borne disease management. They developed "Soil Health Strategy Actions" (The Agricultural European Innovation Partnership (EIP-AGRI) Focus Group, 2015) consisting of prevention (certified seed, sanitation, and weed control), monitoring (soil sampling, bioassay), crop rotation (frequency, sequence, green manure, resistant varieties), and additional measures (grafting, biological control agents, biofumigation, ASD, organic amendments, solarization, etc.).

INTEGRATED SOIL HEALTH MANAGEMENT SYSTEM, AGROECOSYSTEM HEALTH AND ONE HEALTH

We propose that ISHM, as a science and practice, with social movement advocacy for non-toxic agriculture, may evolve similarly to IPM for arthropod pest management; toward biointensive management, increasing prioritization of the role of beneficial organisms, and redesigning cropping systems and cultural practices that prevent soil-borne diseases and induce sustained soil and plant health. At the same time, ISHM is more than a simple application of integrated "soil-borne disease" management, it also encompasses soil's many other functions by improving overall soil health using transdicisplinary participatory approaches.

The proposed ISHM system in this context consists of 4 components (**Figure 1**). First, a comprehensive soil health diagnostic system created by integrating molecular approaches for quantifying pathogens, beneficials, and soil microbial indicators and their thresholds, developed with an existing soil health measurement system measuring physical, chemical, and biological soil properties for assessing soils' other functions such as nutrient cycling, water retention, and carbon transformation (Andrews et al., 2004; Moebius-Clune et al., 2016; Norris et al., 2020). The diagnostic system will determine the disease potential both from the pathogens density in the soil relative to their economic thresholds and the disease suppressiveness of the soil toward target pathogens evaluated by its biotic and abiotic properties (Postma et al., 2014; Schlatter et al., 2017). To ensure healthy crop production, monitoring of plant health indicators (e.g., nutrients and chlorophyll contents, mycorrhiza and endophyte colonization rates, pathogen infection rates,

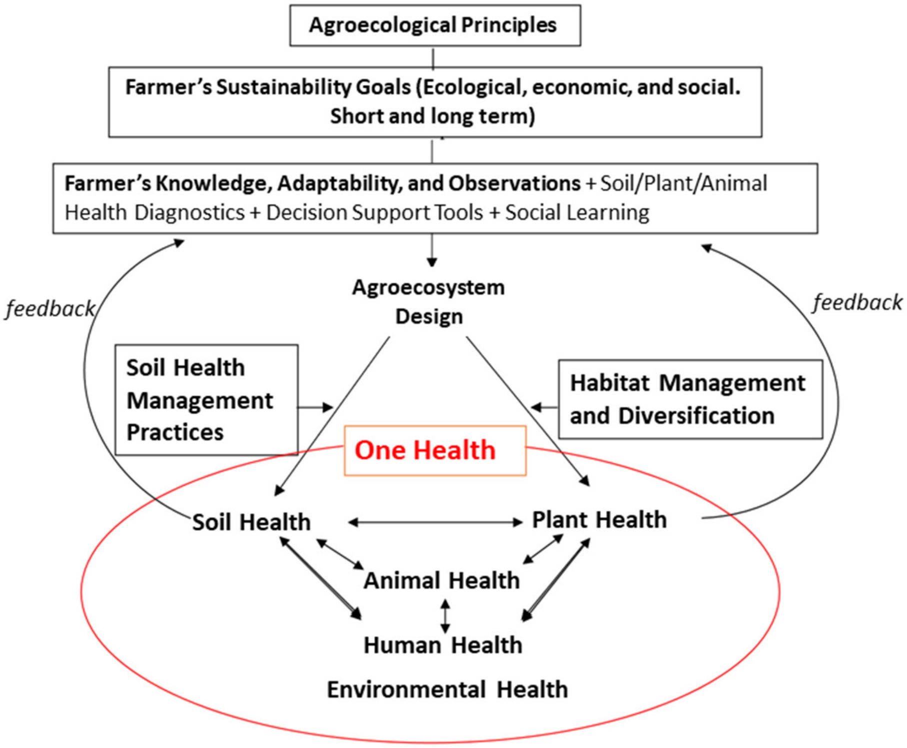

FIGURE 2 | Agroecosystem management and the concept of One Health. Integrated soil health management is embedded in this system. Agroecological principles include recycling, input reduction, soil health, animal health, biodiversity, synergy, economic diversification, co-creation of knowledge, social values and diets, fairness, connectivity, land and natural resource governance, and participation, according to a recent review by Wenzel et al. (2020). Habitat management and diversification have spatial (farm and landscape levels) and temporal dimensions. Environmental health includes the health of air and water. See **Figure 1** for soil health diagnostics, decision support tools, and soil health management practices. Modified from Altieri and Nicholls (2003).

etc.) will complement the soil health assessment during the cropping season.

EU (Clarkson et al., 2015) and Australia lead molecular plant-pathogen diagnostics services. PREDICTA® by the South Australian Research and Development Institute (Stirling et al., 2016; Government of South Australia, 2021), for example, is a fee-based public service for cereals, potatoes, and research, in which more than 10 pathogens and some beneficial microbes are quantified. The cost of quantifying soil microorganisms may hinder accessibility and affordability among diverse stakeholders. Development of portable, accurate, and easy to operate sequencers (Baldi and La Porta, 2020; Cunha et al., 2020) may allow farmers to determine soil and plant biomes in the field as "point-of-care" and may reduce the costs of diagnostics and empower farmers (Clarkson et al., 2015).

This information will then be integrated with farmers' location-specific knowledge and adaptability. Although often overlooked and underappreciated, farmers' location-specific knowledge gained from day-to-day fieldwork and observations and their adaptability to dynamic agroecosystems and climate change (Stockdale, 2011) is central to ISHM. Integration of scientific data obtained by diagnostics and farmers' experiential location-specific knowledge can be synergistic (Lobry de Bruyn and Andrews, 2016; Šumane et al., 2018). Dialogue between farmers and scientists centers farmers as an active player in examining, fine-tuning, and scaling-out agroecological knowledge and practices (Blundell et al., 2020; Anderson et al., 2021). Such participatory and transdisciplinary approaches mobilize knowledge for social change and engage stakeholders in research (Mendez et al., 2016).

The third component is a suite of soil health management practices (SHMPs) known to improve soil health. As seen in the EU program, various SHMPs including practices for prevention and enhancing disease suppression via general or specific suppressiveness (see **Figure 1**. e.g., applying organic amendments, cover cropping, crop rotation, using host resistance) (Abawi and Widmer, 2000; Raaijmakers et al., 2009; Hiddink et al., 2010; Larkin, 2015; Rosskopf et al., 2020) are integrated to tailor a site-specific soil-borne disease and soil health management strategy. A more intensive approach such as ASD and steaming is applied on an "as-needed" basis, depending on the soil health diagnostic result.

Lastly, decision support tools will assist growers in developing site-specific soil health management strategies based on their goals, knowledge, environmental conditions (e.g., soil type, climate, etc.), available SHMPs, results of soil health diagnostics, and other factors. **Figure 2** illustrates how ISHM is embedded in agroecosystem management and how it relates to the health of soil, plants, animals, humans, and agroecosystems and the concept of One Health.

DISCUSSION

Although ISHM provides a framework, there are many knowledge gaps in the components parts. Primary research needs for developing ISHM include utilizing mechanistic models in plants-soil microbe functions such as soil suppressiveness, plant immunity, nutrient uptake (Liu et al., 2016; Trivedi et al., 2017), better chemical and biological characterization of organic amendments and crop residues, and their relationships with soil-borne disease suppressiveness (Bonanomi et al., 2018; Subbarao et al., 2020), increased efficacy of plant growth-promoting microbes in soil-borne disease suppression and nutrient uptake in field conditions (Rosier et al., 2018; Hestrin et al., 2019), and development of crop cultivars with ability to modify their rhizosphere microbiome for their benefits (Berg et al., 2016; Mendes et al., 2018).

ISHM is characterized as a location-specific and knowledge-intensive approach (Jacobsen, 1997), contrasted with the location-general and chemical-intensive fumigation and industrial farming approach. However, the transition to knowledge-intensive systems can present significant obstacles for farmers. As it worked in biocontrol (Warner, 2007), social learning, as seen in farmer-to-farmer networks, has facilitated the implementation and extension of knowledge-intensive soil health management (De Bruyn et al., 2017; Stockdale et al., 2019; Wick et al., 2019; Skaalsveen et al., 2020). Policies and extension activities that support such a process and the adoption of ISHM will be necessary for the greater engagement in the co-development of ISHM with and among stakeholders.

ISHM is additionally important as impacts of soil health may go beyond plant health. Indeed, our understanding of the direct and indirect effects of soil health on human health through microbiomes (Wall et al., 2015; Stegen et al., 2018; Samaddar et al., 2021) is increasing. The "One Health" concept suggests the interconnectedness of soil, plant, animal, human, and ecosystem health through microbiome cycling (van Bruggen et al., 2019, **Figure 2**). More than 70 years ago, Sir Albert Howard, an early student, and advocate of organic farming (Heckman, 2006), wrote, "The birthright of all living things is health. This law is true for soil, plant, animal, and man: the health of these four is one connected chain. Any weakness or defect in the health of any earlier link in the chain is carried on to the next succeeding links, until it reaches the last, mainly, man." (Howard, 1947). Although our understanding is yet at its infancy, future research on microbiome cycling and nutrient cycling (Altieri and Nicholls, 2003; Datnoff et al., 2007) may hold the key to better understanding the chains connecting healthy soils to plants, animals, humans, and ecosystems.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

JM: conceptualization and draft manuscript preparation. DP, JP, and DW: critically revised it, adding conceptual material and clarity. All authors contributed to the article and approved the submitted version.

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