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Review Paper

Cropping systems in agriculture and their impact on soil health-A review

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ABSTRACT

Soil health is defined as the capacity of soil to function, within ecosystem boundaries, to sustain crop and animal productivities, maintain or enhance environmental sustainability, and improve human health worldwide. In agro-ecosystems, the soil health can change due to anthropogenic activities, such as preferred cropping practices and intensive land-use management, which can further impact soil functions. Previous assessment of soil health in agriculture mostly relates to soil eco-functions that are integrated with non-biological properties such as soil nutrients and soil structures. In recent years, biological properties such as soil microorganisms were considered as an essential composition in soil health as well. However, systematic reviews of soil health and its potential feedback to human society under different cropping practices are still limited. In this review, we discussed 1) the impact of common and novel cropping practices in agro-systems on soil health, 2) the evolution of plant–microbe–soil complex and the biochemical mechanisms under the pressure of agriculture that responsible for soil health, 3) changes in the concept of soil quality and health over recent decades in agro-systems and the key indicators currently used for evaluating soil health, and 4) issues in agroecosystems that affect soil health the most, particularly how various cropping practices have developed over time with human activities in agroecosystem. This knowledge, along with necessary policies, will help to ensure healthy soil—a crucial component for sustainable ecosystem development.

1. Introduction

Soil is an extremely complex ecosystem and a highly valuable resource from an ecocentric and anthropocentric perspective. Soil is undoubtedly one of our most essential and strategic resources, due to its many crucial functions, including: (i) provision of food, fiber, and fuel; (ii) decomposition of organic matter (e.g., dead plant and animal material); (iii) recycling of essential nutrients; (iv) detoxification of organic contaminants; (v) carbon sequestration; (vi) regulation of water quality and supply; (vii) habitat provision for myriad of animals and microorganisms (soil is an important biodiversity reservoir); (viii) source of raw materials (clay, sand, gravel). Unfortunately, soil has been and is currently being rapidly degraded at a global scale due to a range of invasive anthropic activities in intensive agriculture, with concomitant adverse effects on human

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and ecosystem health. This is concerning as soil is a non-renewable resource at a human temporal scale (i.e., soil loss and degradation are not recoverable within a human lifespan).

The definition of soil health under various cropping systems has evolved with the development of agriculture. In the past, researchers and farmers were mostly concerned about soil quality and crop production. Since the 1990s, the concept of soil health assessment has focused on specific soil properties and the soil's ability to maintain a range of ecological functions in its appropriate ecosystem, supporting long-term sustainable cropping systems. Thus, soil health is defined as the ability of a soil to function and provide ecosystem services (Van Es and Karlen, 2019), or the soil's fitness to support crop growth without degrading soil or otherwise harming the environment (Acton and Gregorich, 1995). The terms 'soil health' and 'soil quality' have been used interchangeably, with the emphasis mostly on crop production with some concern for environmental sustainability (Doran et al., 1996). Producers typically prefer 'soil health,' as it portrays soil as a living, dynamic organism that functions holistically rather than an inanimate mixture of sand, silt, and clay. Scientists prefer 'soil quality,' as it describes quantifiable physical, chemical, and biological characteristics of the soil. The 'health' of a soil requires value judgments that cannot be quantified. Later studies further defined the role of soil biological properties in soil health (Ahmad et al., 1999; Pankhurst et al., 1995; Rajasekaran and Warren, 1995), as opposed to 'soil fertility', which is defined as the natural and sustainable ability of a soil to produce plants (Anonymous, 2016) or the capacity of the soil to supply nutrients to a crop (Agegnehu and Amede, 2017). In this context, soil nutrient contents are considered fertility indicators while crop yield is a measurement of soil fertility. Since the start of the millennia, numerous studies have been conducted on soil health, with most targeting soil microbiological characteristics along with soil physicochemical properties. Many soil health indicators among cropping systems have since been discussed and developed, including soil microbial composition and enzyme activities (Ozlu et al., 2019; VeVerka et al., 2019), C:N ratio (Byrnes et al., 2018; Gannett et al., 2019), soil biological properties, including mineralizable (Hurisso et al., 2018; Obrycki et al., 2018) and permanganate oxidizable carbon (Thomas et al., 2019; Van Es and Karlen, 2019), soil physical properties such as water holding capacity, water-stable aggregation, surface and subsurface penetration resistance (Van Es and Karlen, 2019); and soil chemical properties such as alkaline phosphatase activity involved in P cycling (Bhandari et al., 2018) and extractable K, Mg, Fe, Mn, Zn contents (Thomas et al., 2019). The most recent developments on soil health assessments include the Cornell comprehensive assessment of soil health-CASH (Gholoubi et al., 2018; Schindelbeck et al., 2008) and 'Haney soil health test-HSHT' (Chu et al., 2019), which quantify soil health under different cropping systems by focusing on soil biology, such as plant-available nutrients, soil respiration, and bioavailable C and N.

It is essential to design initiatives and implement actions to protect and restore soil health in agriculture. However, the concept of soil health is not easy to define or grasp; consequently, it has been a topic of intense debate and controversy (Sojka and Upchurch, 1999; Sojka et al., 2003). A commonly used definition of 'soil health' or 'soil quality' is "the continued capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain biological productivity, promote the quality of air and water environments, and maintain plant, animal and human health" (Doran and Parkin, 1996; Doran and Zeiss, 2000). However, Pankhurst et al. (1997) suggested using 'soil quality' when referring to the "soil's capacity to meet defined human needs" (e.g., to support a particular crop), and 'soil health' when speaking about the "soil's continued capacity to maintain its functions." Interestingly, 'health' in the context of soil highlights the vital importance of the living component of soils, frequently characterized by overwhelming biodiversity. Here, it must be stated that using 'health' when referring to soils is based on analogy rather than homology, as soil is not a single living organism.

While there are many other definitions of soil health and soil quality in the literature [e.g., "the capacity of soil to perform its functions," "how well is the soil functioning for a specific goal or use" (Karlen et al., 2003); "the capacity of soil to perform its ecosystem processes and services while maintaining ecosystem attributes of ecological relevance" (Garbisu et al., 2011)], most refer to the ability of soil to perform its functions and ecosystem services sustainably. In any case, the terms 'functions' and 'services' have teleological implications, as if soils had a purpose, end, or goal.

One of the most important, well-known limitations of the evaluation of soil health in our current cropping systems is the lack of a healthy control soil that could be used for reference and comparison purposes. This is not surprising because soil is spatially heterogenous (in fact, it is defined more by the heterogeneity of its properties and processes than any average measure) and temporally dynamic. In response to this lack of a healthy reference soil, Karlen et al. (2001) reported that trends over time provide the most suitable way to assess the effects of soil management on soil functional sustainability (i.e., soil health) under different cropping systems. Another problem with the definition of soil health as "the capacity of a given soil to perform its functions" is that often, and specifically depending on the intended soil use, the abovementioned soil functions can be conflicting or incompatible. Therefore, this paper reviews the impact of conventional cropping systems on soil health, microbiological indicators, and other indicators related to soil health evaluation and soil degradation caused by anthropogenic activities in agriculture to provide useful information for future cropping system design and optimization in agriculture.

2. Cropping systems and soil health

Cropping systems, including crop diversification, crop rotation and intercropping, and related agronomic practices used in agriculture impact soil health and quality from various spatial and temporal aspects (Vukicevich et al., 2016). Cropping systems were initially designed to maximize yield from agro-systems, but modern agriculture has become increasingly concerned about the environmental sustainability of cropping systems (Fargione et al., 2018). The goal of soil health maintenance is to ensure long-term stable high productivity and environmental sustainability of cropping systems under five essential function evaluation standards, namely nutrient cycling, water relations, biodiversity and habitat, filtering and buffering, and physical stability and support (Hatfield et al., 2017). Fig. 1 illustrates an example of how an optimized cropping system increases soil health, relative to monoculture.

2.1. Crop diversification

Crop diversification is often described as the 'planned diversity' of cropping systems (Matson et al., 1997). It is not only critical for optimizing crop production but also important for increasing soil health by balancing soil biodiversity, enhancing soil nutrient use efficiency, and reducing soil-borne pathogens (Barbieri et al., 2019; Gurr et al., 2016). It is well accepted that optimized crop diversification has various benefits, not only to growers but also to the environment, as increasing crop diversity can enhance heterogeneity of soil chemical nutrients, soil physical structures, and functional microorganisms at different spatial scales, leading to improved soil health and crop yields (Bardgett and van der Putten, 2014; Maron et al., 2011). However, this relationship can vary with species redundancy and host-specificity of some soil-borne pathogens (Naeem, 1998; Zhu et al., 2000). For example, Bainard et al. (2017b) reported that increased crop diversity did not necessarily reduce soil-borne diseases; in particular, including more pulse crops in rotations significantly increased the pathogen index, which may be due to an increase in pulse-specific pathogens.

The overall richness of crop species in agroecosystems could be the ultimate driver of soil health; thus, to optimize the benefits that crop diversification can bring to the system, the diversity of plant functional groups may be important for crop diversification management (Milcu et al., 2013). Plant functional groups/types were initially used to classify plants according to their biological and physiological characteristics to develop a vegetation model for land-use studies (Bonan et al., 2002). In agroecosystems, the most common functional crop mixtures consist of a mixture of any of the four main groups, namely C3 grasses (such as cotton), C4 grasses (such as maize), legumes which fix N from atmosphere, and non-leguminous forbs (Vukicevich et al., 2016), as plants with different eco-functional types often grow well in community due to their different needs in the temporal and spatial niche and soil nutrient availabilities (Roscher et al., 2013). Similarly, higher diversity of plant eco-functional groups creates heterogeneity of the favorable niches for different soil functional microbes; therefore, crop diversification management with more plant functional groups could enhance soil health and ecosystem services (Vukicevich et al., 2016).

In modern agriculture, growing new crop varieties with improved compatibility of beneficial soil biota could be a powerful way to improve soil health in agroecosystems, as plant genotypes can significantly influence soil microbial communities and

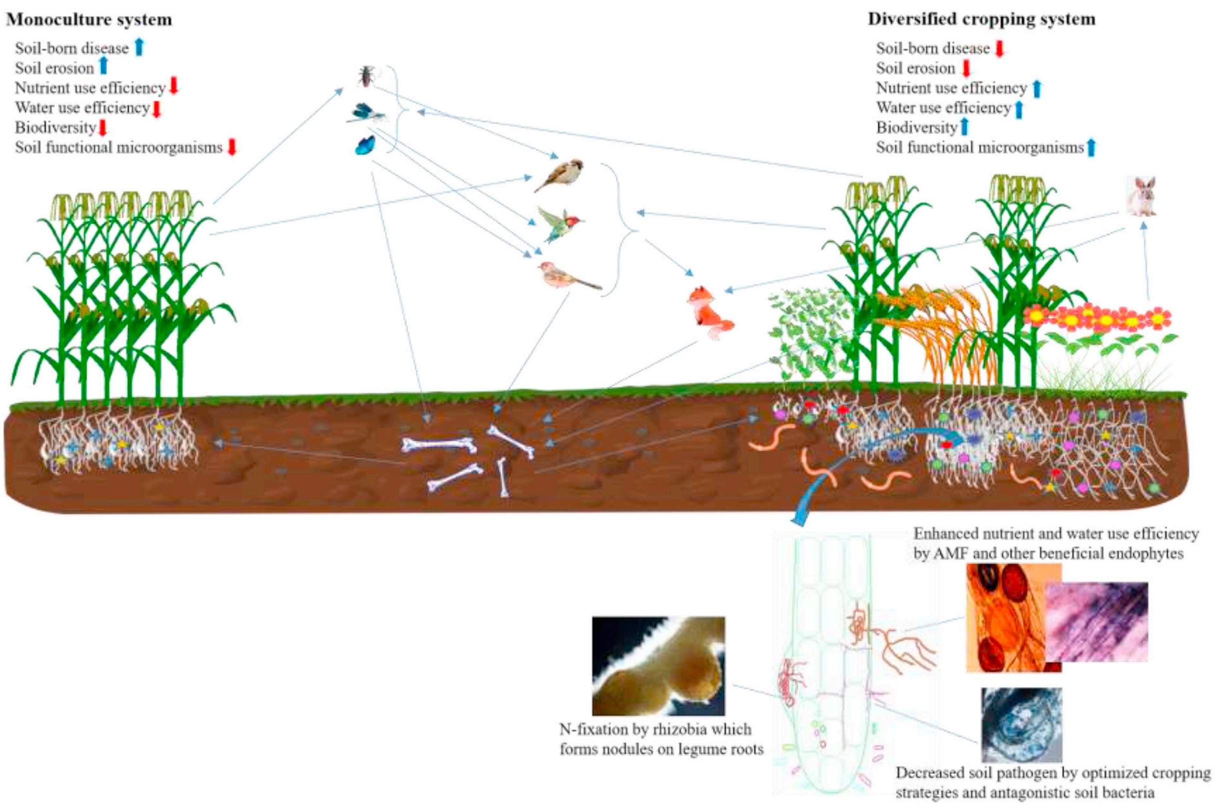

Fig. 1. Soil health comparison in optimized cropping systems and monocultures.

their functionalities in agroecosystems (Ellouze et al., 2013). Studies have shown that some modern breeding programs can produce new cultivars with better nutrient use efficiency and diminished capacity to form close symbiotic relationships with soil functional microorganisms (Pan et al., 2017). Optimized crop diversification creates diverse microhabitats that maintain good diversity and structure of beneficial soil microbial community and functional complementarity (Pivato et al., 2007). To optimize crop diversification with the best cultivar selections, genetically modified cultivars have been tested in agriculture to meet the demands for food requirements, industrial uses, and environmental security. For example, a new *Cassava* cultivar carrying the *PTST1*-or *GBSS*-gene can reduce amylose content in its root starch (Bull et al., 2018), which would be favored by the food industry as amylose can severely impact the physicochemical properties of starch during the cooking process. However, such technology must be applied with caution, as its environmental impact on soil health remains largely unknown. Overall, new crop diversification with an improved ability to communicate with beneficial soil biota could be a new angle for enhancing crop productivity, improving soil nutrient use efficiency, and reducing farm input costs and the environmental impacts of artificial chemical applications, thus leading to better soil health and sustainable agroecosystems (Ellouze et al., 2014).

2.2. Crop rotations

Crop rotation is a traditional and practical way for managing agroecosystem biodiversity by enhancing soil health, repressing pests and disease outbreaks (Barbieri et al., 2019), and thus increasing yields. The value and efficiency of a crop rotation depends on several factors, including crop types used in rotation (Tiemann et al., 2015), rotating series and applied frequency of certain crops (Bainard et al., 2017b), rotating length (Bennett et al., 2012), agronomic history on farmland and soil characteristics (Li et al., 2019). These factors can influence soil health in many ways. For instance, crop rotations can provide better opportunities for some soil functional microorganisms growth and limit disease pressure by breaking down the life cycle of soil-borne pathogens associated with specific crop or crop genotype. Certain crops are better in rotation than others, making it difficult to determine the best rotation sequence to maximize soil benefits (Gan et al., 2003). For example, crop rotation with grain legumes can increase productivity and protein content of wheat as the following crop, due to increased soil available N from biological fixation after legumes (Gan et al., 2003). Different chickpea genotypes (cultivars) or legume crops (such as pea and chickpea) in rotation can modify soil functional microbial communities and influence the productivity of pulse crops and the following wheat crop (Yang et al., 2013). More specifically, different crops can produce various residues and root exudates to boost soil microbial diversity and activity, and increase soil microbial biomass and C and N cycling (Gurr et al., 2016; Li et al., 2019). Some non-mycorrhizal plants, such as canola and mustard, cannot establish symbiosis relationships with some functional rhizobacteria thus require more mineral fertilizer (Ellouze et al., 2014), which could change the soil physical—chemical structure in the long-term. Despite the benefits of these crops that bring to producers, including non-mycorrhizal crops in rotation can eliminate arbuscular mycorrhizal fungal populations and mycorrhizal formation in the growth of following crop (Njeru et al., 2014), and further restrict their bio-functions in soil.

Changes in rotation length and frequency of the same crop in rotation over time can affect the incidence of root rot diseases and enhance soil health and crop yield stability (Vilich, 1993). Rotations with short series are more sensitive to host specific disease and thus come with lower yields than these rotations with longer series (Bennett et al., 2012). For example, the wheat phase of a 5-year rotation had higher soil (bulk and rhizosphere) microbial biomass than the wheat phase of s 3-year rotation, which was related to crop residue compost and C inputs into the soil and lead to improved soil health and wheat yields (Lupwayi et al., 2018). In Western Canada, two phases of pea in 4-year rotation doubled soil N contents, while three legume phases significantly changed the composition and function of the rhizosphere bacterial community compared with continuous wheat growth (Hamel et al., 2018). However, increasing the frequency of the same crop in rotation can have negative impacts on soil health, as Bainard et al. (2017b) found that an increased pulse phase in rotation accumulated host-specific fungal pathogens in soil, which could reduce the rotational benefits for soil health and crop yield.

Soil physical—chemical parameters are an important consideration of rotation design as they will impact the abundance, diversity, and distribution of functional soil microorganisms (Allison and Martiny, 2008). For example, in a semi-arid area of Western Canada, producers have traditionally alternated cereals with summer fallow to keep soil bare by using tillage or herbicides. In recent decades, rotating crops including grain legumes (such as field pea, lentil and chickpea) and oilseeds (such as canola and mustard) were introduced in wheat-based rotations in semi-arid areas of Canadian prairie to replace summer fallow, which modified available soil nutrients, soil physical structure changes and soil moisture conservation (Gan et al., 2011). These changes of soil physical and chemical factors will further impact soil health in general.

Another important consideration for crop rotation design is whether the soil-borne pathogens can use alternative crops as a host or remain long-term dormant in soil, and how these crops respond to disease (Bennett et al., 2012). Applying non-host plants for soil-borne disease control in rotations is critical for reducing yield losses due to diseases, especially when considering some pathogens can exist in soil for long term in the form of spores or other dormant structures with the absence of their favored host plant (Merz and Falloon, 2009). For example, severe *Fusarium* root rot injury in pea grown in rotation in the Canadian prairie was related to a limited soil microbial community and lower abundance of beneficial bacteria and arbuscular mycorrhiza (AM) fungi (Nayyar et al., 2009). In other cases, continuous cropping with higher crop diversification increased amount of antagonistic soil microorganisms thus reduced soil pathogen populations, mitigating the “take-all” impact in wheat (Garbeva et al., 2004). In general, three and more crops should be included in a cropping design to improve soil health for better yield (Bennett et al., 2012).

2.3. Intercropping system

Intercropping practices can enhance soil health by reducing artificial chemical pollution (Lemaire et al., 2014), inhibiting soil disease (Vukicevich et al., 2016), increasing plant root function (Bukovsky-Reyes et al., 2019), enhancing soil nutrient and spatial use efficiency (Hinsinger et al., 2011) and promoting bio-functionalities of soil microorganisms (Sun et al., 2019). For example, a study in a semi-arid area in Gansu, China, found that intercropping systems, including corn, wheat, and faba beans, had about 23%, 4%, and 11% higher root biomass and organic C and N contents in the top 20 cm soil layer than those species in rotation (Cong et al., 2015). In Pernambuco, Brazil, intercropping cassava with pigeon pea and beans significantly reduced black root rot (*Scytalidium lignicola*) in cassava by up to 50% compared with cassava in monoculture (de Medeiros et al., 2019). In addition, the intercropping soil had higher organic C and other nutrients, microbial biomass, and enzyme activities, than the monoculture soil, which were correlated with a decline in disease severity (de Medeiros et al., 2019).

Although increased spatial plant diversity is typically associated with enhanced resource use in intercropping systems, substantial environmental benefits can be gained by intercropping with carefully chosen crop species (Matson et al., 1997). For example, grasses usually dominate in soils with high nitrogen availability, and legumes are advantageous for soils due to their symbiotic relationship with nitrogen-fixing bacteria; thus, grass−legume intercrops can self-regulate soil nitrogen levels to optimize soil nutrient use and reduce the carbon footprint (de Araújo Santos et al., 2019). However, the ecological influences and biological functions of these crops in intercropping systems are not well understood, as intercropping systems with higher yields do not necessarily reflect better soil health (Jungers et al., 2019). For example, total shoot biomass increased significantly in an intercropping practice using *Medicago sativa* and *Dactylis glomerata*, relative to sole cropping, but the N_2O production rate also increased, suggesting that understanding the nature of these intercropping designs is critical for soil and environmental health maintenance (Graf et al., 2019).

2.4. Prairie strip as a new cropping strategy for improving soil health

As a relatively new farmland conservation cropping practice applied in North America, prairie strips have already shown benefits for improving soil health, protecting the environment, and providing habitat for wildlife, while maintaining good yields (Schulte et al., 2017). A research team in the US has shown that including local prairie grass species into cropping with crop plants—in the form of in-field contour buffer strips and edge-of-field filter strips—can bring disproportionate benefits for environment in agroecosystems (https://www.nrem.iastate.edu/research/STRIPS/content/what-are-prairie-strips). Prairie strip cropping systems bring many more benefits than other perennial crop systems in North America due to the diversity of native plant species incorporated, their unique root morphologic structure to efficiently use water and nutrient resources, and strong stems that can hold up in heavy rain.

In agroecosystems, low-yielding farmlands are an excellent opportunity for integrating perennial vegetation with prairie strips. Prairie strips have the potential to generate many benefits for soil health (Batic, 2009). Compared with traditional methods, such as terraces and sediment-control basins, prairie strips not only control soil erosion and retain P and N in the soil system but also improve groundwater quality control with less N leaching, financial cost, and other environmental issues for local producers (Schulte et al., 2017; Tyndall et al., 2013). For example, converting 10% of a crop field (corn or soybean) to diverse, native perennial vegetation reduced sediment movement off-field up to 95% and total P and N lost through runoff up to over 85% (Schulte et al., 2017); the authors survey data analysis suggested that policies and programs designed in modern agriculture should prioritize some ecosystem services for prairie strips.

Compared with other cropping systems, prairie strips can improve soil water infiltration, soil organic matter content, and nutrient retention with fewer management challenges in agroecosystems (Poeplau and Don, 2015). While longer crop rotations can reduce soil disease levels and enhance financial impacts of some additional crops, such as small grains and forages, these require additional labor, equipment, and management practices. Therefore, prairie strip practices could be combined with other crop rotations to provide better ecosystem services for soil health (Schulte et al., 2017). For example, perennial native grass species grown with other crops in rotation offer substantial diversification opportunities to help meet both economic and environmental goals (Robertson et al., 2017; Werling et al., 2014), but the levels of benefits brought by prairie strips varies with crop species planted close to prairie strips and agronomic managements practiced in field (Brandes et al., 2016). Overall, prairie strips are a relatively low-cost approach with many benefits for improving soil health, requiring minimal changes to existing farming operations.

3. Soil-microbe-plant interactions in cropping practices and their effects on soil health

3.1. Co-evolution of plant microbes and signaling system development

Plants have co-evolved with microorganisms for more than 400 million years, since they left their aquatic environment to colonize the land to form very complicated soil−microbe−plant systems that preform many critical biological and ecological functions in nutrient cycling, carbon sequestration, soil fertility maintenance, and ecosystem resilience (Fierer, 2017; Remy et al., 1994). In agriculture, these soil-microbe-plant interactions are even stronger, considering that highly selected crop species are used in different cropping systems for food and fiber gains which also significantly enhance the “host effects” on soil microorganisms. As sessile organisms, plants developed multiple chemical signaling pathways during their co-evolution to invest and manage the root microbiome (Berg and Smalla, 2009; Fierer, 2017). Fig. 2 is an example of chemical signaling pathways as the driving power of some critical plant–microbe interactions. Different plants can select specific rhizosphere microbial communities for their benefit (Maarastawi et al., 2018). The composition of this specific microbial community, also called the 'root microbiome,' is constrained by the properties of the soil environment (Chen et al., 2019) and heavily shaped by host plants (Ellouze et al., 2014; Mhlongo et al., 2018). In particular, root exudates released by plants are important carbon and energy sources for soil microorganisms and can significantly change the soil physical–chemical properties, especially in the rhizosphere (Ji et al., 2015), thus modifying the microhabitats to which microorganisms are exposed (Maltais-Landry et al., 2014). Furthermore, these root exudates play critical roles in chemical signaling processes with soil microorganisms, which can further interfere with their eco-functions and soil health (Mhlongo et al., 2018). For example, plant hormones, such as strigolactones, salicylic acid, jasmonic acid, ethylene, gibberellic acid, auxin and cytokinin, are common signaling compounds produced by plants that regulate plant–microbe recognition processes (Bari and Jones, 2009). In particular, salicylic acid, jasmonic acids, and ethylene can trigger plant defense systems to prevent pathogen infections (Bari and Jones, 2009; Maruri-López et al., 2019). Strigolactones are involved in plant defense signaling as well as stimulating hyphal branching in the presymbiotic stage of AM symbioses (Kretzschmar et al., 2012) and triggering pathogen infection in plant root tissue with certain phenolic compounds (Steinkellner et al., 2007). Flavonoids initiate symbiosis formation in the signaling of recognition process with symbiotic diazotrophs (Miransari et al., 2013). Some peptides produced by plants are also involved in microbe–plant signaling and act as hormones (Bari and Jones, 2009) or enzymes (Fritig et al., 1998; Turrini et al., 2004) in defense of environmental stresses. For example, tryptophan dimers produced by plant roots can stimulate AM fungal growth under water stress (Horii et al., 2009). Some volatile organic compounds released from plant roots act as critical signaling compounds that can suppress the growth of pathogens, such as *Fusarium* spp. (Cruz et al., 2012).

The type and amount of root exudates can be affected by many environmental factors, depending on the environmental stress level and plant species involved (Preece and Peñuelas, 2016). In cropping systems, many factors can interfere with the soil–microbe–plant complex and thus influence its functionality. Soil type (Dai et al., 2012), organic carbon level (Wu et al., 2015), temperature and moisture (Yang et al., 2010), oxygen level (Maarastawi et al., 2018), electrical conductivity, calcium level and pH (Bainard et al., 2017a) are all factors that can change the composition and functionality of soil microbial communities. For example, insufficient soil P and N will enhance the production of strigolactones, which could further trigger AM fungi symbiosis and growth (Yoneyama et al., 2013). Low N availability in the soil can increase glyphosate levels, which will

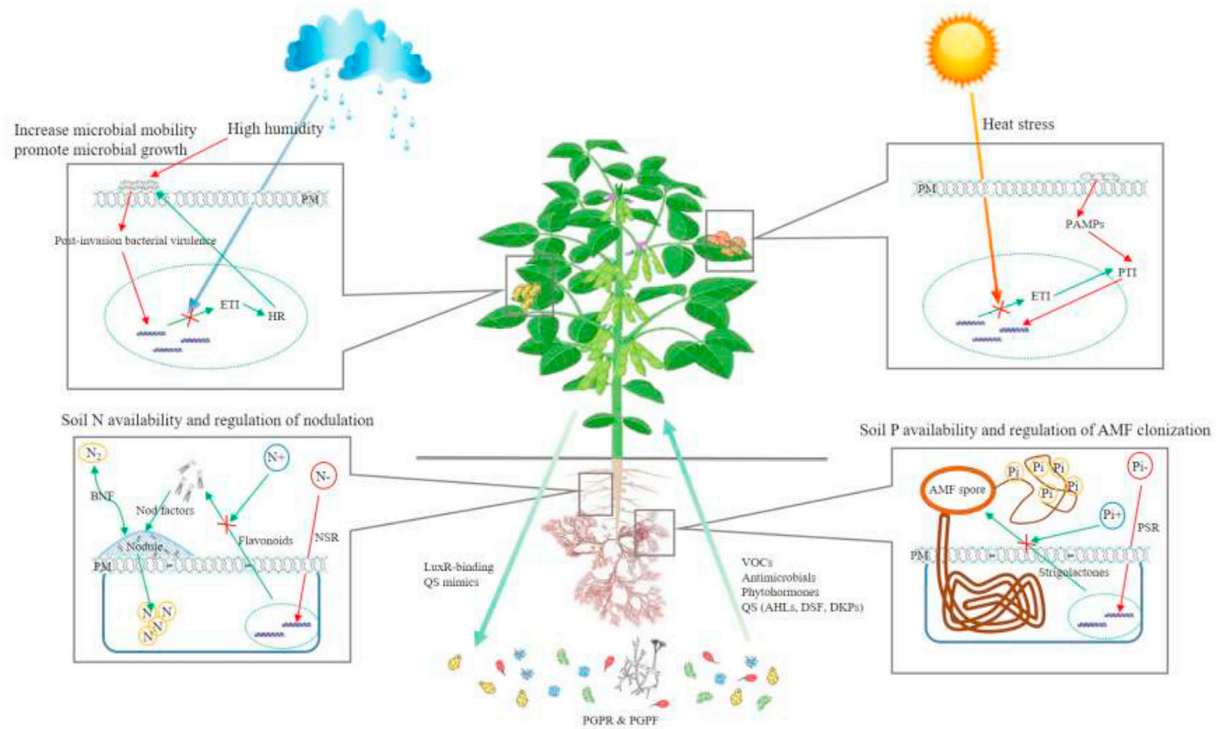

Fig. 2. Chemical signaling pathways in the plant–microbe–soil complex that are regulated by environmental factors (Cheng et al., 2019; Venturi and Keel, 2016). PM: phospholipid membrane; PAMPs: pathogen-associated molecular patterns; PTI: PAMP-triggered immunity; ETI: effector-triggered immunity; NSR: nitrogen starvation response; PSR: phosphate starvation response; BNF: biological nitrogen fixation; N+: N-sufficiency; N−: N-deficiency; P+: P-sufficiency; P−: P-deficiency; N_2: nitrogen gas; Pi: available P; AMF: arbuscular mycorrhizal fungi; VOCs: volatile organic compounds; QS: quorum sensing; AHLs: *N*-acyl homoserine lactones; DSF: diffusible signal factor; DKPs: diketopiperazines; PGPR/PGPF: plant growth promoting rhizobacteria/fungi.

increase the relative abundance of AM fungi and stimulate some related bacteria growth in the rhizosphere (Sheng et al., 2012). In general, environmental conditions modulate the strength and extent of plant–microbe signaling, which are considered important for managing soil microbial diversity to improve soil health.

Soil microorganisms also develop signaling pathways to actively interact with their host plants, which further impact soil health. For example, after legume crops produce flavonoids to trigger the *nod* gene in *Rhizobia* during nodulation, these bacteria will produce lipo-chitooligosaccharide (LCO) signals, which can trigger mitotic cell division in plant root tissues, leading to successful colonization and nodulation (Hayat et al., 2010). Soil microorganisms produce various signaling chemical compounds that are directly or indirectly involved in many critical eco-functions in soil, including C, N and P cycles, organic matter decomposition and plant growth regulation; this could be a key driver for plant diversification and community structure in terrestrial ecosystems (Van Der Heijden et al., 2008), which could further impact soil health.

3.2. Symbiosis microbiome and its relationship with soil health

In cropping systems, the symbiosis of diverse soil microorganisms has multiple benefits for crop plants (Fierer, 2017; Philippot et al., 2013). In particular, many bio-functions of agroecosystems rely on symbioses with functional microorganisms, including mycorrhizal fungi (Bolan, 1991), beneficial endophytic fungi (Rodriguez and Redman, 2008), and plant growth-promoting bacteria (PGPR) (Peoples and Craswell, 1992). Fig. 2 illustrates an AMF and rhizobia symbiosis. Plant–microbe symbionts can contribute to plant fitness, e.g., by improving nutrient status and increasing plant resistance to environmental stresses or disease defense.

The concept of a beneficial symbiosis microbiome was used to investigate the microbial community structure associated with host plants to understand and exploit their functionalities in sustainable agriculture. According to Vandenkoornhuyse et al. (2015), a 'pan-microbiome' comprises the microorganisms associated with one plant species, an 'eco-microbiome' comprises the microorganisms associated with a whole plant population in a specific environment, and a 'core-microbiome' comprises a subset of microorganisms always associated with one plant species. The core-microbiome concept is of interest in the context of agricultural production due to its consistency through time and space, which can be reliably managed through plant selection. By definition, the core microbes of a given plant species are always found with this plant species. However, the size of a functional core-microbiome in the rhizosphere can only be determined by a few key microorganisms. For example, among the 6376 bacterial and 679 fungal operational taxonomic units (OTU) recorded in the root microbiome of canola growing in the Western Canadian Prairie, only 14 bacterial and one fungal OTUs constituted the core-microbiome of canola roots; of these, only four bacteria and one fungus were positively correlated with canola yield (Lay et al., 2018).

Since symbiotic beneficial soil microorganisms are critical for soil health, understanding their taxonomic structure and phylogenetic information are essential for sustainable agriculture. However, linking taxonomic information to microbiome function and determining their value for agriculture is difficult (Fierer, 2017; Vandenkoornhuyse et al., 2015). Some positive correlations between certain microbial taxa and desirable plant traits, such as yield, do not necessarily reflect relationships among functional microbial groups and plant traits (Lay et al., 2018). For example, plant productivity and the proliferation of microorganisms with an r-strategist lifestyle were favored by high soil N fertility, while the plant and microbes were competing for the resource rather than helping each other. It is possible to link microbial community data to their bio-functions by assigning functional guilds to taxonomic structure using bioinformatics tools, such as FunGuild (Nguyen et al., 2016) and PICRUST2 (Douglas et al., 2019) which can infer eco-functions of these microorganisms based on their taxonomic placement. This is particularly useful for soil microorganism functional analysis, especially as a large proportion of root microbiome DNA sequences belong to microorganisms that cannot be classified. Shotgun metagenomics is another popular technology for drawing a global picture of microbial communities at both the taxonomic and function level.

3.3. Free-living microbiome and its relationship with soil health

While symbiotic soil microbes have tight relationships with their host plants and related eco-functions, free-living soil microorganisms also have potential benefits for plant growth and soil health in cropping systems (Müller et al., 2016). Beneficial free-living soil microorganisms that live outside plant cells are tightly associated with soil health for plant–microbe interactions in the rhizosphere. For example, some strains of *Azotobacter, Azospirillum, Bacillus*, and *Klebsiella* sp., which are associated with biological nitrogen fixation, have been inoculated globally to enhance plant productivity (Lynch, 1983). In addition, P-solubilizing microorganisms (such as *Bacillus* and *Paenibacillus*) have been used to improve soil P availabilities for plants to use in agroecosystems (Brown, 1974). A study found that wheat head numbers and potential yield increases are very likely due to the activities of some free-living microorganisms belonging to *Firmicutes* or *Actinobacteria* that accumulated in the previous pulse phase in rotation (Yang et al., 2012).

Generally, free-living soil microorganisms have the potentials to contribute to the establishment of sustainable agriculture in three ways: synthesizing particular compounds to support crops growth, enhancing certain nutrients uptake capabilities of crops from the soil, and preventing plant disease by competing either niches or nutrients with pathogens (Glick, 2003). In particular, free-living soil microorganisms can: (1) produce enzymes to reduce ethylene levels in plant tissue, thus increasing root development and plant growth; (2) produce hormones that can regulate plant growth; (3) antagonize phytopathogenic microorganisms by producing bio-control chemical compounds; (4) solubilize and mineralize soil mineral nutrients; (5) enhance resistance to environmental stresses such as drought and salinity (Hayat et al., 2010). Free-living microorganisms can also remediate contaminated soils (Zhuang et al., 2007). Therefore, it is important to develop the best combinations of beneficial soil microorganisms in sustainable agriculture to achieve good production with healthy soil systems.

4. Indicators for evaluating soil health in cropping systems

Apart from problems with defining soil health, its qualitative and quantitative assessment is somewhat overwhelming and poorly understood, as soil is an extremely complex bio-matrix whose functioning depends on myriad of soil organisms that live within a highly intricate soil architecture that can shift with cropping system. In any case, it is important to include physical, chemical, and biological properties when assessing soil health (Bünemann et al., 2018). Ideally, indicators of soil health should be related and/or correlated to soil processes and be responsive to changes in management and environmental conditions. Traditionally, physicochemical properties (texture, depth, bulk density, water holding capacity, porosity, pH, electrical conductivity, organic matter, cation exchange capacity, nutrient content) have been used as soil health indicators. Soil biological properties, particularly microbial properties, are becoming increasingly used owing to their ecological relevance, quick response, sensitivity, and capacity to integrate information and responses from various environmental factors (Barrutia et al., 2011; Galende et al., 2014; Mijangos et al., 2006). Soil parameters that provide information on the biomass, activity, and diversity of soil microorganisms are being used as bio-indicators of soil health (Epelde et al., 2010; Mijangos et al., 2006; Pardo et al., 2014), which is not surprising as soil microorganisms play a key role in many critical soil processes, such as organic matter decomposition and the accompanying recycling of nutrients related to primary biogeochemical cycles. Fig. 3 illustrates how soil microbial profiles are related to crop yield in various crop rotating systems.

Many other taxonomic groups of soil biota (e.g., members of soil macro- or meso-fauna, such as earthworms, enchytraeids, mites, springtails, and nematodes) can be used as bio-indicators of soil health (Bünemann et al., 2018). A drawback of all biological indicators of soil health is the lack of standardized and harmonized information, relative to soil physicochemical indicators, resulting in a lack of suitable reference values, which hinders the interpretation of soil biological parameters.

A particular disadvantage of using soil microbial parameters as indicators of soil health are the technical constraints when studying soil microbial communities. It is true that the development of advanced molecular methods, specifically next-generation sequencing techniques (e.g., amplicon sequencing and shotgun sequencing for structural and functional microbial diversity studies, respectively) has facilitated the study of the non-culturable fraction of soil microbial communities (yet, the majority of soil microorganisms do not grow on laboratory culture media). Nonetheless, these new techniques have limitations that must be considered when interpreting the data. It is undeniable that novel and powerful analytical techniques (not only molecular, but also biophysical, microscopic, etc.) are shedding light on the complex structural and

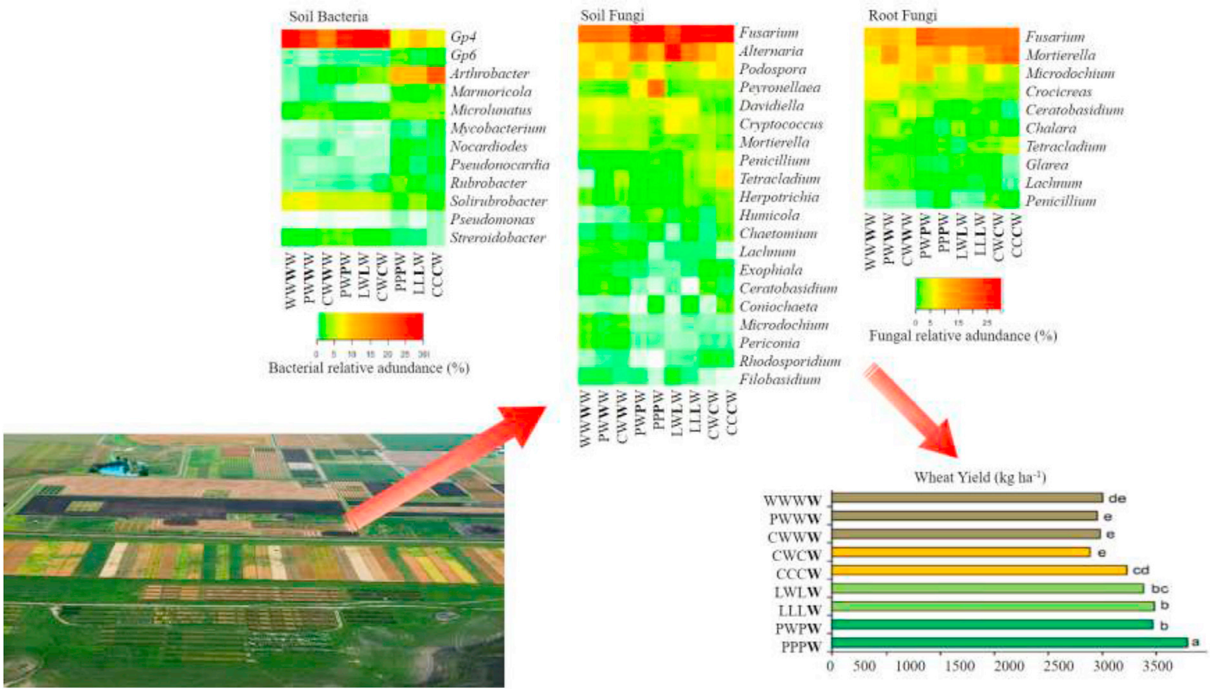

Fig. 3. Optimized soil microbial community promotes crop yield in cropping practices (Bainard et al., 2017b; Hamel et al., 2018; Niu et al., 2017). Capital letters for rotation abbreviations: W: durum wheat; P: pea; C: chickpea; L: lentil. Bold capital letters indicate the rotation stage of sampling. Different lower-case letters in the wheat yield graph indicate significant differences at the 5% similarity level.

functional aspects of soil microbial communities, and hence soil health. Another important limitation of using microbial parameters as indicators of soil health is that most microbial measurements are context-dependent (i.e., values strongly depend on sampling time, soil type and physicochemical variables, specific location, climate, soil history, etc.). In other words, while soil microorganisms have a key role in soil functioning and are, hence, *a priori* excellent indicators of soil health, the reality is that research is needed to fully understand the overwhelming complexity of microbial communities (in terms of both the countless components and innumerable interactions of most microbial networks), particularly those in soil due to the recognized difficulty of identifying soil ecosystem function with its marked spatial heterogeneity (at surface and at depth), temporal dynamicity, and vast biodiversity (related to the presence of a seemingly endless number of niches).

It is not surprising that various authors have proposed more general and integrative ‘attributes’ as indicators of soil health; for instance, (i) biodiversity, stability and self-recovery from stress (Parr et al., 1992); (ii) vigor, organization, stability, suppressiveness and redundancy (Garbisu et al., 2011); and (iii) ecosystem services (Velásquez et al., 2007). The determination of soil biodiversity is undoubtedly a key aspect when assessing soil health as, by definition, higher biodiversity offers superior potential for interactions and, in turn, a more intricate system of interactions frequently results in more resilience to disturbances. In any event, biodiversity and ecological stability (the term ‘ecological stability’ includes two concepts: *resistance* or the ability to continue to function without change when stressed by disturbance, and *resilience* or the speed and manner with which ecosystems recover after disturbance) should unquestionably be included in the list of important aspects for soil health.

Indicators of soil health can be used as individual properties or integrated into indices. Many soil health indices (simple and complex multi-parametric indices) have been proposed in the literature (Klimkowicz-Pawlas et al., 2019; Velásquez et al., 2007). As is often the case, the use of indices greatly facilitates interpretation and, above all, decision-making by soil managers, with the additional advantage that indices integrate information from several, or many, soil physicochemical and/or biological properties (in other words, they have an integrative character). By contrast, their use can imply the loss of valuable information (provided by each parameter when interpreted singly) and often leads to an oversimplification of the multifaceted responses of the extremely complex soil ecosystem against natural or anthropogenic disturbances (e.g., agricultural practices).

Finally, soil health monitoring networks are indispensable tools for gathering more data on the impact of natural or anthropogenic disturbances on soil health and, in general, for understanding the soil ecosystem better so that we can establish valid comparisons across variations in climate, soil types, management practices, etc.

5. Soil degradation from global cropping systems

Many anthropogenic activities that are used in various cropping systems, such as intensive tillage, fossil fuel consumption, draining of wetlands, adaptation of heavy equipment in farming practices, fertilization, and pesticide management, are factors that cause global soil degradation in agriculture. Other effects like erosion by water, erosion by wind, decline of organic matter in peat and mineral soils, compaction, sealing, contamination, salinization, desertification, flooding and landslides, and decline in biodiversity also threaten soil health (Stolte et al., 2015). Soil degradation is one of the most severe socio-economic and environmental problems threatening our survival and well-being, mainly when analyzed for food security and safety. In this respect, it is unquestionable that feeding the rapidly growing human population is one of the most critical and disquieting challenges our society will face in the present 21st century, particularly in light of the existing situation with climate change and its expected strong negative impact on food production (Smith and Gregory, 2013).

Taking into consideration that most food and fiber resources come directly or indirectly from the soil (95% of the food and feed produced for humans and animals depends on soils) (Panagos et al., 2016), the degradation of soil, in particular agricultural soil under different cropping systems, is an environmental and socioeconomic problem that must be urgently, responsibly and exhaustively addressed. As reported by Bhattacharya (2019), soil degradation in agriculture is mainly due to inadequate and imbalanced fertilization, mineral nutrient leading, and the consequent problems developed during nutrient management. For example, the estimated supply−demand gap was about 1.8 million tons for N and P in 2012, and continues to increase. Global concern is due to low mineral fertilization use efficiency (N is around 50−60% in cereal crops, P is about 15−20% in most crops and K is 60−80%), as low nutrient recovery efficiency not only increases food costs but also reduces soil health and causes other environmental problems (Bhattacharya, 2019). Another factor that decreases soil health and quality in agriculture is tillage activities. Tillage is one of the most common agronomic practices used in agriculture for weed and some disease control. However, previous field studies, especially long-term studies, have shown a negative effect of tillage on soil health. For example, tillage can change the soil physical structure, which can further affect other soil health factors, such as pH, organic compounds, available N and C, and nutrient and micronutrient availabilities, such as Zn and Mn (Congreves et al., 2015; Grahmann et al., 2020), and increase soil degradation by water and wind erosion (Carr, 2017). These tillage related concerns on soil health, coupled with demands of a rapidly growing of food consumption, have challenged researchers and producers to develop alternative agronomic strategies to improve soil health and quality while maintaining the quantity and quality of crop products. Also, monoculture systems, which have been used in agriculture for many years, especially for cereal crops due to the reasonable grain price and market requirements (Angus et al., 2015), have adverse effects on soil health. Continuously growing the same crop in the same field leads to a low diversity of functional soil microbial community, accumulation of some host-specific soil-borne pathogens, and an imbalance of soil nutrient contents (Bai et al., 2019; Wang et al., 2018).

Therefore, sustainable and cost-effective measures for both the prevention of soil degradation and the recovery of degraded soils must be promptly implemented to minimize the manifold negative social, economic and environmental consequences associated with soil degradation, in terms of reducing their capacity to perform valuable functions and provide key sustainable ecosystem services.

6. Conclusion

Significant achievements, including refine content of soil health and the development of new evaluation standards for 'soil health and quality' by combining various soil health indicators (such as soil physicochemical properties, soil microorganisms status, and cropping practices) into indices in agroecosystems, can be used to evaluate and guide soil and crop management decisions. Enhancing the science-base for soil health assessment is the foundation for developing new tools and methodologies for quantifying soil biological properties and processes (such as genomic sequencing and mapping). Even though soil biology has been established and recognized as an important component of soil science for centuries, new research strategies and commercial investments regarding the impact of anthropogenic activities on soil health and quality are rousing topics. Future opportunities to advance soil health evaluation include the development of *in-situ* sensors that can provide efficient estimates for biotic and abiotic indicators, such as soil available carbon, bulk soil density, pH, soil water capacity, and soil microbial activities. We believe that these methods and techniques will significantly advance soil health assessments and improve our capacity to optimize soil health and quality sustainably. We also believe that global advancements in soil biology, new IT technology, and metadata analyzing techniques for interpreting and summarizing soil health indicators data under different environmental conditions will lead to more reliable guidance for sustainable land management, which will help to mitigate and prevent global soil degradation.

Declaration of competing interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01118.

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