CHAPTER FOUR

# Soil health in agricultural ecosystems: Current status and future perspectives

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## Contents



## Abstract

Humanity thrives when soils are healthy as soils provide food, fiber, shelter, and a life-sustaining climate. Awareness of the need to optimize soil functions to grow food for an expanding human population and a desire to sustain environmental quality has

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led to an intense interest among stakeholders and practitioners in enhancing soil health. The public has become aware of soil health only in the last few years; however, for the seasoned soil scientists and agronomists, the journey to improve soil health began a long time ago, starting with the Dust Bowl Era and later to what was called soil quality movement. This article aims to review our current understanding of soil health by examining the history and evolving definition of soil health and then exploring the best soil health indicators from the physical, chemical, and biological domains that could be used to support practices for enhancing soil functions. Improving soil health will enhance soil functions, and so the conclusion that improving soil health involves enhancing soil organic carbon is justified. We briefly review the various soil health indicators and management options for enhancing soil health and explore. the social and economic perspectives of the call for farmers to use soil health practices. We conclude the review by examining the current knowledge gaps and suggesting ways to advance soil health understanding and conversation. For the agricultural community, we present a new definition of *soil health as the capacity of soils to provide a sink for carbon to mitigate climate change and a reservoir for storing essential nutrients for sustained ecosystem productivity.*

# 1. Introduction

## 1.1 Objectives of the review

The objectives of this article are to:

**(i)** examine the current state of efforts on soil health with a focus on currently used soil health assessment techniques and matrices,

**(ii)** review the field management practices used to improve soil organic carbon and enhance soil health, and

**(iii)** discuss end-user perceptions, communication needs, and economics of managing and maintaining soil health.

The review's primary focus is on the ongoing efforts in the United States; however, the recommendations and framework suggested could be adopted in other parts of the world by realizing the differences in social, cultural, and management practices.

## 1.2 History and concept of soil health

Soil conservation has progressed from a priority in the United States in 1937 when President Franklin D. Roosevelt said, "*The Nation that destroys its soil destroys itself*" in the wake of catastrophic dust storms to the present-day international efforts when the United Nations declared 2015–2024 the International Decade of Soils. With the severe drought of the 1930s leading to the Dust Bowl Era, the adverse impacts of increased tillage and poor management practices on soils were realized (Baumhardt, 2003; Hubanks et al., 2018; Williams and Bloomquist, 1996). This resulted in the development and adoption of government policies centered on improving farming practices. A major emphasis was placed on diversification of crops, and use of reduced and noninverting tillage implements capable of penetrating soils, which resulted in less physical disturbance and retention of more crop residues in soils, which in turn, helped to improve soil water and organic matter (Baumhardt, 2003; Hubanks et al., 2018). Soon after the dust bowl, Soil Conservation Service came into existence in the United States, now known as Natural Resources Conservation Service. In 2015, UN Secretary-General Ban Ki-Moon cited the FAO's estimate that 33% of global soils are degraded (https://www.un.org/sustainabledevelopment/blog/2015/12/at-end-of-international-year-of-soils-un-chief-appeals-for-reverse-in-rate-of-soil-degradation/). He stated: "sustainable soil management is fundamental to achieving the Sustainable Development Goals—many of which reflect the centrality of soils to sustain life, food and water." The UN seeks to create awareness and spur action by decision-makers to recognize the contributions of soils to food security, climate change adaptation and mitigation, essential ecosystem services, poverty alleviation, and sustainable development. With the world's fate now squarely centered on improving soil health in agricultural settings, developing objective tools to describe, quantify, and optimize practices to boost soil health are needed.

Recent degradation of soils can be traced to the discovery of the Haber-Bosch process, an industrial nitrogen fixation process, which yielded abundant nitrogen fertilizers and resulted in the Green Revolution in the early 20th century. Worldwide crop productivity was improved with a little concern for chemical impacts on soil productivity. The Green Revolution and the use of chemicals (fertilizers, pesticides) resulted in quadrupling yields of short-stalked varieties of wheat and rice (Hafner, 2003; Smil, 2011). With this, traditional farm practices geared toward maintaining and cycling soil nutrients dwindled as mono-cropping systems were established. During the late 20th and early 21st century, scientists and practitioners became increasingly aware of various adverse effects of technological innovations on soils (Bhagat, 1990; Doran and Parkin, 1994; Sagan, 1992). As a result, in the 1970s to 1990s, the terms "soil quality" and "soil health" were coined to evaluate the quality of soil (Anderson, 2003; Karlen et al., 2008). The term "soil properties" refers to soil characteristics that do not change easily, such as soil texture, and are inherently linked to soil quality and organic matter, which can be influenced by management practices. The dynamic soil properties which need to be monitored from time to time are referred to as "soil quality"—a term introduced by Mausel (1971). Doran and Parkin (1994) advocated to the soil science community to go beyond the classic soil testing regime and focus on a holistic assessment of soils. They further emphasized a need to define soil quality and its measurement as soil's ability to produce the desired crop.

The soil quality is described as a unique property of soils intrinsically linked to land management and represents soil productivity and human-soil interactions (Bünemann et al., 2018; Hurni et al., 2015; Larson and Pierce, 1991). On the other hand, the "soil health" term was used by Haberern (1992) and Doran and Parkin (1994) interchangeably with soil quality, and by Gregorich and Acton (1995) for soil assessment. Conceptually, soil health draws an analogy to the health of an organism or human or community (Doran and Parkin, 1994; Larson and Pierce, 1991) and is also rooted in the idea that soils operate as an ecological system central in delivering functions that sustain life on earth by controlling plant health, and henceforth animal and human health (Warkentin, 1995).

The soil quality concept was criticized for transforming soil science into a value-based system enterprise (e.g., Letey et al., 2003; Sojka et al., 2003). It evolved more as a representation, inclusive of the living and dynamic components of soil—the soil flora and fauna, soil microorganisms, and soil food webs, or in other words, "ecology." Though both terms are used interchangeably or synonymously, Moebius-Clune et al. (2016) clarified that soil quality includes inherent and dynamic soil properties, whereas soil health represents dynamic soil quality, which is linked to soil functions. The focus on the soil as a living system performing soil functions that provides various ecosystem services (Glenk et al., 2019) beyond its capacity to support crop production represents the soil health perspective. This subtle yet significant paradigm shift of the soil health concept from a focus on cropping to a holistic ecosystem has entailed renewed interest and demands reorientation and updating in assessment approaches and management practices. Like human health, soil health has been thought to be broadly tested with vital sign checks, running a slew of biochemical profile tests, and assigning scores for assessment (Dick, 2018; Larson and Pierce, 1991). Hence, in the modern-day comprehensive management of soils and its assessment, soil health is a more practical term for the research and farming community. The coining of the terminology "soil health" thus justifies perhaps the intent of placing soils in a domain where public perceptions and farmer perspectives play as much of a role in its development as do scientific perspectives and research findings.

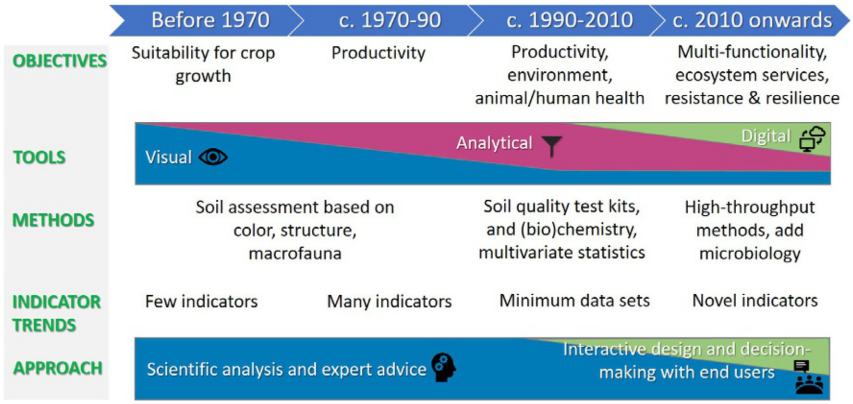


**Fig. 1** Evolution of soil quality assessment over time in terms of objectives, tools, methods, and overall approach. *Redrawn after Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality—a critical review. Soil Biol. Biochem. 120, 105–125.*

The evolution of soil quality assessment concept over time with changes in the objectives, tools, methods, and indicators is shown in Fig. 1. For example, the main objective of assessment before the 1970s was determining the suitability of soils for crop growth, after 2010 the objective changed to a multi-functionality, ecosystem services, resistance, and resilience of soils. This change in objectives has resulted in more advanced methods and novel indicators to determine soil quality/health. Considerable interest in soils has led to an increase in research productivity. For example, according to the Web of Science Core database, from 1945 to 2019, the number of articles that mentioned soil health, soil quality, and soil property in their abstracts was 2065, 9197, and 26,132, respectively. The number of articles with soil health, though much fewer, shows an increasing trend (Fig. 2).

## 1.3 Definition and current status of soil health

In general, the characteristics of healthy soil include (i) good soil tilth, (ii) sufficient depth of roots to access water and nutrients, (iii) adequate supply (but not excess) of nutrients, (iv) optimal pH, (v) low population of pathogens and insect pests, (vi) high and diverse population of beneficial organisms for organic matter decomposition and nutrient cycling and soil structure maintenance, (vii) low weed pressure, (viii) free of harmful chemicals and toxins, and (ix) resistant to degradation or resilient soils (Magdoff, 2001; Mann et al., 2019; Phatak, 1998). Many of these

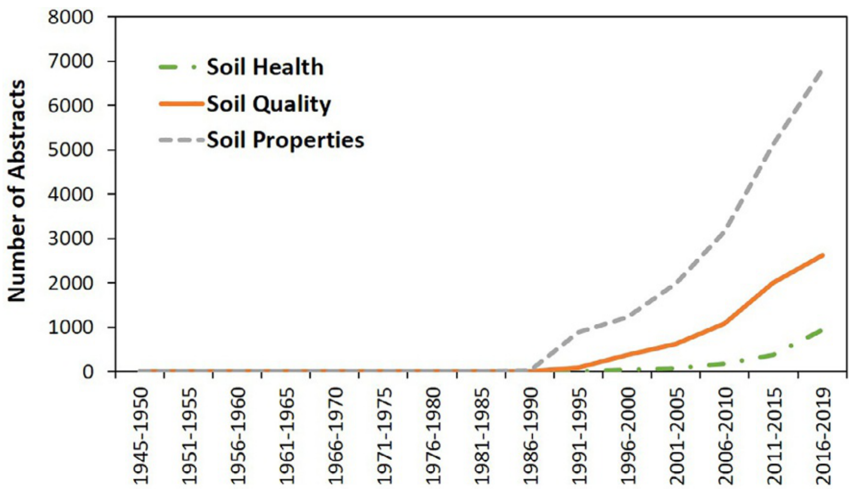


**Fig. 2** Abstracts from peer-reviewed literature from 1945 to 2019. *Source: Web of Science Core Collection database with the keyword soil properties, soil quality, and soil health.*

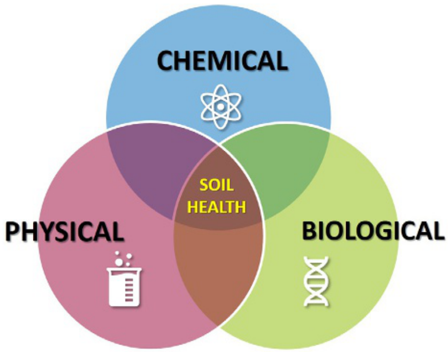


**Fig. 3** Soil health is regulated by the interactions of the physical, chemical, and biological properties of soils.

characteristics represent properties in the physical, chemical, and biological domains of soils and healthy soils should have an overlap of these characteristics, as shown in Fig. 3.

Soil quality was defined by Doran and Parkin (1994) as "the capacity of a soil to function, within the ecosystem and land use boundaries, to sustain productivity, maintain environmental quality, and promote plant and animal health." The terms "soil health" and "soil quality" are generally interchangeable where soil quality depends more on inherent soil characteristics such as parent material and soil texture, and soil health is considered more of dynamic nature. Thus, the United States Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) refers to soil health as soil quality and defines it as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans." This broad and perhaps vague definition captures the concept of soil as a dynamic system, forming the cornerstone for thriving, living systems on earth, and creating the foundation of the value-based imperative for present society to manage soils well so that they are sustainable for future generations. However, the definition fails to fully capture the important role of soils as the largest reservoir of terrestrial carbon and essential nutrients for plant growth. There is an opportunity for more clearly defining the role of soil organic carbon as an immutable part of the soil health equation for two main reasons. First, to compensate for greenhouse gas emissions by anthropogenic sources with the establishment of the "4 per mille Soils for Food Security and Climate" research program to increase global soil organic matter stocks by 0.4% per year (Minasny et al., 2017). Second, the commitment by signatories to a voluntary action plan to implement farming practices that maintain or enhance soil organic carbon stocks in agricultural soils (Chambers et al., 2016; Lal, 2016; Minasny et al., 2017).

As many of the soil health and conservation programs aim to increase soil organic carbon stocks and thereby provide a sink for carbon dioxide as well as promote improved soil health, we propose the following targeted definition of soil health for the agricultural community as this captures the importance of carbon in soils and soils as a storehouse of nutrients: *Soil health is the capacity of soils to provide a sink for carbon to mitigate climate change and a reservoir for storing essential nutrients for sustained ecosystem productivity*.

This is an exciting time for the soil health movement in the United States. There are engaged organizations across the country that advocate going beyond the routine soil testing to measure soil health. The recently established Soil Health Institute by the Noble Foundation, the Soil Health Partnership, and initiatives such as the Cornell Comprehensive Assessment of Soil Health support the agenda of improving soil health across the country through research, implementation, and partnership. The strides of nonprofits such as the World Wide Fund for Nature, The Nature Conservancy, Bill and Melinda Gates Foundation, and the advancing technologies of big and small agribusiness can play a dominant role in shaping the future of healthy soils. Several state governments are actively taking steps to adopt agricultural practices to improve soil health and increase soil organic carbon sequestration. For example, the State of Maryland passed legislation on soil health in 2017, Massachusetts has proposed a bill to educate farmers about the soils, New York has introduced legislation to make tax credits available to farmers who increase soil organic carbon, and Hawaii has passed legislation to keep the state aligned with the Paris agreement and also created a task force to research carbon farming. Other carbon farming projects are also progressing in Colorado, Arizona, and Montana (Velasquez-Manoff, 2018). California has led the way on carbon farming with the California Healthy Soils Initiative enlisting agriculture as a key component toward climate mitigation besides setting aims to reduce greenhouse gas emissions.

In early 2019, a group of agricultural traders and food companies launched the Ecosystem Services Market Consortium, a market-based approach to pay farmers and ranchers to adopt conservation management practices to improve soil health and reduce emissions. Although in the pilot stage, the consortium ushers a new source of funding to support soil health. The visibility of soil health and its evolving understanding has advanced with increasing coverage in leading communication outlets such as National Geographic, The New York Times, and other articles, videos, and documentaries. In the op-ed piece in New York Times (Velasquez-Manoff, 2018), the author describes that increased carbon storage was possible on the semiarid grasslands with the use of good soil management practices, and in a matter of a few years resulted in better soil health. This and other articles on regenerative agricultural practices, such as no-till, ground cover, less herbicide, and fertilizer use, have spurred public interest and conversations on improving soil health.

## 2. Soil health indicators

Various organizations in the United States have proposed indicators to assess soil health. These indicators refer to measurable attributes used to evaluate overall soil health or detect the effect of management practices on soil health. The goal of utilizing indicators is to be able to tune indicator values relative to a threshold level reflective of the natural state. The indicators can be used across various environmental, biological, economic, social, institutional, and political disciplines to represent soil conditions and track changes in soil health (Allen et al., 2011). The main criteria for selecting soil health indicators of an agroecosystem and making sound management decisions are (i) good correlation to key soil functions, (ii) sensitivity to management practices, (iii) cost and ease to measure in standard laboratory settings,

(iv) accuracy and repeatability, and (v) usefulness that refers to standalone interpretability and/or interpretability in conjunction with other indicators for understanding soil health status (Laishram et al., 2012; Stott, 2019). Once the appropriate soil health indicators are selected, operating procedures for various analyses should be standardized. Variation in procedures for an indicator measurement is a drawback that needs to be addressed by agencies and laboratories. As with the indicators, soil sampling, storing, and processing (field and laboratory methods and protocols) of samples before analyses need to be standardized. It is also imperative that as techniques evolve and the knowledge base builds and expands, new soil health indicators should be evaluated. This implies a need to review and update the indicators, perhaps every 3–5 years (Stott, 2019).

## 2.1 Domains of soil health indicators

The major indicators used to assess soil health have been categorized into three groups: physical, chemical, and biological (Moebius-Clune et al., 2016). Fig. 4 shows a simplified overview of select soil health indicators, where a measure of the *water availability* spans in the physical domain as it is influenced by texture, bulk density, and aggregation, *nutrient availability* in the chemical domain as it is influenced by pH, EC, cation exchange

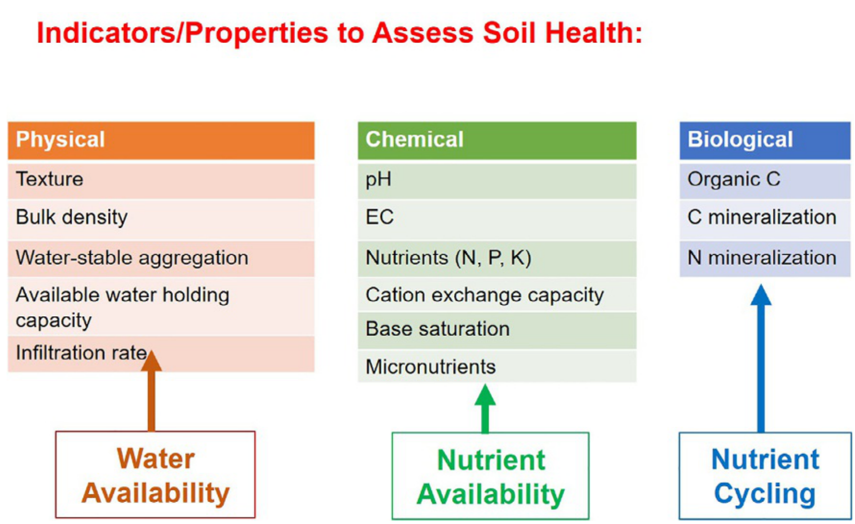


**Fig. 4** A simplified overview of soil health indicators in the physical, chemical, and biological domains.

capacity, and base saturation, and *nutrient cycling* in the biological domain as it is influenced by organic carbon, and mineralization of carbon and nitrogen. While the chemical and physical indicators have been used to assess soil physical and chemical properties for decades, biological indicators have traditionally occupied the backseat with their role in soil health being complex and difficult to isolate and measure. Historically and still today, soil assessments have been focused on soil nutrients (i.e., chemical indicators), fulfilling agronomic requirements, and providing management recommendations (Cardoso et al., 2013). Though soil biology has been an important component in the soil health discussion, it is only in the last few decades with an enhanced focus on soil health and advancements in soil microbiological techniques that biological indicators are now front-runners in deciphering the health of soils. Many biological processes are responsible for important soil functions, such as decomposition of organic matter, mineralization of and recycling of nutrients, nitrogen fixation, detoxification of pollutants, maintenance of soil structure, and biological suppression of plant pests and parasites (Brackinic et al., 2017). These processes are also closely linked to both the chemical and physical properties of soils. While all this information will lead to a better understanding of soils, one could argue that farmers do not need this complex information to successfully grow crops. Similarly, human health is assessed with annual exams that measure key indicators like heart/lung function and guidance for nutrition and fitness. More complex health testing only occurs when symptoms dictate the need for them, so cancer screening only occurs as risk and symptoms require. From the perspective of plants, water and nutrient availability are the two most essential needs. As water and nutrients in soils are influenced by other variables, a measure of these variables can provide a proxy for the likelihood of their availability to successfully grow crops.

## 2.2 Recommendations for soil health indicators

The Soil Management Assessment Framework (SMAF), developed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) and Natural Resources Conservation Service (USDA-NRCS), uses select soil health indicators, which translate the measurements to site/soil-specific conditions (Andrews et al., 2004). The site-specific conditions include textural class, suborder soil organic matter (SOM) content, iron oxide ($Fe_2O_3$) content, mineral class, climate, weathering class, slope, sampling time, crop sequence, and land management practices; all of these impact soil physical, chemical, and biological properties. Thus, SMAF interprets soil health indicator measurements to assess management effects on soil functions in croplands and pastures. Recently, USDA-NRCS issued a technical note for a group of recommended standard methods for soil health indicators, which have been selected by a collaborative multi-organizational effort (Stott, 2019; USDA-NRCS, 2018). These efforts identified six key soil physical and biological processes linked to measured indicators that must function well in healthy soil. Thus, the emphasis is on the relationship of soil health indicators to (i) organic matter dynamics and carbon sequestration, (ii) soil structural stability, (iii) general microbial activity, (iv) carbon food source, (v) bioavailable nitrogen, and (vi) microbial community diversity (USDA-NRCS, 2018). Hence, the need to standardize the methods to assess the soil health indicators is warranted.

The Soil Health Institute (SHI) is an independent, nonprofit organization established by the Samuel Roberts Noble Foundation and the Farm Foundation, which coordinates and supports soil stewardship. Fig. 5 shows the Tier 1, Tier 2, and Tier 3 indicators by SHI for characterizing soil health (SHI, 2020). The Tier 1 indicators are defined by soil groupings, with known thresholds, and the capability to suggest specific management strategies for improving soil functions. Examples of Tier 1 indicators include routine soil tests and others, as shown in Fig. 4, to assess water and nutrient availability. The Tier 2 indicators do not have known thresholds for characterizing healthy soils, but they add to the knowledge base for prescribing management practices. Some examples of Tier 2 include active carbon and bioavailable nitrogen. Though none of the biological indicators are included in Tier 1, there is a scope for upgrading based on research improvements. Tier 3 indicators have the potential to add significant information about soil health in specific locations, however, the relationship between measured values and soil processes needs to be first established.

The Comprehensive Assessment of Soil Health (CASH) framework developed at Cornell University, previously referred to as the Cornell Soil Health Test, was developed based on the SMAF paradigm; however, it gravitated more toward meeting the needs of the agricultural land managers (Moebius-Clune et al., 2016). Like a physician diagnosing a health ailment, the framework emphasizes the identification of specific soil constraints within agroecosystems, thus, warranting management solutions to increase productivity and minimize environmental impact (Idowu et al., 2009; Moebius-Clune et al., 2016; van Es and Karlen, 2019). In addition to the basic set of soil health indicators, the framework assesses add-on indicators like sodicity (amount of sodium), heavy metals, or root pathogen pressure rating.

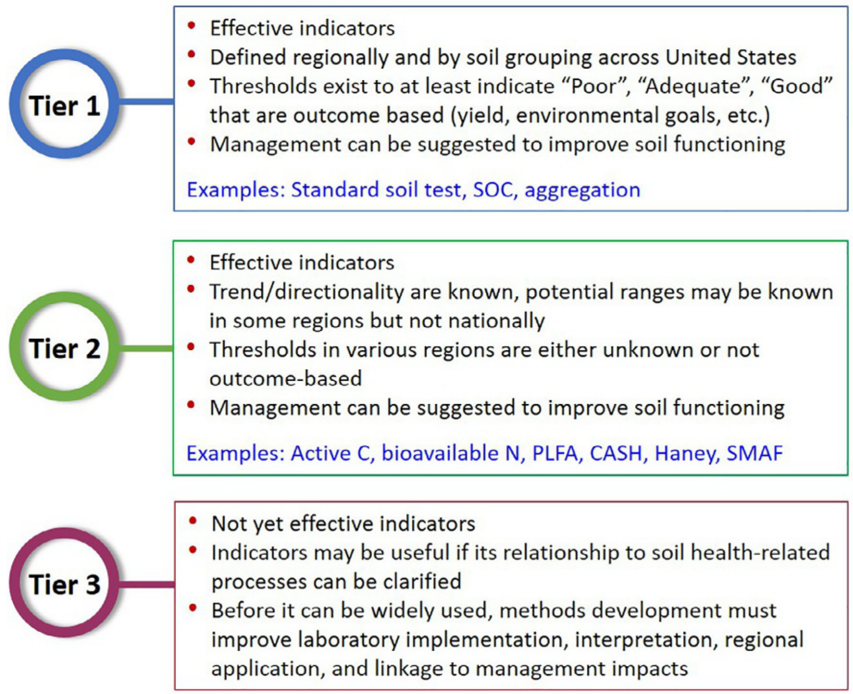


**Fig. 5** The proposed Tier 1, Tier 2, and Tier 3 indicators for characterizing soil health by the Soil Health Institute.

The Soil Health Tool, analyzing soil nutrient dynamics, has been developed by USDA-ARS scientists in Temple, TX. Previously known as the Haney soil health test (HSHT), it recognizes the soil as a living and highly-integrated system (Haney et al., 2006). The Soil Health Tool stands apart from other soil assessment systems as it incorporates indicators to measure both inorganic and organic forms such as plant-available nitrogen (nitrate-nitrogen, ammonium-nitrogen), water-extractable organic carbon, and water-extractable organic nitrogen (Haney et al., 2018). These tests provide insights into the quality of organic matter that provides the energy source for soil microbial activity (Haney et al., 2012) and uses the Haney, Haney, Hossner, Arnold (H3A) extractant (Haney et al., 2010), which is composed of weak organic acids that mimic plant root exudates.

The scientific literature shows that researchers have used a variety of indicators for assessing soil quality. For example, Bünemann et al. (2018) reviewed 65 studies and found that frequency of detection in soils was 15%–30% for four biological indicators, 15%–90% for 13 chemical

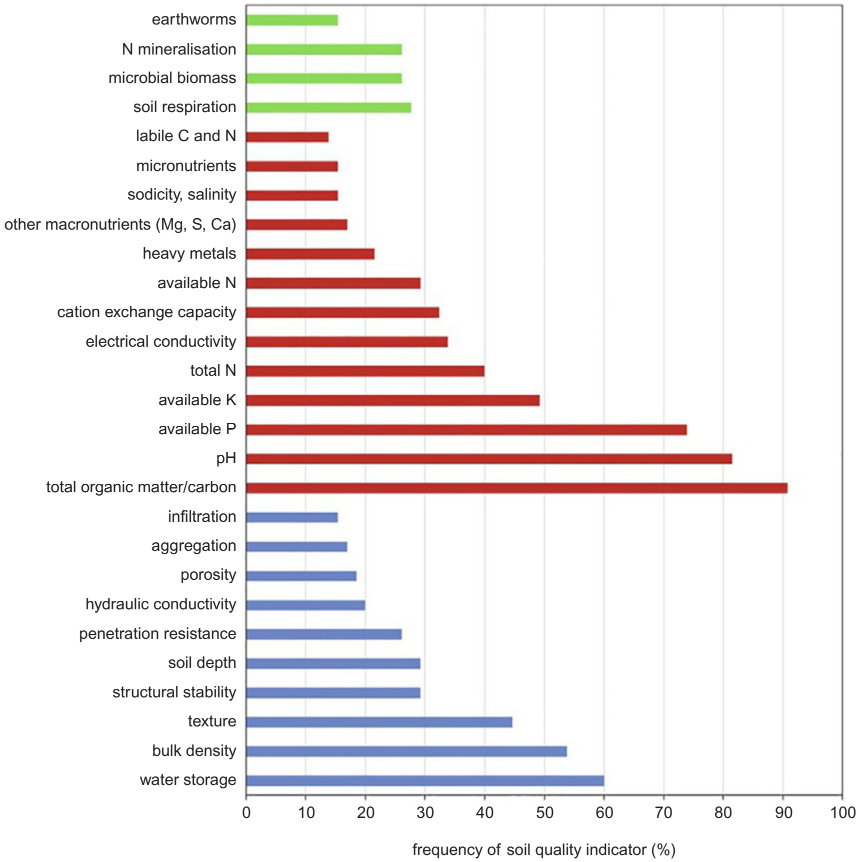


**Fig. 6** Percent frequency of detection of physical (blue color bars), chemical (red color bars), and biological (green color bars) soil indicators in the scientific literature on soil quality assessment. *Adapted from Bünemann, E.K., Bongiorno, G., Bai, Z., Creamer, R.E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T.W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J.W., Brussaard, L., 2018. Soil quality—a critical review. Soil Biol. Biochem. 120, 105–125.*

indicators with the highest detection for phosphorus, pH, and organic matter/carbon, and 15%–60% for ten physical indicators with the highest detection for texture, bulk density, and water storage (Fig. 6).

## 2.3 Interpreting soil health indicator values and determining soil health score

When soil health indicators are combined into different scoring systems, often using complicated formulas to generate weighted values, they can be used to ultimately produce an index for assessment. This soil health assessment aims to enhance end-user knowledge to improve effective soil management. Thus, an aggregated representation of assessment results of different soil parameters, or a soil health index is desirable. However, choosing indicators is a daunting task since it is difficult to determine which indicators and threshold values of indicators would be the best representation of a particular soil type or assessing the effectiveness of management practices to improve soil health. The rule of the thumb is to select indicators depending on soil management and specific soil functions that need attention for a particular soil type (Hubanks et al., 2018). Though it might be exciting to use a comprehensive list of soil health indicators to build an index, it is expensive and impractical. Many studies have indicated that selecting a few indicators is much more effective in detecting management impacts on soil quality (Andrews et al., 2002; Hubanks et al., 2018; Lima et al., 2013). Thus, a minimum set of easy and economic indicators are more appropriate for use in assessment and to construct a soil health index that is easy to interpret and use. Additionally, color coding or schematic/graphical representation of standalone indicators or when grouped as representative of soil functions are more helpful than building and interpreting complex soil indices.

## 2.4 Emerging soil health indicators

Though soil organisms play a central role in soil functioning, their present use as indicators is only focused on microorganisms. Macroorganisms such as earthworms, nematodes, micro/macro arthropods, and a suite of soil biota can be used as indicators of soil functions (Velasquez et al., 2007). Hence, there is room for improvement in investigating the scope of their use in soil health assessment. Molecular methods focusing on DNA and RNA offer faster, cheaper, and more informative soil biota measurements than conventional techniques (Bouchez et al., 2016). However, results obtained with the molecular methods are faced with biases introduced by spatial and temporal variability along with analytical issues (Bünemann et al., 2018; Schloter et al., 2018). The analysis of the "big data" generated with sequencing poses challenges in terms of time and interpretation as a large proportion of soil organisms have yet to be characterized in taxonomic and functional terms (Bouchez et al., 2016; Schloter et al., 2018). Thus, more research in the future will pave the way to investigate their use as mainstream indicators. Other molecular techniques such as metabolomics and metaproteomics may yield suitable indicators as measurements are directly linked to soil functions, but are limited in their application by the difficulty in extractions (Vestergaard et al., 2017). Stable isotope probing in conjunction with phospholipid fatty acid analysis (PLFA) and DNA probing could also help to link soil biodiversity to soil processes (Abraham, 2014; Fowler and Gieg, 2014). Soil spectroscopic techniques, such as near-infrared spectroscopy and soil remote sensing, offer the opportunity to measure various soil properties in a fast and inexpensive way (Gandariasbeitia et al., 2017). Combining laboratory-based visible and near-infrared spectroscopy with *in situ* measurements such as electrical conductivity (EC) can be useful in soil health assessments. In a nutshell, the use of innovative techniques to assess soil properties is exploding. Although one could argue whether a farmer needs all these detailed and complicated information to successfully grow crops.

Defining and assessing soil health in a changing climate requires regular updates to methodologies as most soil functions are influenced by global change drivers such as increased global temperature, elevated carbon dioxide, and changing precipitation patterns. Soil health indicators can help to measure the extent of the impact of climate change on soil health. Soil organic matter, soil organic carbon, aggregate stability, microbial biomass and communities, soil respiration, and enzyme activities are influenced by climate change. While soil health testing moves increasingly toward a minimum dataset of soil health indicators, choosing a minimum set should be done carefully to include those sensitive to climate change drivers.

## 3. Soil health and management practices

### 3.1 Practices to increase soil organic carbon stocks

Soil organic carbon plays a dynamic role in the global carbon cycle and climate change. Soils are the major reservoir of carbon in terrestrial ecosystems and regulate soil health and productivity (Mehra et al., 2018). Enormous scientific progress has been made in understanding soil functional characteristics relating to soil organic carbon dynamics in agroecosystems (Stockmann et al., 2013). Soil health relies heavily on organic matter and microbial activity in the soil, which correlates to soil organic carbon. It is thus necessary to include soil organic carbon in all soil health management plans to support sustainable agriculture and connect soil health to climate change mitigation policy (Lal, 2016). The potential of agricultural soils in mitigating climate change is often overlooked while strategizing for soil health improvements to obtain long-term agricultural benefits. Soil health assessments incorporating climate change mitigation may support the use of private capital investment in farming practices and meet an increasing regulatory burden. Soil assessments of land that has high value may further increase its economic value. All these benefits may ultimately garner political force for soil health assessments and initiatives (Moebius-Clune et al., 2016). Reproducible and accurate methods for soil health assessment are important for monitoring soil organic carbon sequestration.

Several studies have elucidated the link between cropland capacity to sequester increased soil organic carbon using less intensive tillage practices such as zone-tillage or no-tillage. Tillage results in significant fracturing of peds, reduced soil aggregation, mixing of soil horizons/loss of stratification, and decline in soil organic carbon stocks (Das et al., 2018; Dimassi et al., 2013; Six et al., 1999). Though there is an ongoing debate if such practices cause increased soil organic carbon stocks in the surface horizons while simultaneously causing decreases in deeper horizons, more long-term research is needed to refute such claims with scientific data. Management practices that replace annual crops with perennials introduce species with greater root mass, or crop rotations or adopt cover cropping, all provide greater carbon inputs, ultimately leading to increased soil organic carbon stocks. The addition of soil amendments that decompose slowly, such as compost and biochar, is also an important management strategy for increasing soil organic carbon stocks (Paustian et al., 2016).

Although considerable momentum has gathered around the soil health movement with emerging national/international frameworks and developing policies and incentives, there is tremendous room for improvement in soil health assessment matrices and testing their sensitivity across management practices and soil types (Roper et al., 2017; Stewart et al., 2018), in stakeholder engagement for developing assessment approaches for better adoption and outcome on the ground (Bünemann et al., 2018), for an increase in partnership and investment (Vermeulen et al., 2019), and for integrating soil health into climate-smart agricultural practices.

Enormous knowledge gaps exist in the area of implementing climate-smart agricultural practices in the field. While there has been great progress in understanding soil functional characteristics, their relation to carbon dynamics in agroecosystems (Stockmann et al., 2013), and elucidating soil organic carbon pools and their dynamics, soil's role in mitigating greenhouse gas emissions has been historically overlooked and connecting this aspect to soil health framework is lacking. The need is to incorporate climate-smart agriculture/soil management practices into the soil health equation (McCarthy et al., 2011; Paustian et al., 2016). Not much data are available about what specific additional resources or how much investments are needed or how much short-term yield reductions or other operational difficulties can be expected from climate-smart soil operations. Therefore, if the goal is to connect economic and environmentally sustainable agriculture with climate change mitigation, soil health processes need to promote the accumulation of organic matter (hence, organic carbon) and reduce agricultural greenhouse gas emissions.

## 3.2 Field practices to improve soil health

Sustainable agriculture is underpinned by preserving and protecting two natural resources: soil and water. This implies improving soil health is achieved by using field practices that enhance physical, chemical, and biological properties. Soil health field practices, as shown in Fig. 7, are based on four basic soil principles: (i) minimize soil disturbance, (ii) keep soil covered, (iii) maximize the period of living root growth, and (iv) maximize plant biodiversity (USDA-NRCS, 2018).

Building soil organic matter is increasingly recognized and viewed as the key principle of soil health improvement strategies. These four soil health principles essentially guide the broader framework for all soil health management practices. The strategy for improving soil health is not an all-inclusive list as they are interconnected with the goal to improve soil health. Here, we briefly discuss these principles and the associated soil strategies.

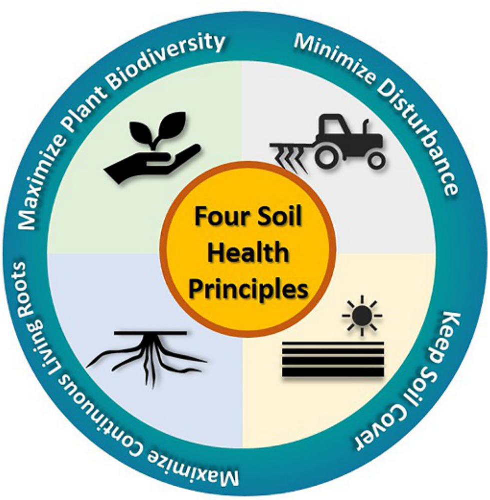


**Fig. 7** Four soil health principles.

*Principle 1: Minimize soil disturbance*. Soil disturbance can be physical, chemical, or biological. Physical soil disturbance is caused by conventional tillage systems involving primary operations such as soil loosening, weed removal, incorporating fertilizers, amendments, and secondary operations such as seedbed preparation before planting crops. Chemical disturbance includes fertilizer and pesticide applications (USDA-NRCS, 2018). Biological disturbance includes over-grazing animals and monocultures, which can lead to compaction and biological imbalance, reduced root mass, and increased runoff (Larkin, 2015). Excessive tillage using conventional tools, such as moldboard plow, chisel plow, disks, harrows, and rollers, causes adverse impacts on soil structure, which is at the centerpiece of soil health. These adverse effects include increased decomposition of organic matter, disruption of soil aggregates, creation of dense pans below the depth of plowing, increased runoff and erosion due to the lack of surface residues, and restricted root growth due to hardsetting (Abbas et al., 2020). To minimize soil disturbance, conservation or reduced tillage systems such as no-tillage, strip/zone tillage, ridge tillage are recommended as these reduce erosion by keeping more than 30% of the soil surface covered with crop residues (Abbas et al., 2020; Sims and Vadas, 2005; Singh et al., 2018). No-tillage farming has been highly recommended to improve soil organic carbon and soil health and reduce energy consumption (USDA-NRCS, 2016). The no-tillage system loosens the soil only in a very narrow and shallow area immediately around the seed zone. This localized disturbance is typically accomplished with a conservation planter (for row crops) or seed drill (for narrow-seeded crops). The leftover surface residue protects against erosion and increases biological activity by protecting the soil from temperature extremes. Surface residues also reduce evaporation, which when combined with deeper rooting, reduce soil susceptibility to drought (SARE, 2020). No-tillage systems sometimes have initial lower yields than conventional tillage systems, mainly due to the lower availability of nitrogen in the early years of no-tillage. Thus, increased nitrogen due to the legumes, manures, and fertilizers is necessary when transitioning from conventional tillage to no-tillage system. The zone-, strip-, and ridge-tillage systems disturb soil only in a narrow strip along the plant row and are more commonly adapted to wide-row and vegetable crops (Fig. 8).

No-tillage comprises land cultivation without soil disturbance and causes less soil erosion and more water infiltration than other systems (Busari et al., 2015). Soil quality improvement in zone tillage systems is similar to those of no-tillage. However, zone tillage is more energy-intensive and generally

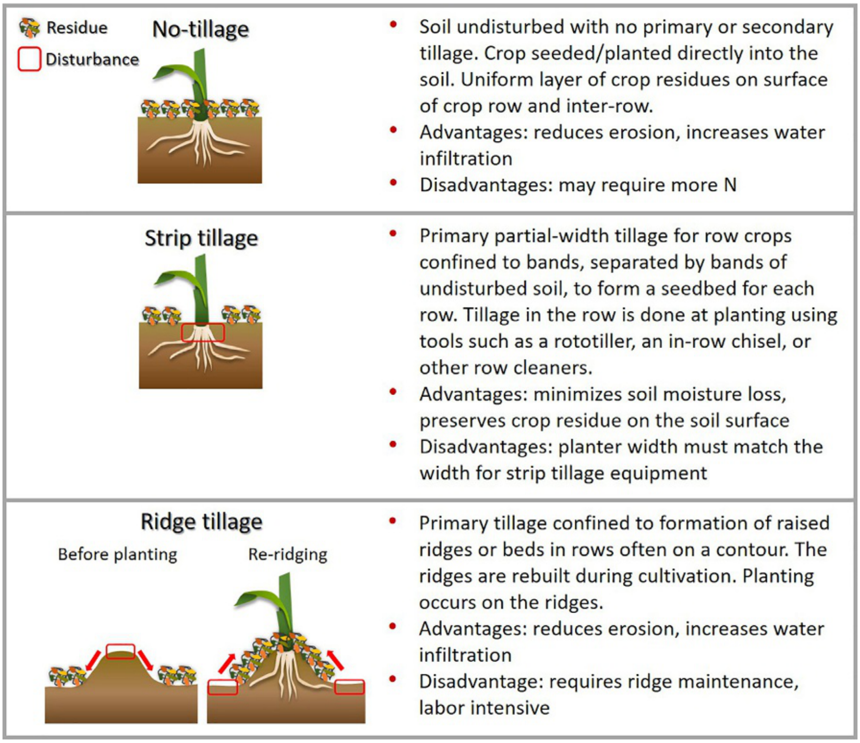


**Fig. 8** A visual depiction of no-tillage, strip tillage, and ridge tillage. *Redrawn from Williams, A., Kane, D.A., Ewing, P.M., Atwood, L.W., Jilling, A., Li, M., Lou, Y., Davis, A.S., Grandy, A.S., Huerd, S.C., Hunter, M.C., Koide, R.T., Mortensen, D.A., Smith, R.G., Snapp, S.S., Spokas, K.A., Yannarell, A.C., Jordan, N.R., 2016. Soil functional zone management: a vehicle for enhancing production and soil ecosystem Services in row-Crop Agroecosystems. Front. Plant Sci. 7. and Carter, M.R., 2005. CONSERVATION TILLAGE. In: Hillel, D. (Ed.), Encyclopedia of Soils in the Environment. Elsevier, Oxford, pp. 306–311.*

preferred over strict no-tillage systems in soils with compaction problems such as soils that receive liquid manure or where crops are harvested when the soil is wet, especially in humid and cold climates (SARE, 2020). Strip-tillage uses minimum tillage where the seedbed (15–30 cm wide) is tilled and cleared of residue while the area between the rows is undisturbed. Since most of the soil remains covered with residues and strip tillage uses shallow tillage shanks, it tends to reduce soil erosion, keep soil moisture, and reduce energy consumption (Fig. 8). In temperate climates, zone building and strip tillage are often performed in the fall before spring row crop planting to allow for soil settling. Ridge tillage combines limited tillage with a ridging operation and controlled traffic, which is useful in cold and wet soils. The ridging operation is often combined with mechanical weed control facilitating the band application of herbicides. In vegetable systems, raised beds and wide ridges provide better drainage and warmer temperature. In ridge-tillage, crop residues accumulate between the ridges, and in general, this increases water infiltration and reduces erosion.

*Principle 2: Keep soil covered*. When either living plants or plant residues protect soils, there is a significant decrease in erosion and increases in microbial activity, organic matter, and soil fertility. Cover crops keep the soil covered during periods of time, i.e., winter when cash crops are not growing. Thus, cover crops protect the soil and decrease erosion and enhance organic matter due to the biomass addition (Fig. 9). Other benefits of using cover crops include increased water infiltration, reduced nutrient loss, increased number of mycorrhizae, and weed and pest disease control (Sarrantonio and Gallandt, 2008). Cover crop residue also minimizes the impact of raindrops on the soil surface and serves as a habitat and food source for soil microbes. Cover crops also add carbon into the soil and help tie up nutrients, especially by scavenging nitrogen from the soil during winter (Hubbard et al., 2013). Cover crops can prevent some of the nutrient loss and recycle nitrogen, eventually releasing the nitrogen from the residue as soil organisms begin the decomposition process. Further, cover crops with taproots can create macropores and alleviate compaction, while fibrous-rooted cover

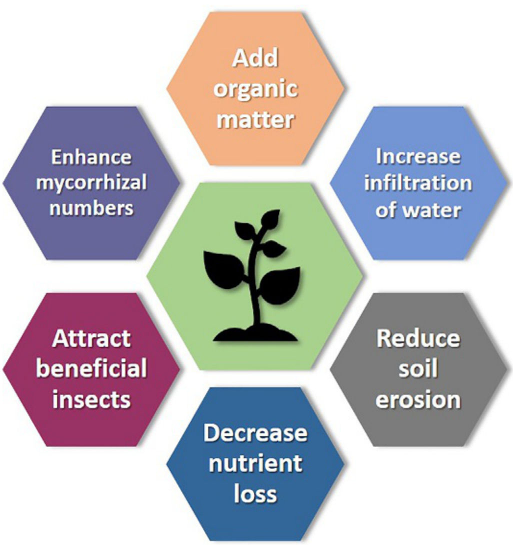


**Fig. 9** Examples of benefits of cover crops.

crops can promote aggregation and stabilize the soil (SARE, 2007). Legume cover crops can add nitrogen to the soil through nitrogen fixation. Choosing species that die in the winter (such as oats and radish) rather than species that overwinter (such as cereal rye and annual ryegrass) influences the amount of soil nitrogen scavenged and the timing of its release. As the use of cover crops reduces erosion, this can also reduce the loss of phosphorus attached to soil particles, however, the loss of dissolved phosphorus can still occur in fields planted with cover crops.

*Principle 3: Maximize the period of living root growth.* Keeping living roots with cover crops and perennial crops helps sustain the microbial population in the soil. When plants are alive, they produce sugars through photosynthesis, which are then released and lost in the soil through the roots. Live roots in the soil provide those exudates to the microbes to stimulate more activity, which leads to faster decomposition and contributes to nutrient cycling in soils. Thus, growing plants throughout the year, such as long-season crops, crop rotations, cover crops, can provide multiple benefits for soil health.

*Principle 4: Maximize plant diversity.* The diversity of plant species and plant-soil-microorganisms interactions promotes soil biodiversity. Healthy soil requires active decomposition, nutrient cycling, and soil functions, which can be accomplished with crop rotations, cover crops, and organic matter amendments. Diverse crop rotations offer plant diversity, which helps break up soil-borne pest and disease life cycles, improve crop health, help manage weeds, reduce nutrient losses from soils, and improve soil health (Larkin, 2015). Diverse plants in time and space in cropping systems release sugars, which support diverse food webs and energy chains essential for cropping systems and microbial activity in soils. Some examples of crop rotations include corn-soybean, continuous corn rotation, winter wheat-soybean, which provide benefits in the short-term (Mourtzinis et al., 2017). Cover crops diversity also contributes to healthy macro- and micro-flora in soils. Perennial crop species such as fruit trees and pastures use other practices to diversify plant species cover. For example, perennials can serve as a living mulch and further reduce soil disturbance and erosion during the wet season.

Apart from the cover crops, crop diversity and rotations, adding organic matter amendments such as composts, manures, mulches, and biosolids provide a source of active organic matter to supply crop nutrients in soils and can enhance soil physical (water holding capacity, bulk density), chemical (pH), and biological properties (Doran and Zeiss, 2000; Ryals et al., 2014). Composting transforms organic materials into stabilized compost, which provides numerous agronomic benefits. For example, biochar (charred organic matter produced by pyrolysis) is a soil amendment with multiple uses in agriculture, facilitating soil organic carbon sequestration and enhancing nutrient availability and soil health (Lehmann et al., 2006; Sohi et al., 2010). However, pure biochar addition to the soil in conventional agricultural practices does not necessarily increase soil quality and crop yields (Hagemann et al., 2017; Jeffery et al., 2015). The combination of biochar and compost has recently received increasing attention due to the promising results. The improved properties of co-composted biochar are thought to be due to the slow release of nutrients (Kammann et al., 2016), which results in the reduction of nitrogen leaching (Steiner et al., 2010), apart from increases in crop yields and improved soil health. In summary, combining no-till and cover crops in crop rotation system is a great way to achieve four soil health principles that will minimize soil disturbance, keep the soil covered over winter, maximize living root growth, and maximize plant diversity.

## 3.3 Soil health indicators sensitivity to agronomic management systems

A key aspect of using management practices is maintaining a balance between crop yield increase and soil health improvement. Hence, soil measurements and tests to evaluate soil health should be sensitive to management practices. The capacity of soil health indicators to detect changes in management over space and time within a few years is of prime importance and interest. However, the interpretation of soil health assessments is confounding due to the complexity of soil systems across different landscapes. Therefore, it is imperative to calibrate soil tests to quantify the responses to management on diverse soil types. This will help to provide recommendations that consider the limitations of different soils.

A nationwide meta-analysis based on 302 studies conducted in the United States examined four tillage intensities, including perennial cropping systems (zero soil disturbance), no-tillage (minimal soil disturbance), chisel plow (intermediate tillage), and moldboard plow (most intensive tillage), on soil organic carbon and biological soil health indicators (Nunes et al., 2020). The review indicated that the effects of tillage intensity on soil organic carbon were mainly in the topsoil (0–15 cm), and the soil organic carbon content was highest in sites with zero soil disturbance, followed by no-tillage, intermediate tillage, and most intensive tillage. Further, switching the tillage from most intensive to no-tillage in the topsoil increased soil organic carbon content and soil health indicators, i.e., microbial biomass, microbial biomass nitrogen, soil respiration, active carbon, soil protein, and beta-glucosidase activity. Similarly, a meta-analysis conducted by Virto et al. (2012) showed that soil organic carbon was 3.4 Mg/ha (∼7%) more in no-tillage than most intensive tillage systems. Residue decomposes more slowly under a reduced tillage system. One reason is that fewer aggregates are broken with less intensive tillage, so the less organic matter is exposed to decomposition. A second reason is that reduced tillage can make soil temperatures slightly cooler, which helps to preserve more organic matter because the residue is not rapidly decomposed. Moreover, reduced tillage does not disrupt earthworm burrowing and helps protect the network created by mycorrhizal fungi that connects them to their host plant. Leaving residue on the soil surface also acts as a barrier against raindrops and wind that could cause erosion. Overall, these studies suggest that soil health can be improved by reducing tillage intensity, planting cover crops, and keeping crop residue and that biological soil health indicators associated with labile carbon and nitrogen are most impacted by management practices such as tillage intensity.

## 3.4 Nutrient management discussion as a core component of the soil health dialogue

Nitrogen and phosphorus are essential nutrients for plant growth. Fertilizers and amendments are added to soils to supplement nutrients essential for optimum plant growth. It is estimated that 40%–60% of crop production is supported by fertilizers (Johnston and Bruulsema, 2014). However, groundwater and surface water pollution from excess nutrients occurs unless timing, application method, and the amount of nutrient applications are carefully managed. Best management practices (BMPs) for nutrients are farming methods designed to minimize adverse environmental effects while maintaining agricultural production. Though the primary focus of such BMPs is to meet crop nutrient demands and reduce nutrient loss from the application area to the water bodies, key aspects of soil health can be simultaneously addressed with these BMPs. Nutrient BMPs are popularly referred to as the "4R"s—Right source, Right time, Right rate, and Right place (Fig. 10). Right source means matching the fertilizer product or nutrient source to the crop needs and soil type to ensure a balanced supply of nutrients. Right time means making fertilizer nutrients available when crops need them by assessing crop nutrient dynamics. Right rate means matching the fertilizer applied to the crop need. Right place means keeping

| 4Rs | Scientific basis | Associate practices |
|---|---|---|
| <br>Right Source | • Supply in plant available forms<br>• Suit soil properties<br>• Recognize synergisms among elements<br>• Blend compatibility | • Commercial fertilizer<br>• Livestock manure<br>• Compost<br>• Crop residue |
| <br>Right Time | • Assess timing of crop uptake<br>• Assess dynamics of soil nutrient supply<br>• Recognize timing of weather factors<br>• Evaluate logistics of field operations | • Apply nutrients:<br>Pre-planting<br>At planting<br>At flowering |
| <br>Right Rate | • Assess soil nutrient supply<br>• Assess all available nutrient sources<br>• Assess plant demand<br>• Predict fertilizer use efficiency<br>• Consider rate-specific economics | • Test soil for nutrients<br>• Balance crop removal |
| <br>Right Place | • Recognize root-soil dynamics<br>• Manage spatial variability<br>• Fit needs of tillage system<br>• Limit potential off-field transport | • Broadcast<br>• Band/drill/inject<br>• Variable-rate application |

**Fig. 10** 4R nutrient stewardship approach. *Redrawn from IFA, 2009. The Global '4R' Nutrient Stewardship Framework. International Fertilizer Industry Association, Paris, p 10. and Richards, M., Butterbach-Bahl, K., Jat, M., Lipinski, B., Ortiz-Monasterio, I., Sapkota, T., 2016. Site-Specific Nutrient Management: Implementation Guidance for Policymakers and Investors. Practice brief on CSA.*

nutrients where crops can use them. The 4R guidelines were developed as a process to guide fertilizer BMPs to ensure fertilizer application can be managed to achieve economic, social, and environmental goals set by stakeholders. How 4R principles are used locally depends on the field and site-specific characteristics such as climate, soil types, management practices, and regulatory constraints. For example, in the Corn Belt states of the mid-west United States, phosphorus fertilizer is typically applied in advance of crop planting or for multiple crops in the rotation (Johnston and Bruulsema, 2014). In general, it is recommended to choose an ideal method to incorporate nutrients into the soil based on soil, crop, type of fertilizer, and tillage regime. To estimate the right rate of fertilizer, knowledge about the expected yield in a field, and the associated removal of nutrients from the field is needed. Further, nutrient management needs to go hand-in-hand with major or subtle changes made to soil management strategies, such as adjusting fertilization rates after switching from conventional tillage to reduced tillage or introducing cover crops, increasing organic matter inputs with waste products (Debaeke et al., 2017). Using diverse nutrient sources can help to maintain soil health. For example, compost or manure to meet the nitrogen needs of the crop can result in excessive phosphorus addition in the soil. Combining modest manure or compost additions to meet phosphorus needs with additional nitrogen inputs from legume cover or forage crops in a crop rotation can balance nitrogen and phosphorus inputs. This will translate to nutrient balances on farms and less risk of nutrient losses in runoff and leaching. Fertilizer application must be optimized, as soil microbiota are extremely sensitive to nutrient doses. With optimum nutrients, plants grow quickly and better withstand pest damage, soil microbes, and soil fauna thrive optimally for maintaining necessary soil functions.

## 3.5 Linking soil health to soil functioning and ecosystem services

Ecosystem services are the wide range of goods and services that nature provides to society (MEA, 2005). Though studies have typically linked soil properties to different ecosystem functionalities, very few have directly connected soil health or key soil properties to ecosystem services. Ecosystem services fall under four groups: provisioning, regulating, cultural, and supporting (nutrient cycling, production, habitat, biodiversity) (Fig. 11) (Adhikari and Hartemink, 2016; Smith et al., 2013). Provisioning services relate to products such as food, freshwater, wood, fiber, and fuel. Regulating

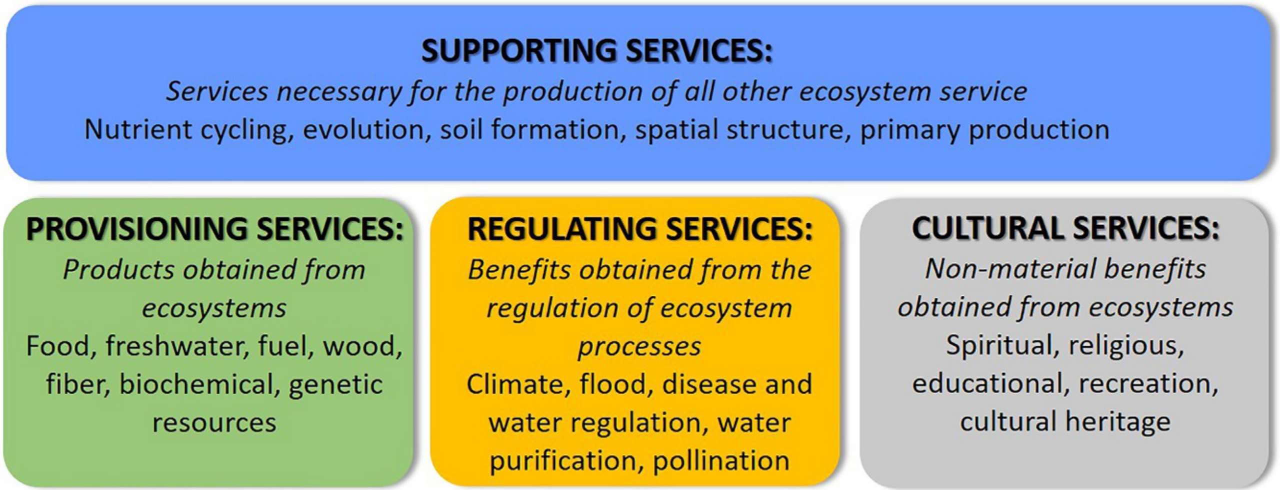


**Fig. 11** The four groups of ecosystem services. *Redrawn from Ecosystem Services Mid-Atlantic Regional Ocean Assessment 2020 (https://roa.midatlanticocean.org/ocean-ecosystem-and-resources/characterizing-the-mid-atlantic-ocean-ecosystem/ecosystem-services/).*

services include benefits such as regulation of gas and water, climate, and pollination, and diseases. Cultural services are the non-material benefits that people obtain from ecosystems such as recreation, cultural heritage, and religious services. Supporting services include soil formation and habitat sustenance, which are necessary to produce ecosystem services. While soil physical and chemical properties in relation to regulating and provisioning services have been studied the most, soil organic carbon is the most studied parameter in relation to regulating services (Adhikari and Hartemink, 2016). Supporting services are also linked to soil physical, chemical, and biological properties. To move the soil health conversation forward, we suggest linking and quantifying the connection between soil health and ecosystem services.

Soil functions refer to soil-based ecosystem services. An overview of the ecosystem services delivered by soils that enable life on earth is given in Fig. 12. The soil functions selected by Food and Agriculture Organization (FAO) include carbon and nutrient cycling, water cycling and quality,

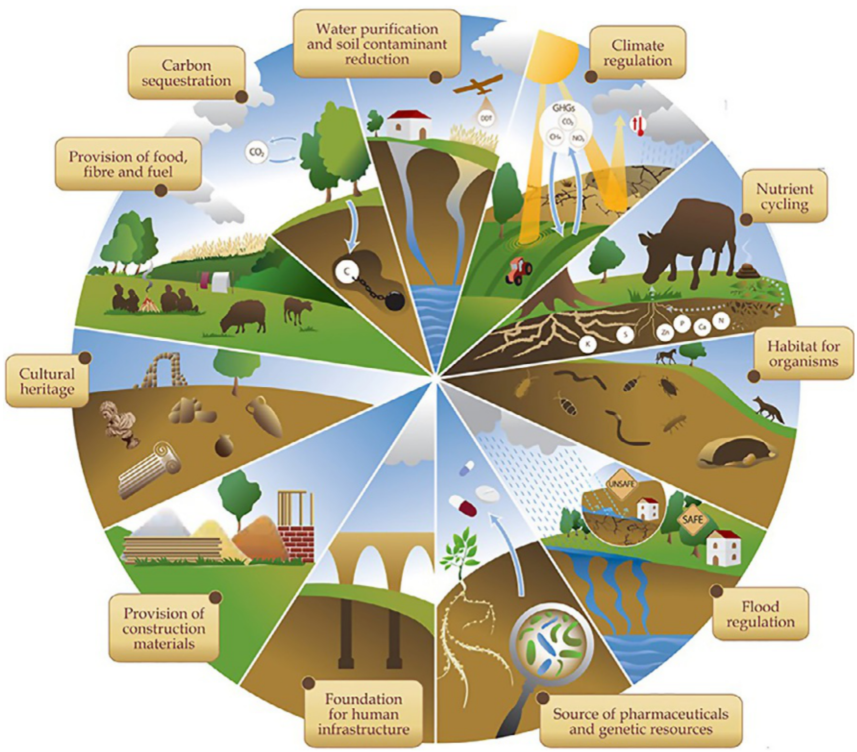


**Fig. 12** An overview of ecosystem services delivered by soils. *Source: http://www.fao.org/resources/infographics/infographics-details/en/c/284478/*

filtering and transforming compounds, support through the provision of physical stability and habit for organisms (Ball et al., 2018).

Soil contains large amounts of stored carbon (~1500 petagrams), nearly two times higher than the atmosphere, and three times higher than the vegetation (Vicente-Vicente et al., 2016). Soil provides nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and other trace elements. Physical, chemical, and biological processes in the soil affect the balance in soil organic carbon as well as other nutrients. For example, in flooded areas, methane, which is produced by methanogenesis from microbial metabolism under anaerobic conditions, can cause significant gaseous carbon efflux (Oertel et al., 2016). Schröder et al. (2016) identified four processes of nutrient cycling which include: (i) the capacity of receiving nutrients, (ii) the capacity to make and keep available nutrients for crops, (iii) the capacity to support the nutrient uptake by crops, and (iv) the capacity to support nutrient removal in the harvested crop. Each step of carbon and nutrient cycling relies on the properties of soil, local climate, and management options, which may enhance one of the processes of cycling and weaken others. Agricultural practices such as fertilization application and enteric fermentation in animals and land use changes result in part of the stored carbon and nutrients loss to the environment. For example, extensive use of fertilizers in some areas has resulted in greenhouse gas emissions (e.g., carbon dioxide, methane) and eutrophication in water bodies (Galloway et al., 2008; Oertel et al., 2016). Overall, the balanced nutrient cycling in soil must be maintained to sustain soil function (FAO and ITPS, 2015).

Soil functions associated with water cycling include storing (storage), accepting (sorptivity), transmitting (hydraulic conductivity), and cleaning (filtering) of water (FAO and ITPS, 2015). Infiltration rate and soil hydraulic conductivity control soil water storage. Water content and transmission times control the supply and removal of contaminants in soil and affect the cleaning function of soils. Water quality involves multiple parameters such as nutrient levels, organic pollutants, suspended sediments, color, and temperature (Smith et al., 2013). In broad terms, water quality is mostly associated with sources and processes in a given catchment. In agricultural landscapes, water quality issues include runoff of nutrients, suspended sediments from soil erosion, and organic contaminants from livestock. The management of water bodies and adjacent land (e.g., riparian buffer, floodplain) can help mitigate water quality impacts (Smith et al., 2013).

Further, better soil management is needed to protect and enhance water quality and optimize nutrient cycling under future climate change scenarios.

Soil supports the growth of diverse plants, animals, and microorganisms. It was estimated that 1 g of soil contains up to $10^9$ bacteria cells (Gans et al., 2005), up to $10^4$ species, and more than 100 m of fungal hyphae (Curtis et al., 2002; Leake et al., 2004). Soil habitat function is the provision of above- and below-ground habitats for communities of variety species (van Leeuwen et al., 2019). Soil biodiversity is critical to crop production, nutrient cycling, greenhouse gas emissions, and water purification (FAO and ITPS, 2015). Bacteria regulate biogeochemical cycling, benefit plant growth, and degrade organic contaminants in soil (Baer and Birgé, 2018). Microbial community composition in the soil can also affect disease and pests in agriculture (Smith et al., 2013).

## 4. Social and economic perspectives on soil health

### 4.1 Stakeholder perceptions and relevance

This is an exciting time in the history of the soil health movement in the United States. Many farmers are aware of the benefits of practices such as reduced physical disturbance, reduced tillage, cover cropping, perennial cropping and living roots, crop diversity, crop rotations, and intercropping. However, there is a long way before passionate stewards of soils emerge, armed with peer-reviewed knowledge of soil health assessments (with affordable access) that will translate to desirable functions. Many generational farmers are stewards of the land and have an interest in maintaining the health of their lands; however, the lack of knowledge or appropriate and easy access to the resources can hinder the implementation of strategies to improve soil health (Bhattacherjee, 2012; Hubanks et al., 2018). Success in adopting any soil health monitoring program/index/scoring system to address long-term improvements in soil health should be based largely on farmers' perceptions and receptiveness of soil health testing.

Farmers are not the only stakeholders in society's effort to understand and assess soil health. In recent years, the public sector, government, and non-governmental organizations (NGOs) have focused on soil health as a tool to support carbon sequestration for climate mitigation. Additionally, various advocacy groups have connected soil health practices with a value-based assessment of farming and farming practices (Ingram and

Mills, 2019; Jian et al., 2020). These sectors, NGOs, and consumers represent both an opportunity and a threat to effective soil management. The attention of trusted environmental conservation NGOs like the World Wildlife Foundation, The Nature Conservancy, and Environmental Defense Fund can influence consumers to value agricultural practices that prioritize soil health management. Smaller, more national and regional NGOs like African Forest Landscape Restoration Initiative and Aga Khan Rural Support Program in India, DeCo!, A Ghanaian NGO, and many others work at the regional and local levels to build trusted relationships with farmers and consumers. Informed consumers can exhibit a willingness to pay for soil health practices through labeling of products or government subsidies and cost-share programs. However, without science-based evidence, the advice of well-meaning intermediaries could confuse or result in adopting practices that have no soil health benefits.

In developed nations, the number of consumers who know a farmer or rancher is dwindling as the proportion of farmers in a population is declining with time. For example, currently only ~1% of the U.S. population constitutes farmers (USDA, 2020), which can result in a disconnect that can be used to demonize the farming community. Terms like "factory farming" imply that large corporations own and run most farms when, according to the USDA, 98% of farms are family-owned (Burns and MacDonald, 2018; USDA-NRCS, 2018). Advocacy organizations may push a message that only small farms are *good*, thus demonizing conventional or larger farm operations. The advocacy groups urge the implementation of regenerative agriculture with specifics like composting yet do not provide credible or measurable outcomes to measure the impact on runoff, animal welfare, or local food availability. Thus, the NGOs pick "winners and losers" by subjectively naming good farmers (small regenerative) and bad farmers (large conventional). The support fails to address agricultural practices' economic needs and challenges and imposes an arbitrary assessment on farming. This subjective approach can threaten both the non-agricultural benefits of soil health, pollution reduction, climate mitigation, and the economic well-being of food producers because it may fail to recognize objective soil health management. Like ecological systems, economies thrive on diversity and innovation; thus all agriculture, both large and small, should receive incentives to support soil health with objective metrics.

If goals external to agriculture like climate mitigation through carbon sequestration are to be realized. In that case, society must support the additional costs associated with soil health management in the largest farms as well as small and subsistence farming. The opportunity of NGOs, both multinational and national, to support consumer awareness of soil health is needed to promote the implementation of sometimes expensive and long-term soil health practices. Realizing this opportunity requires that metrics link practices to measured outcomes, which are then consistently applied across regions, soil types, and agricultural practices. So, soil health must have objective metrics so that society can support practices that achieve agricultural benefits and environmental co-benefits.

Support will come when stakeholders understand the issue and have buy-in for the soil health practices. Without understanding or trust, it is unlikely that consumers will value and thus pay soil health practices. Trust needs to be built with the science-based evidence of soil health indicators across all agricultural sectors and landscapes. In summary, value-based management will not support specific goals, like carbon sequestration, efficient nutrient cycling with solvent agricultural practices, and effective good public policy that needs to be grounded in measurable outcomes.

## 4.2 Communicating soil heath to end-users

Effective communication of the benefits and costs of improved soil health to end-users requires trusted sources of information for both the farm community and consumers. Consumers are responsible for directly paying for food or indirectly for cost-share and government subsidies for farms. Some U.S. farmers have existing and established sources of information like Agricultural Extension and other academic sources, federal and state agencies, industry representatives, like Farm Bureau and nonprofit think tanks like the Farm Trust. These trusted sources use information from agronomic research and convey information applicable to farming and consider the economic impact of practices. In contrast, consumers' access to trusted and science-based information is more tenuous (Clapp, 2012).

On the other hand, consumers rely on the media and occasionally on NGOs as sources to interpret complex information. Thus, science communication to these intermediaries must provide easy to understand chunks of information conveyed in a framework that holds the audience's interest. Careful management of information is required when research improves or changes paradigms. Without consideration of the risk associated with science communication, it is easy to lose trust and, therefore, the buy-in of important stakeholders like consumers and decision-makers whose interest is inherently connected to funding.

Scientists and farmers often convey information without considering the frame around which intermediaries are positioning these facts. Intermediaries access stakeholders' limited attention by selecting one perspective like the environmental benefit of soil health and may omit the cost of the practice (Druckman and Lupia, 2017). Thus, communication requires that scientists understand the frame from which an intermediary is discussing soil health. NGOs will have a mission statement that should accurately describe the organization's priorities like climate change or public health. Care should be taken to accurately communicate realistic soil health outcomes for nutrient reduction, carbon sequestration and/or economic benefit to farmers vs aspirational or value-based outcomes associated with farming practices.

The reality of communication intermediaries, therefore, involves risk in conveying preliminary outcomes. Health communication offers a valuable comparison. As science progresses in healthcare, it inevitably evolves to incorporate complexity, much like cholesterol and the concept of "good" and "bad" cholesterol. To be effective, the patient must have a trusted source of information to convey complex information. The alternative is for a patient to reject health advice as conflicted "I thought cholesterol was bad now you're telling me its good? I give up." Medical doctors use markers like "bad cholesterol" or low-density lipoprotein levels should be less than 100 mg/dL and high-density lipoprotein or "good" and total cholesterol should be between 125 and 200 mg/dL. Similar markers and measures are needed to effectively convey the complex and changing field of soil health management, although these might not be realistic given that soils are complex. If the public knows that a particular farm soil has high soil organic carbon, and this aligns with their food production goals, then their willingness to pay a premium can be triggered. If the message is confused or the accuracy of the threshold is questioned, trust is breached along with the interest and support for investment in soil health practices (SHI, 2018).

## 4.3 Economics of maintaining and measuring soil health

Farmers operate complex business models with competing needs, like managing profits by balancing increased yield with the increased cost of inputs.

Often, the primary driver of economic viability is yield, and farming practices that increase yields are preferred. The profit margin of yield is impacted by external market conditions that may be local or global, the fixed costs associated with equipment, and the variable costs associated with inputs. External factors like global pricing and weather are often out of the control of farmers and must be considered a risk to be managed effectively. Practices that offer an immediate increase in yield are therefore selected to increase the profits of a farm. Practices like soil health that may take years to show yield improvements through increased production, decreased costs, or risk management must be more carefully considered before they are adopted. These considerations are more relevant when a farm practice operates on a minimal profit margin or in a high-risk environment.

The public has an interest in increased use of soil health practices on farms if those practices produce outcomes like greenhouse gas reduction and reduced nutrient runoff. Regulations and cost-share present farmers with a carrot or a stick scenario that can support soil health practices. However, if outcomes are not accurately and objectively measured, then the local/regional public policy can drive farmers out of business. Regulations put in place in one region, and not others can increase the costs of operating a farm resulting in an "uneven playing field." The reality or perception of increased business costs in one region will drive farmers out of that region and areas with decreased costs. This has already happened in the United States, where many beef cattle lots have moved to the western states and several lots have further moved out of the county to Mexico. Cost-share programs can provide enough value to support the incorporation of new practices. For example, Maryland has the highest adoption of cover-crop in the United States because a statewide cost-share program offsets most of the costs of the practice (Hamilton et al., 2017). Thus, farmers can realize the long-term benefits of cover crops like reduced soil erosion and improved soil health while the public may realize a measurable decrease in the nutrient runoff. Successful public policy depends on outcomes that are consistent and verified. The cost-share program in Maryland is supported by the research and modeling that measures nutrient reduction (e.g., Staver and Brinsfield, 1998). Without trusted measurements, support for the policy will diminish either through the lobbying of industry representatives or the loss of willingness to pay for cost-sharing if the public does not perceive value in outcomes.

Private sector investment is another tool that can support the adoption of expensive or time-consuming agricultural practices. Nutrient and carbon trading requires some entity, often a government, to impose a value on a measured outcome. A market can be developed with demand generated by government-imposed limitations on the amount of pollution that different sectors can produce—the more stringent these limitations, the higher value the nutrient reduction on the supply side of the market. The supply side of the market is developed when entities like wastewater treatment plants upgrade facilities beyond their permitted requirements. The difference between the maximum permitted nutrient release, and the actual amount of nutrient discharge can be quantified and traded or sold to an entity that cannot meet their permit requirements.

Trading markets depend on trusted, independently verified results (Choi and Storr, 2020). The same models and objective research that supports the cost-share programs can support nutrient trading for farmers. Where clear markers can establish that a farm has adopted pollution reduction practices above nutrient management standards, then the excess supply of nutrient controls could be sold on a trading market. Nutrient management standards are a regulatory control that can produce a baseline of practices that society requires. In areas without regulations, any adopted nutrient management, including soil health practices, can be sold on trading markets. Some trading markets prohibit public funding for practices to ensure that benefits are additive to existing subsidies. Conservation farming practices are often the most cost-effective way to reduce nutrient inputs in a region.

Similar to nutrient controls, carbon sequestration as a tool to mitigate climate change has used private capital investments along with regulations and cost-share approaches. Cap and trade programs have been used to value carbon dioxide reduction globally. This approach sets an emission maximum (cap) and allows market forces to determine how best to achieve the results (https://www.c2es.org/content/cap-and-trade-basics/). Cap and Trade has been in place in Europe since 2005 and has expanded to include North America, Europe, and parts of Asia. In the United States, an effort to establish a national program was defeated in 2009; however, two regional efforts have come into being, one in California with connection to Quebec Canada and the Regional Greenhouse Gas Initiative (RGGI) in the Northeast and mid-Atlantic states.

The agriculture sector has yet to fully engage in these markets despite efforts in California, where credits can be generated by adopting conservation practices by rice producers and rangeland managers (Lehner and Rosenberg, 2017). RGGI has approved only forestland sequestration and methane capture from manure management. The low cost of carbon credits represents the primary reason for the low engagement of agriculture in these programs (Antle et al., 2007), but other impediments slow adoption. Farmers are suspicious that cap and trade programs are simply a pathway to additional regulation. The complex transactional costs can themselves limit interest by farmers to participate in the markets, especially where they require disclosure of practice history, inputs, and soil types. Suspicion of the intent of these government-controlled markets in an environment of increasing agricultural regulations often prevents engagement. Finally, carbon trusted and verified standards need to be accepted and applied across diverse soil types and farming practices. Secondary economic incentives may include private capital investment opportunities like nutrient trading and carbon trading. These secondary benefits will not provide enough capital to sustain a farm but may boost profit to offset external factors like market volatility and weather impacts.

Carbon markets require an accurate and verifiable carbon measure to be valued in an economic framework. Without consistency across practices and regions, the market will not survive. Other questions that need to be addressed are over what time frame should carbon sequestration be measured? Research suggests that several years (~5 years) after the implementation of field practices are needed to observe differences in soil organic carbon. The methodological constraints given the tremendous spatial variability in soils further present challenges in accurately quantifying soil organic carbon levels (e.g., Yang et al., 2020). Yang et al. (2020) used a grid-sampling approach to determine the variability and current soil organic carbon stocks in three typical Maryland agricultural fields. Each field was divided into eight grids (20 × 25 m) for soil sample collection at three fixed depths intervals (0–20 cm, 20–40 cm, and 40–60 cm) (Fig. 13). They reported that soil organic carbon stocks in the top 60 cm depth ranged from 37 to 47 Mg/ha, and suggested that re-sampling these grids in the future can lead to accurately tracking changes in soil organic carbon stocks in agricultural fields. Fields, with sandy soils have a low ability, to sequester carbon, and so the incentive framework for these farmers is different. In fields with little potential for carbon storage, it may be too expensive to increase soil organic carbon stocks. In contrast, in fields rich in carbon, there might not be a need or possibility to further enhance soil organic carbon stocks. Whereas in the fields in the middle may present an opportunity to improve soil organic carbon stocks.

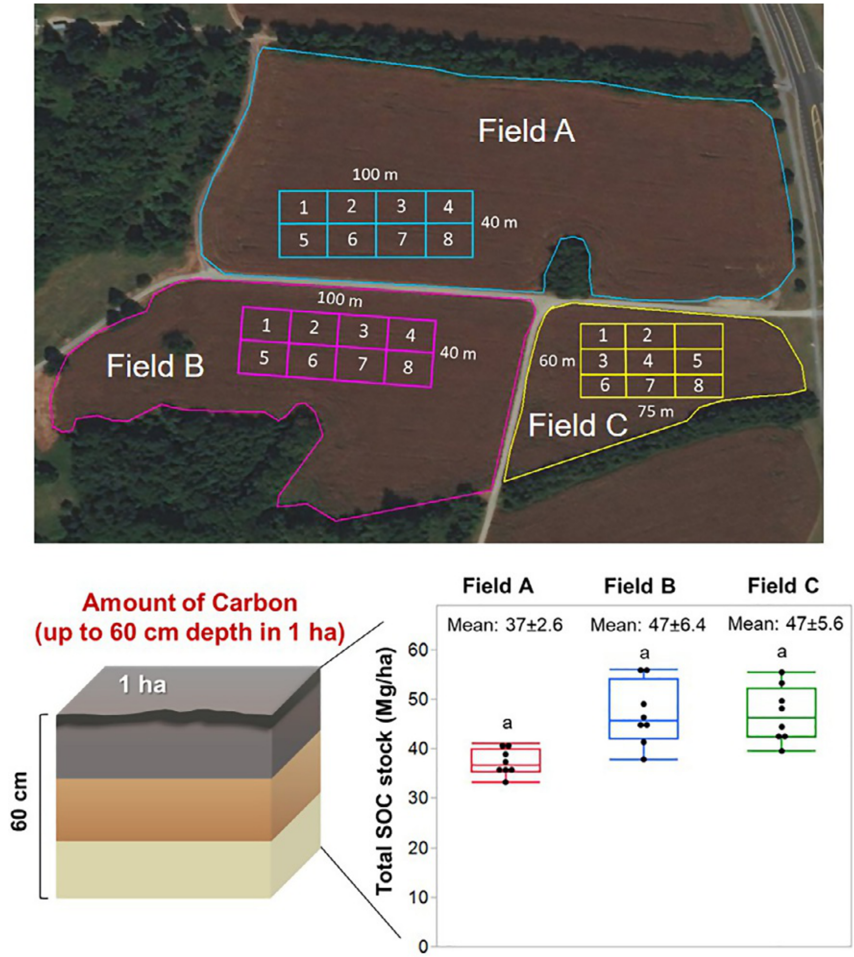


**Fig. 13** Soil organic carbon stocks at 0–60 cm depth in eight sampled grids in three typical agricultural fields in Maryland, United State. *Adapted from Yang, Y.-Y., Goldsmith, A., Herold, I., Lecha, S., Toor, G.S., 2020. Assessing soil organic carbon in soils to enhance and track future carbon stocks. Agronomy 10, 1139.*

## 5. Knowledge gaps, future directions, and conclusions

The tremendous interest in soil health, offer important perspectives on the connection of soil health (Bünemann et al., 2018; Hubanks et al., 2018; Stewart et al., 2018) to soil carbon and climate change (Mehra et al., 2018; Vermeulen et al., 2019). While Bünemann et al. (2018) is an exhaustive summary of the soil quality concepts and worldwide assessment procedures and principles, it lacks an assessment of whether procedures are working or not working. Hubanks et al. (2018) fails to make clear the availability of the state-of-the-art assessment procedures and the future directions of these assessments. Stewart et al. (2018), though, provides an in-depth meta-analysis of the key management practices and their link to soil health assessment indices but does not connect these to the big picture of soil health or its core principles. Based on the comprehensive literature review conducted as part of this review article, we have identified several knowledge gaps as discussed below and visually shown in Fig. 14.

*Gap 1*. The challenges of the applicability of soil health evaluation to detect differences in management strategies are increasingly being realized, as measurements of similar properties or indices vary across soil types in various physiographic regions. Interpreting measured values against a comprehensive database and calibrating against a site/soil type standard is the only way for precise soil health assessment, which can help in formulating effective management strategies. Unfortunately, this component is critically missing from most soil health evaluations or methods to establish scoring functions. Simply put, the inability of almost all soil health tests to factor in soil diversity information and thus provide standard, calibrated assessment results are a major drawback and a knowledge gap in soil health evaluation. This can be overcome by building a database of results from systematic and replicated surveys and soil health studies (short- and long-term) across varied soil types.

*Gap 2*. The lack of correlation between soil health assessment measurements and their correlation to crop yields (Dick, 2018; Roper et al., 2017) needs to be investigated. Hence, there exists tremendous scope to pair measured soil health values to climate, soil, management, pests, and disease parameters and to be able to predict plant yields. Establishing a clear relationship between improvements in soil health and crop yields will result in more buying-in from farmers and help move forward soil health.

*Gap 3*. The lack of consistent sampling techniques and protocols in soil assessment procedures is an important gap in our current understanding (Hubanks et al., 2018; Stewart et al., 2018). More research is needed to recommend a standard approach for soil sampling, and whether a grid-sampling approach as used by Yang et al. (2020) to investigate soil organic carbon stocks in agricultural fields in Maryland is suitable in other parts of the world. Further, various depths, a varied number of replicates, different types of equipment, procedures, and parameter choices, often make comparisons

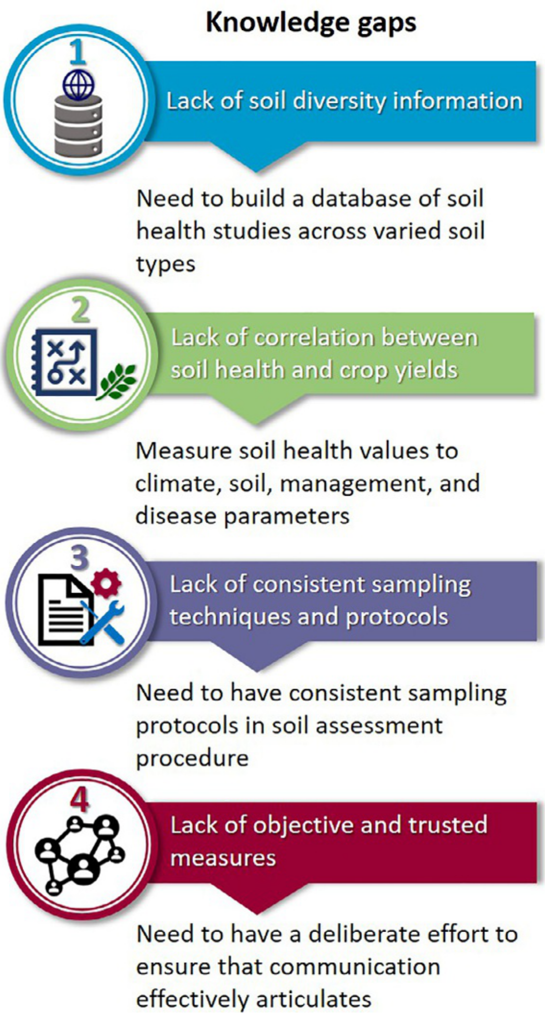


**Fig. 14** Knowledge gaps in current understanding of soil health.

difficult. Some parameters, such as water stable aggregates, are measured by outdated procedures that do not capture and soil health information.

*Gap 4.* A deliberate effort to ensure that communication effectively articulates the real and the unreal opportunities that soil health has in addressing societal needs is needed. Without objective and trusted measures, public policy and consumer buying trends could support agricultural practices that fail to produce desired outcomes like carbon sequestration, local food production, and nutrient reductions.

In addition to addressing these four knowledge gaps, future directions should result in one or more assessments made from objective and well-tested indices connected to desired outcomes. It may not be reasonable that the crop yield assessment is exactly the same as the assessment for carbon sequestration. However, the ability to accurately describe the current status of a particular farm/ranch within a soil health assessment spectrum tuned to recognize soil properties should be a goal. The science that underpinning these assessments should be well established. The assessments themselves should be easy to understand for lay people and decision-makers. For instance, a farm could be evaluated with "Soil Health Crop Yield Assessment" of 8 out of 10 based on both quantitative and qualitative parameters. The evaluation should list indices that produce the assessment. These could be Soil Health Carbon Sequestration Assessment: XX tons of carbon/acre; Soil Health Nutrient Reduction Assessment: XX Kg of nitrogen and XX Kg of phosphorus; and the extent of Soil Health Cultural Benefits as Low, Medium, or High. While some of these assessments are subjective, the tools to categorize them should be based on verifiable scientific soil indices. The use of such metrics by policymakers, who with public support develop cost-share and private capital market, depends on understandable and accurate assessments of soil health. Being proactive with a consumer market can influence the types of food and fiber choices that will promote sound agricultural practices.

In conclusion, the objective indices are needed to support healthy soils across the diversity of global soil types. To provide the policy and economic support for achieving agronomic, environmental, and cultural goals for soil health, farmers and ranchers need objective soil health indices combined with the ability to communicate about a complex system at a time of expanding scientific understanding. Using key indices, similar to the health field, is a useful model. Indices or metrics should be understandable within a particular framework like climate change. Finally, as science improves and therefore changes thresholds for soil health indices, care must be taken to avoid losing the trust of consumers and policymakers. An emphasis on effective communication using intermediaries to promote measurable outcomes can result in the establishment of economic tools like cost-share for practice implementation and trading for carbon sequestration or nutrient reductions to improve environmental and agronomic outcomes.

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