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Review

Soil Health Assessment and Management: Recent Development in Science and Practices

Mingxin Guo

Department of Agriculture & Natural Resources, Delaware State University, Dover, DE 19901, USA; mguo@desu.edu

Abstract: In the past decade soil health has been intensively studied as a science and practiced as a means to help improve the global social, environmental, and economic sustainability. This paper reviews the recent advances of the scientific soil health system. The current understanding and interpretation of soil health from the perspectives of soil functions, processes, and properties is summarized. Multi-tier soil health indicators were selected from relevant soil physical, chemical, and biological parameters. A suite of soil health assessment methods have been developed, such as soil health card, Solvita soil health tests, Haney soil health test, and comprehensive assessment of soil health. An array of soil health management practices have been recommended, including proper land use, crop rotation, cover crops, conservation tillage, soil organic amendment, crop-range-livestock integration, and rotational grazing. Overall, the recommended soil health indicators and assessment methods need further validation and improvement in relevance, scientific validity, practicality, and local adaptation. Continuous research, education, and outreach efforts are warranted to promote localized development, adoption, and implementation of soil health assessment and management.

Keywords: soil health indicators; comprehensive assessment; cover crop; conservation tillage; rotational grazing

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1. Introduction

Natural soil is an ecosystem consisting of minerals, organic matter (OM), living organisms, water, and air and maintaining an unceasing flow of matter and energy within and with the surrounding environment via various physical, chemical, and biological processes [1]. It is also through these processes such as water retention, chemical oxidation, and microbial decomposition that natural soil functions to support plant growth, regulate water movement and purify water, decompose OM and recycle nutrients, harbor organisms, and buffer environmental changes [1]. The capability of a soil to provide these environmental functions (e.g., ecosystem services), however, is determined by the efficiency of the soil to perform the intrinsic physical, chemical, and biological processes under particular geographic and climate conditions and is indicated by the emerging term "soil health."

Soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" [2]. A lengthier version of the definition is "the capacity of soil to function as a vital living system, within ecosystem and land-use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" [3]. In brief, soil health indicates the capability of a soil to provide ecosystem services. The health of a soil reflects how well the soil can carry out its environmental functions. A soil is evaluated as "healthy" if it provides comparable or better ecosystem services relative to undisturbed reference soils of similar type in the same region. Otherwise, the soil is unhealthy, unable to perform the normal environmental functions of similar soils in the inherent ecosystem [4].

Soil health is a comprehensive expression of the relevant soil physical, chemical, and biological properties (Figure 1). Soil (health) degradation is "the loss of the intrinsic physical, chemical, and/or biological qualities of soil either by natural or anthropic processes, which result in the diminution or annihilation of important ecosystem functions" [5]. Land uses, disturbances, and management practices may alter soil properties and subsequently, impact soil health. Tillage, for example, deteriorates soil structure and promotes OM mineralization, leading to significant health degradation of cropland soil [6]. Soil health degradation has been a worldwide overarching problem that threatens global food security. For agricultural soils, the degradation is typically demonstrated as OM decline, accelerated erosion, compaction, salinization, contamination, and loss of biodiversity [5,7]. High agricultural production may temporarily be achieved with high inputs of fertilizers, pesticides, and energy, yet sustainable agriculture demands healthy soils [8]. Effective and efficient management practices are warranted to restore degraded agricultural soils to the "healthy" status capable of supporting satisfactory food and fiber production while delivering other essential ecosystem services [9].

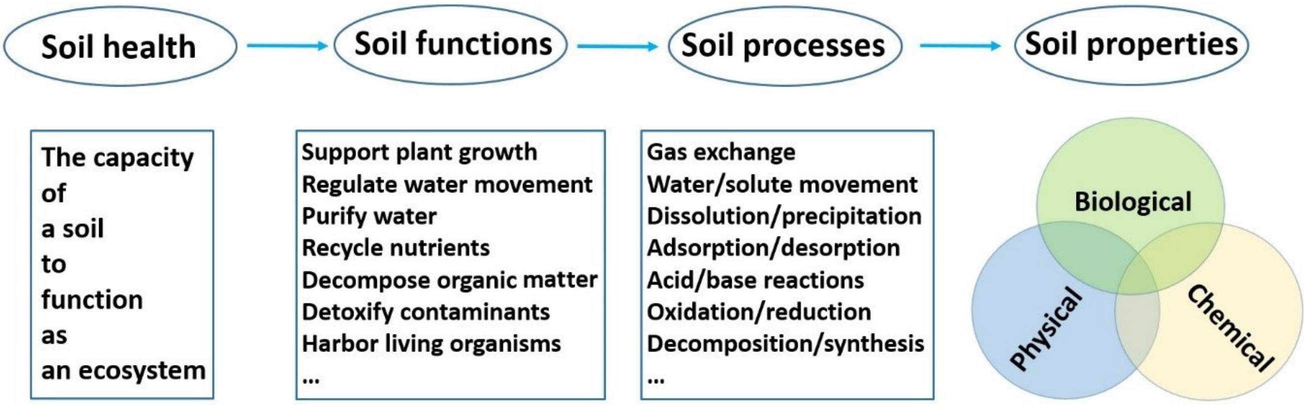


Figure 1. Soil health as a comprehensive expression of various soil properties.

It is rather challenging to scientifically assess and manage soil health owing to the complexity of soil ecosystems and the interconnecting nature of numerous soil processes [10]. Intensive research has been conducted in the past decades to select viable soil health indicators, develop assessment methods, and identify management practices. A suite of soil physical, chemical, and biological properties were tested to indicate the health of agricultural soils on supporting crop production [11–13]. The selection criteria for soil health indicators include the ability to indicate soil function changes, ease of sampling and measurement, accessibility and interpretability to general users, applicability to field conditions, and sensitivity to climate and management variations [14]. Field and laboratory methods were developed to assess and index the health of cropland soils, exemplified as the soil health card [15], Solvita soil health tests [16], the Haney test for soil health, [17], and the comprehensive assessment of soil health (CASH) [13]. These methods, demanding further validation by scientific evidence and field applications, demonstrate individualized advantages and limitations on soil health diagnosis and evaluation. An array of land management practices was advocated to sustain and improve soil health, such as reduced tillage, crop rotation, cover crops, organic amendments, production system diversification, rotational grazing, and proper soil water and nutrient management [6,18–20]. The U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) adopted four soil health management strategies: "Manage more by disturbing soil less," "diversify soil biota with plant diversity," "keep a living root growing throughout the year," and "keep the soil covered as much as possible" [21]. Strict implementation of these soil health management strategies and practices, however, may generate neutral or negative impacts on crop productivity [22]. This paper is to review the development in science and practices of soil health assessment and management, with the aim to better understand the soil health system for sustainable agriculture.

2. The Evolution of the Scientific Soil Health System

The current concept of soil health was evolved in the 1990s from “soil quality,” referring to “the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health” [3,23,24]. Brevik (2018) explored the origin and evolution of the term “soil health” [25]. The term was first mentioned by Mr. Henry A. Wallace in 1910 in an unpublished thesis to describe soil fertility [26]. In 1936, the USDA published a document entitled “Soil Health and National Wealth” to promote soil fertility and nutrient management [25]. U.S. farmers started to adopt the term in the 1990s [27], motivating the scientific community to re-define soil health. Doran and Parkin (1994) proposed equalizing soil quality and soil health by sharing a broader definition with ecosystem and soil function perspectives [3,28,29]. This proposal was initially criticized, as more commonly accepted was that soil health was equivalent to soil condition—the ability of a soil to perform according to its potential [30]. By the new millennium, soil quality was predominately used to describe soil management-related works [23]. The term “soil health” significantly increased its public acceptance in the 2000s and became popular in the 2010s, presumably a result of the 2007–2008 global food crisis and the recognition of soil’s carbon (C) sequestration potential for mitigating climate change [31,32]. A Google Scholar search for “soil health” returned 1740, 13,000, and 93,700 publications for the decades of 1990–1999, 2000–2009, and 2010–2019, respectively [25]. The rapid popularity increase in the concept of soil health after 2010 might have resulted from its flexibility to allow diverse stakeholders, including policymakers, to use the term in their own way [23]. Indeed, the recent definition empowers “soil health,” a broad term, to involve the major areas of soil science, including soil ecosystem services, environmental functions, processes, properties, fertility, and management (Figure 1). Furthermore, the term declares that soil is a living entity in analogy with an organism or a community that can be evaluated by healthiness. Lehmann et al. (2020) commented that the concept of soil health “connects agricultural and soil science to policy, stakeholder needs and sustainable supply-chain management” [23]. In the most recent decade, soil health has been replacing soil quality in communication, though the two terms are used interchangeably on many occasions [2]. There may be delicate differences between the two terms: Soil health describes the capacity of a soil to function from the ecosystem perspective. As an ecosystem, soil can be healthy or unhealthy, depending on how well the ecosystem is maintained and its stability, resilience, and stresses are self-regulated; soil quality reflects the ability of a soil to function to provide human-desired services. A soil can be good or poor, depending on its capability to sustain plant and animal productivity and to maintain or enhance air and water quality [1,23].

The scientific system of soil health covers primarily three aspects: concept, assessment, and management of soil health (Figure 2). Lehmann et al. (2020) compared the concept of soil health to soil fertility (the capacity of a soil to supply the nutrients needed for the growth of crops), soil quality, and soil security (the quantity, quality, and accessibility of the global soil resource for producing adequate food, fiber, and freshwater; maintaining biodiversity; and contributing to energy and climate sustainability [33]) and concluded that in relevance to the presently active sustainable development goals, soil health is narrower than soil security yet broader than soil quality and further broader than soil fertility [23]. As a nearly synonymous successor of soil quality, soil health in scientific development and field practices has been similarly centered on the primary function of soil to support plant growth, as illustrated by a minor definition: “soil health is the state of the soil being in sound physical, chemical, and biological condition, having the capability to sustain the growth and development of land plants” [19]. The health status of an agricultural soil is illustrated by its actual capacity relative to that of a population of like soils in the same region for sustaining satisfactory crop productivity by maintaining desirable nutrient cycles, soil structure, C transformation, and pest and disease regulations [9]. Healthy agricultural soils are usually characterized by a higher-than-average crop productivity, sufficient supply of nutrients, appropriate OM contents, correct tilth and drainage, dominating presence of beneficial organisms over pathogens, high resistance to erosion and degradation, and being contamination free [13]. Compared to less healthy ones, healthier soils generally demonstrate a wider working range and a higher input-to-output conversion efficiency [9].

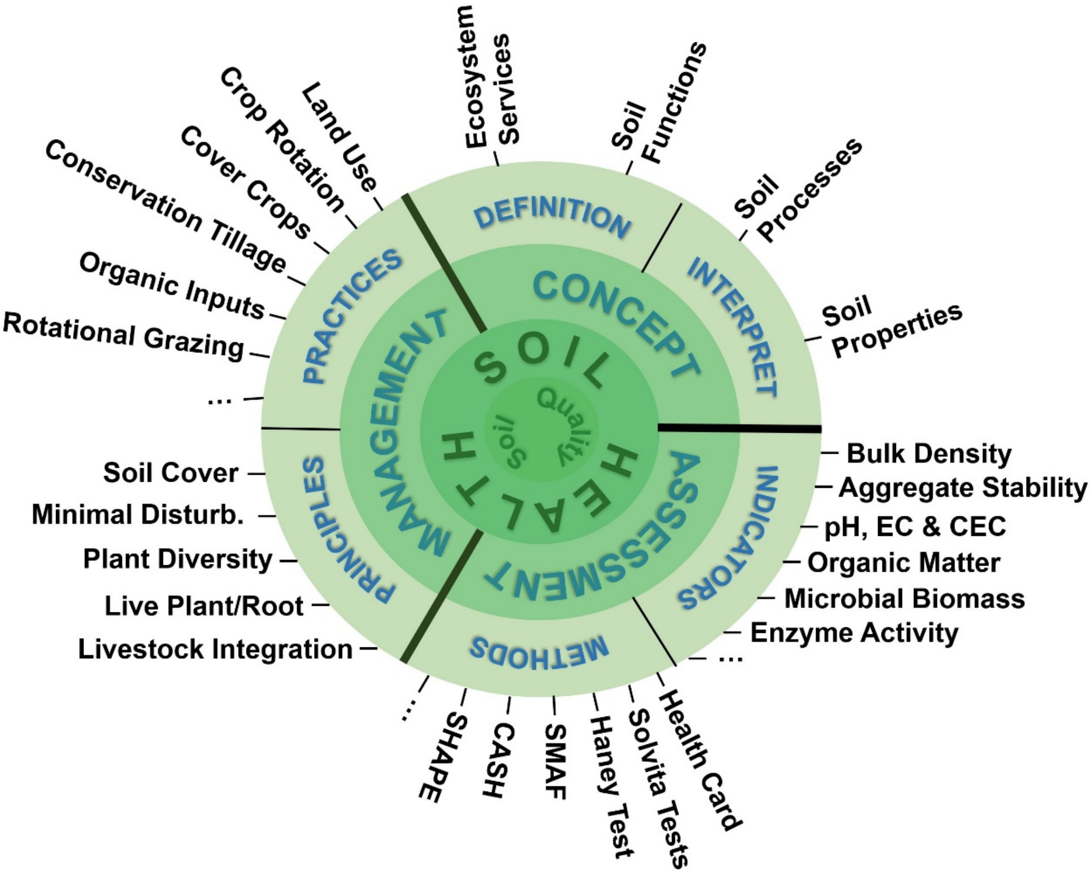


Figure 2. Development of the science of soil health with concept, assessment, and management as the three focal areas. CEC: cation exchange capacity; EC: electrical conductivity; CASH: comprehensive assessment of soil health; SHAPE: soil health assessment protocol and evaluation; SMAF: soil management assessment framework.

The “healthiness” of a soil can be indicated by the relevant physical, chemical, and biological attributes. Numerous soil properties have been examined to indicate soil health [19,34,35]. The relevance of a soil property to soil health is commonly evaluated based on the response of specific soil functions to a practical shift in the soil property [36]. As illustrated in Table 1, soil OM (e.g., total organic C content and particulate OM content) and the abundance of earthworms are the characteristics most relevant to soil health. This is rather reliable, as OM is the essence of natural mineral soil and the main components, “humic substances,” influence the vast majority of other soil physical, chemical, and biological properties, including the presence of earthworms [1]. According to the relative relevance to soil functions and the ease of practical use, the soil properties selected as potential soil health indicators are divided into three tiers: Tier 1 indicators, which have been widely accepted; Tier 2 indicators, which are regionally validated but need additional research for improved adoption; and Tier 3 indicators, which are promising to mirror soil health yet extensive research is warranted for improvements in measurement, interpretation, and use (Table 2). So far only Tier 1 indicators are practiced in agricultural soil health assessment, including soil texture, bulk density, penetration resistance, water-stable aggregation, erosion rating, available water-holding capacity (AWC), and infiltration rate (saturated hydraulic conductivity); pH, salinity (electrical conductivity), cation exchange capacity, base saturation, plant-available phosphorus (P), potassium (K) and micronutrients, and total nitrogen (N) content; and organic C content, short-term C mineralization, N mineralization rate, and crop productivity [13,23,37,38]. In 2019, the USDA-NRCS published a technical note to describe its recommended soil health indicators and associated laboratory procedures, in which soil organic C content, readily available C pool, water-stable aggregation, short-term C mineralization, available organic N pool, soil enzyme activity, and soil microbial community structure were covered [39]. Although four criteria (indicator effectiveness, production readiness, measurement repeatability, and result interpretability) were considered for selecting the recommended soil health indicators [39], a few of the listed candidates, the last two in particular, met only the first criterion. The recommendation list highlights the importance of soil biological properties yet fails to give deserved weights to soil physical and chemical properties in soil health assessment. Reliable, holistic soil health assessment could not be achieved without collectively analyzing a suite of indicators that encompasses soil physical, chemical, and biological characteristics [35].

Table 1. The relevance of a soil health indicator to soil functions as shown via number of crosses. The reliability of the relevance increases with an increasing number of crosses [36].

Soil Health Indicator	Soil Function				
	Sustain Biological Diversity, Activity, and Productivity	Regulate and Partition Water and Solute Flow	Filter, Buffer, Degrade, Detoxify Organic and Inorganic Materials	Store and Cycle Nutrients and Carbon	Physical Stability and Support for Plants and Engineering Structures
SAS	++++	++++		++++	+++++
AWC	++++++	+++++		++++	
Bulk density	+++++	++++++		++	++++++
Earthworms	++++++		++++++	++++++	++++++
Infiltration		++++	++		
POM	++++++	++++++	++++++	++++++	++++++
PMN	++++++			++++++	
Reactive C	++++	++	++++++	++++	++++
Slaking	++	+++++			
Soil crusts		+++++			
Soil EC		++++++			
Soil enzymes	++++++			++++++	
Soil nitrate	++	++			
Soil pH	++++	++++++	++++++	++++++	
Soil respiration	++++++		++	++++++	++++
Soil structure	+++	+++	++	++	++++
TOC	++++++	++++++	++++++	++++++	++++++

SAS: soil aggregate stability; AWC: available water-holding capacity; POM: particulate organic matter; PMN: potentially mineralizable nitrogen; EC: electrical conductivity; TOC: total organic carbon.

Table 2. Different tiers of soil health indicators [38].

Soil Health Indicators	Criteria	Examples
Tier 1	• Widely considered effective to indicate soil health • Defined regionally and by soil groupings • Known thresholds to index outcome-based soil health status • Responsive to land use and management practices for soil function improvement	Soil texture Soil bulk density Soil aggregate stability Available water-holding capacity Saturated hydraulic conductivity Soil pH Soil electrical conductivity Cation exchange capacity Base saturation Extractable P, Ca, Mg, K, Fe, Mn, Cu, Zn Extractable Al, As, B, Ba, Cd, Co, Cr, Mo, Ni, Pb, Si, Sr Soil total nitrogen content Nitrogen mineralization rate Soil organic carbon content Short-term carbon mineralization Crop yield
Tier 2	• Proven relevant to soil health • Impacting trends on soil health are clear • Ranges and outcome-based thresholds are known for some regions • Improvement strategies can be suggested • Additional research is needed for further validation	Soil sodium adsorption ratio Macro-aggregate stability Soil stability index Soil active carbon Soil protein index Soil β-glucosidase Soil N-acetyl-β-D glucosaminidase Soil phosphomonoesterase Soil arylsulfatase Soil phospholipid fatty acid (PLFA) profile Soil fatty acid methyl ester (FAME) profile Soil microbial genomics Soil reflectance
Tier 3	• Has the potential to be a soil health indicator • More research is needed before users can have adequate confidence in its measurement, use, and interpretation	Soil microbial community structure Soil microbial DNA extraction and sequencing

Multiple indicators are necessary to be measured in soil health assessment, as any single soil properties cannot adequately reflect the features or disclose the issues that underwrite soil health [9]. The major environmental functions (e.g., plant support, nutrient recycling, and organic residue decomposition) that natural soil delivers are outputs of soil biological processes as directly influenced by the physical and chemical settings [9]. The three categories of soil properties should share comparable or equal importance in soil health assessment. Soil physical and chemical properties are typically at more ease than biological processes to measure and interpret and therefore, were overweighed in historic soil quality assessment [23]. A number of biological indicators have been developed in the recent soil health system, such as soil microbial biomass, short-term C mineralization (soil respiration rate), soil enzymes, soil protein index, fatty acid methyl ester (FAME) profile, phospholipid fatty acid (PLFA) analysis, biodiversity, microbial activity, abundance of earthworms, presence of pathogens and parasites, and DNA sequencing for soil microbial community structure (Table 2) [10,23,34,39]. Nunes et al. (2021) selected, for example, seven biological indicators (soil organic C, active C, microbial biomass C, microbial biomass N, respiration rate, β-glucosidase activity, and protein index) to construct a soil heath assessment system [40]. Paz-Ferreiro and Fu (2016) conducted a comprehensive review on soil biological indices for soil health evaluation [41]. More scientific data are needed to further validate the soil health relevance and practicality of these biological indicators [41,42].

Substantial research efforts have been attempted to establish a quantitative assessment system that integrates major soil health indicators and is able to index the overall health of soils and quantify the efficacy of soil management practices. The Soil Management Assessment Framework (SMAF) [43,44], CASH [13], Soil Health Assessment Protocol and Evaluation (SHAPE) [40], Soil Management Index [6], Soil Health Calculator [45], and other integrative scoring curve methods (e.g., the Soil Conditioning Index [46] and AgroEcosystem Performance Assessment Tool [47]) were proposed. The establishment of a universally applicable quantitative soil health index system may culminate the science of soil health, yet there are still many outstanding challenges to overcome. In particular, it is rather difficult to transform various soil health indicators, including those categorical ones, into quantitative values, assign scientific weights to individual indicators, and integrate them into a single numerical score [23]. Furthermore, there may be unknown soil health effects resulting from potential interactions between numerous soil processes and properties [9]. Soil health is ecosystem specific. A soil health assessment protocol developed for a particular geographic or climate region or a cropping system may not be applicable to others [19]. Frequently, different indicators are chosen to assess the health of local soils for intended uses. The primary purpose of soil health assessment is to identify the principal causes of soil function issues and decide effective management practices for improvement. Intensive measurement of related soil health indicators and comparison of the results to the localized threshold values of individual indicators would meet the purpose. It may not be necessary to score the overall soil health.

Remarkable progress has been achieved in the scientific development and practice of soil health management (Figure 2). Experimental trials were conducted to identify the best management approaches for restoring degraded or unhealthy soils, evaluate the effects of common land use and farming practices on soil health, substantiate the effectiveness of existing land management methods for soil health improvement, and extend soil health management principles [6,18,44,45]. Soil health can be maintained and promoted by implementing the four strategies: minimizing soil disturbance; maximizing soil coverage, especially with living plants; increasing crop diversity; and applying organic amendments [9,13,21]. A variety of available soil management practices (e.g., crop rotation, cover crop planting, conservation tillage, crop residue return, land application of manure and compost, biochar amendment, liming, and agronomic fertilization) have been recommended and practiced for promoting the health of agricultural soils [6,8,18–20].

To promote the vitality of soil and enhance the soil health of agricultural lands from the federal policy perspective, the USDA-NRCS Soil Health Division was created in 2014 [48]. The Soil Health Institute was founded in 2016 as a U.S. non-profit organization to facilitate soil health research and scientific advancement [49]. The European Commission formed the Mission Board for Soil Health and Food in 2019 to develop the interim targets and long-term goals on soil health and food to "ensure that 75% of soils are healthy by 2030 and are able to provide essential ecosystem services" [50]. In 2013 in Australia, the former Governor General was appointed by the Minister for Agriculture and Water Resources as the National Advocate for Soil Health to promote the science and practice of soil health in collaboration with the non-profit organization Healthy Soil Australia [51]. The concept of a "soil health gap," referring to the difference in specific property or function-based soil health between an agricultural soil and an undisturbed native soil, was introduced to establish a benchmark for deciding on an attainable goal of soil health management [52]. Worldwide, an open, dynamic database (SoilHealthDB) has been initiated to collect and store global soil health data [53]. With the invention of portable soil sensors capable of efficiently collecting field *in-situ* data at low costs for soil health assessment, the concept of soil health has been gradually embraced by farmers, soil conservationists, and policymakers around the world [54]. Using visible-near-infrared reflectance spectroscopy, the sensors are able to estimate organic C content, soil respiration rate, β-glucosidase activity, microbial biomass C, and other biological properties of soils in the field [55,56]. Through a comprehensive literature review, Karlen et al. (2019) summarized the major scientific advances of the soil health system in biological indicator development, soil data interpretation, and field applications of soil health assessment [35].

3. Soil Health Assessment Methods

3.1. Farmer Perceptions of Soil Health

Farmers, in particular experienced crop growers, have the ability and skills to estimate the soil health (quality) of local cropland. The ability is typically gained through years of soil cultivation and crop production experience. Proficient farmers usually divide their cropland into "good" and "poor" categories based on the soil health, major underlying soil health issues are identified for "poor" cropland, and rectifying measures are implemented to improve the soil health and crop productivity of "poor" cropland. Farmers estimate the soil health of cropland by direct sense-based examination: observing the surroundings and watching, feeling, and smelling the soil to collect the rough information of soil color, aroma (e.g., earthy, sweet vs. sour, putrid), structure (e.g., soft, crumbly vs. hard, chunky), surface crusting, compaction, infiltration, drainage, and ease of tilth. With additional reference to available crop productivity records, a near correct prediction on the healthiness of the soil can be drawn.

Farmer perceptions of soil health are generally reliable. Gruver and Weil (2006) investigated farmer perceptions of soil health [57]. Seventy-five (75) farmers in the U.S. Mid-Atlantic region were asked to select 45 paired sites on local farms that they perceived as having "good" and "poor" soils. The main contrasting soil health characteristics such as good tilth vs. poor tilth, higher crop yield vs. lower yield, cover crop vs. no cover crop, and conventional tillage vs. no-till crop productivity were also identified for the paired sites. Soil samples were then collected by scientists and analyzed in the laboratory for total organic C content, microbial biomass C, aggregate stability, porosity, pH, and other soil health parameters. Soil health indexes (SHI) were computed by averaging normalized values of the top five soil health parameters that most agreed with farmer soil health ratings. The calculated SHI showed a significantly high ($p < 0.0001$) level of agreement with farmer soil health ratings [57]. The correctness of farmer soil health perceptions was corroborated by a recent study using Columbia coffee growers and cropland [58].

3.2. Soil Health Card Methods

A soil health card is a field tool for assessing soil health and identifying the underlying issues. It is usually designed by soil conservation offices in collaboration with local farmers and agricultural cooperative extension agents to enhance the adaptation [59]. A localized soil health card lists a number of soil health indicators selected by farmers based on their farming experience and knowledge of the local environment. These indicators can be assessed in the field without the aid of laboratory instrumentation. Descriptive ratings associated with these indicators are also provided on the card to guide users to estimate the soil health of agricultural lands.

The Maryland Soil Health Card is illustrated in Figure 3. Seven soil health indicators are displayed on the card: surface cover (with living plants and crop residues), infiltration, compaction and root growth, OM content, soil structure/aggregation, earthworms and macroinvertebrates, and soil odor. For each indicator, the descriptive ratings (scorings) of excellent (9–11 points), good (6–8 points), fair (3–5 points), and poor (0–2 points) are defined. Instructions to determine the indicator descriptive ratings are available [60]. In addition, a free 13 min YouTube video (youtube.com/watch?v=GE2QWaPQ7Sk; accessed 2 October 2021) demonstrates how to conduct field soil health assessment using the Maryland Soil Health Card. The health of a cropland soil is excellent, good, fair, or poor when the total score (sum of the points from the seven individual soil health indicator ratings) falls in the range of 60–77, 40–56, 20–39, and 0–19, respectively (Figure 3).

MARYLAND SOIL HEALTH CARD

Farm/Tract/Field#s:	**Assisted by:**	**Date and air temp:**
Current Tillage System with number and kind of crops in rotation:	**Soil Series and Map unit sym:**	**Soil Surface Texture at site:**
Data from recent soil pH and/or organic matter analysis (if available):		

Indicators	**Descriptive Ratings and Potential Scoring Points**					
	Excellent 9-11 pts	***Good 6-8 pts***	***Fair 3-5 pts***	***Poor 0-2 pts***	**Score**	**Notes**
Surface Cover (Count living plants and dead residue)	>80% living plants and dead residue visible on soil surface.	60-80% living plants and dead residue visible on soil surface.	30-60% living plants and dead residue visible on soil surface.	0-30% living plants and dead residue visible on soil surface.		
Infiltration (Based on soil texture, refer to Infiltration Chart)	Infiltration rate at least two classes higher then listed range, indicates soil absorbs water easily.	Infiltration rate one class higher then listed range, indicates soil absorbs water in a timely nanner and is not susceptible to runoff or ponding.	Infiltration rate within listed range, indicates soil absorbs water, but more slowly, and runoff and ponding may occur.	Slower infiltration rate then listed range, indicates soil absorbs water very slowly, and runoff and ponding will occur.		
Compaction/Root growth (Based on moist topsoil conditions)	Wire flag penetrates easily into 8 inches or more of soil with no resistence; unrestricted root growth.	Wire flag penetrates into 6-8" of soil with a little resistence; requires a little wiggling of pin flag; little root growth restriction	Wire flag penetrates into 4-6 inches of soil with a lot of wiggling of pin flag and moderate force; root growth restricted.	Wire flag penetrates into 2-4 inches of soil with force, roots maybe growing laterally.		
Organic Matter (Compare to samples or Munsell book using Hues 7.5YR, 10YR or 2.5Y)	Soil is black in color; organic matter is visible in the topsoil layer. Value ≤ 2 and chroma ≤ 2.	Soil is dark brown in color; organic matter is visible in the topsoil layer. Value = 3 and chroma = 3.	Soil is somewhat dark in color; little organic matter is visible in topsoil layer. Any value or chroma that doesn't meet Good or Poor numbers	Soil is light brown to dull colored; no organic matter is visible in the topsoil layer. Value > 4 and chroma > 4		
Soil Structure/ Aggregation	Soil is granular, soft and crumbly, held together with many fine roots. Looks like cottage chesse.	Soil is granular, but not soft and crumbly, held together with some fine roots.	Soil is blocky and firmer with few fine roots.	Soil is single grain, massive or platy and hard to break apart. It has few or no fine roots.		
Earthworms and Macroinvertebrates	Earthworms/grubs etc. >7 per spade, obvious middens and casts, and many pores.	Earthworms/grubs etc. 4-6 per spade, obvious middens, casts, and pores.	Earthworms/grubs etc. 1 to 3 per spade, few middens, casts, and pores.	Earthworms/grubs etc. None present per spade, no casts, middens, or pores.		
Soil Odor	Earthy/Sweet odor noticeable > 6 inches from nose.	Earthy/Sweet odor, noticeable when close to nose.	Little odor at all.	No odor at all or sour, metallic, kitchen sink, rotten egg, stagnant.		
					Total Score =	

Interpretation of Total Score Results

Excellent 60-77 pts	***Good 40-56 pts***	***Fair 20-39 pts***	***Poor 0-19 pts***

Figure 3. Maryland Soil Health Card showing individual soil health indicators and the associated descriptive ratings [60].

Soil health card methods have been adopted by international governments to improve the management of soil and land resources. The U.S. government and Indian government, for example, state that "A soil health card is used to assess the current status of soil health and, when used over time, to determine changes in soil health that are affected by land management" [15,61].

3.3. Solvita Soil Health Tests

Solvita soil health tests are a soil test toolkit invented by Woods End Laboratories, Inc. (Mount Vernon, ME, USA) to provide commercial services of soil health evaluation. The toolkit contains laboratory measurements of soil samples for five health indicator traits: OM content, water-soluble organic carbon (WSOC), aggregate stability, soil basal respiration or Solvita CO_2 burst, and Solvita soil labile amino-N (SLAN) [62]. Soil OM content is typically measured by the loss-on-ignition method; WSOC by 24 h, room temperature, 1:5 solid/water ratio extraction and subsequent C analysis; aggregate stability by the wet sieving methods; basal respiration by 24 h lab incubation of a fresh, undisturbed field soil sample; Sovita CO_2 burst by 24 h lab incubation of a rewetted dry soil sample; and SLAN by 24 h lab incubation and subsequent NH_4-N analysis [13,63,64]. The measurements are then rated relative to the maximal local expectations (scoring up to 50 points) to generate a soil health score in the range of 0–50 points. The average of the five individual indicator ratings indicates the overall soil health, with a score greater than 25 points being “good” [62].

A recent study used the methods of Solvita soil health tests to evaluate the long-term effects of crop rotation, tillage, and fertilizer nitrogen on soil health in Canada [65]. The authors concluded that Solvita soil health tests were a useful soil health assessment tool with high level of certainty; in particular, Solvita CO_2 burst and SLAN tests correlated positively with soil organic C and total N contents.

3.4. Haney Soil Health Test

The Haney test for soil health is a laboratory dual extraction procedure for estimating the overall health of agricultural soils. The procedure was developed by Dr. Rick Haney, a USDA-ARS (Agricultural Research Service) scientist, in 2010. The test has been used by many soil-testing laboratories to make fertilization recommendations for crop growers [17].

To conduct the Haney test, soil collected from the crop field is air-dried and processed into <2 mm particles. Aliquots of the soil are extracted with deionized water and analyzed for total N, NH_4-N, NO_3-N, PO_4-P, and organic C in the extracts. Other aliquots of the soil are extracted with citric acid (H3A) and analyzed for extractable total P, organic P, K, Mg, Ca, Na, Zn, Fe, Mn, Cu, S, and Al. A soil sample is further rewetted by capillary action with deionized water at a 2:1 solid/water ratio and incubated at room temperature for 24 h. The CO_2 generated during incubation is quantified to calculate the soil CO_2 burst. A health score is computed for the soil with the following equation:

$$Soil\ health\ score = \frac{[CO_2 - C]}{10} + \frac{[WEOC]}{50} + \frac{[WEON]}{10}$$

where $[CO_2 - C]$ is the soil CO_2-C burst in mg kg^{-1}, $[WEOC]$ is the soil water extractable organic carbon content in mg kg^{-1}, and $[WEON]$ is the soil water extractable organic nitrogen content in mg kg^{-1}. The score ranges from 0 to 50, with a value greater than 7 indicating “good” soil health [17].

The Haney test is relatively simple and convenient to “quickly” evaluate the effects of different land use and soil management practices on soil health. The test, however, needs further research validation and locality adaptation [66]. By analyzing the Haney soil health test and grain yield data of corn field sites in 17 U.S. Midwest states, Yost et al. (2018) noticed that the Haney soil health score was highly correlated with the CO_2-burst indicator and that the two in combination accounted for most of the optimum N rate variations and recommended soil CO_2-burst tests for determining agronomic N fertilization rates [67]. A more recent study indicated that the CO_2-burst test did not reliably estimate soil potentially mineralizable N and the Haney test failed to detect the effects of cover crop planting on soil health in Tennessee, USA [68].

3.5. Comprehensive Assessment of Soil Health (CASH)

Cornell University (Ithaca, NY, USA) developed the intensive laboratory-based CASH protocols to assess the overall health of agricultural soils from a suite of selected soil physical, chemical, and biological properties and make best soil management recommendations based on the major soil health issues.

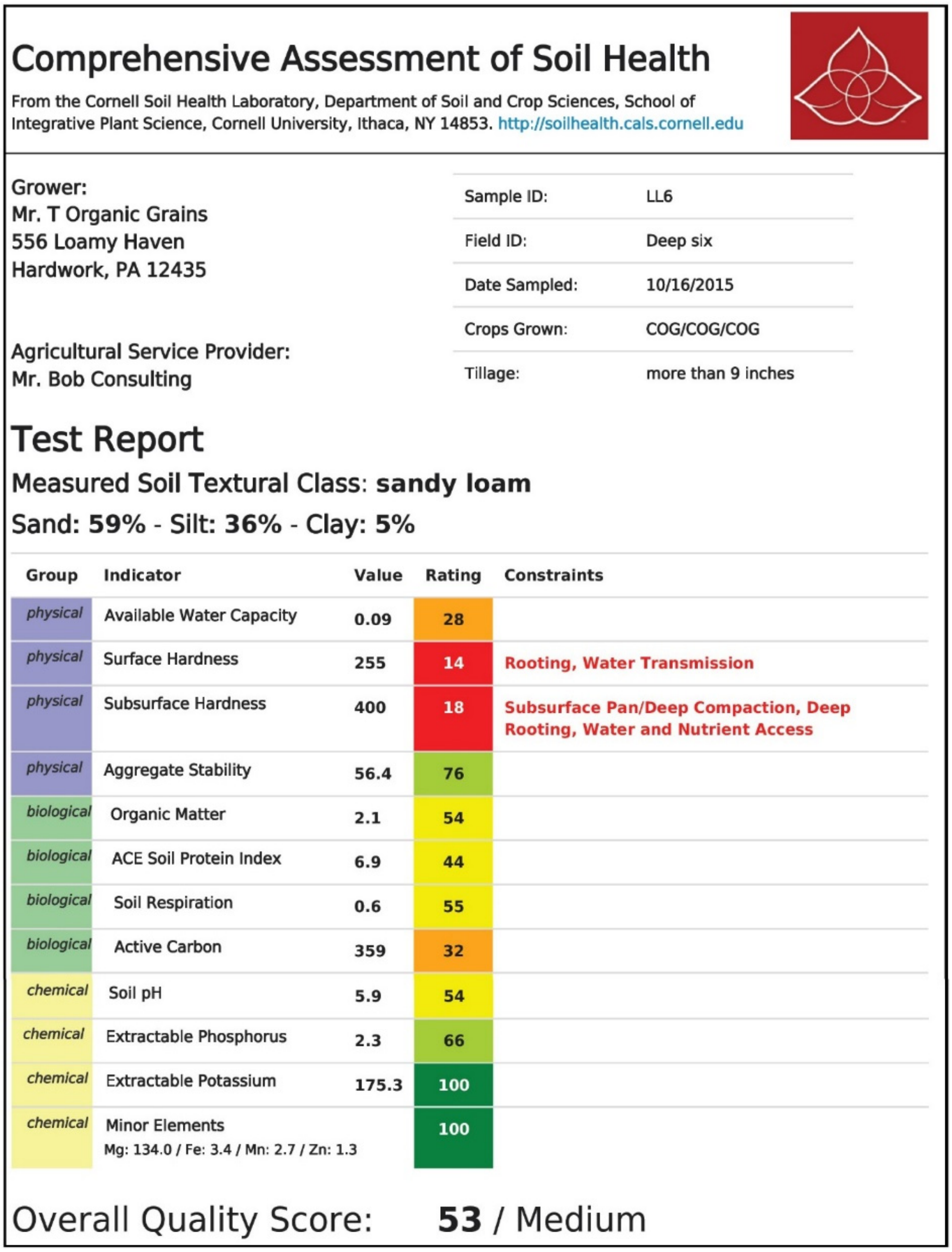
Twelve (12) soil health indicators are included in CASH: soil AWC, surface hardness, subsurface hardness, wet aggregate stability, soil OM, active C, soil respiration, protein index, soil pH, extractable P, extractable K, and extractable minor nutrients [13]. To follow the CASH protocols, a composite soil sample (1–2 L in volume or 1.5–3.0 kg in dry weight) representing a management unit (a farmland area) is collected following appropriate sampling patterns and delivered early to the laboratory. Surface and subsurface hardness of the soil are measured in the field using a penetrometer or soil compaction tester [13]. A portion of the soil is homogenized, air-dried, and passed through a 2 mm sieve. The air-dry soil is characterized for texture following a simplified method with 53 μm sieving and 2 h suspension settling treatments. The soil texture serves as a criterion for later selecting health rating standards. Soil AWC is measured by rewetting air-dry soil with deionized water and extracting the saturated soil on ceramic plates at 10 and 1500 kPa, respectively, in two pressure chambers [13]. Soil aggregate stability is evaluated by particularly designed rain simulation and wet sieving methods. The OM content is measured by the loss on ignition at 500 °C method. Soil protein index is analyzed by extracting air-dry soil with a sodium citrate buffer, autoclaving the extracts, and quantifying the total protein in the extracts using the standard colorimetric protein quantification assay [13]. Soil respiration is estimated by incubating rewetted air-dry soil and quantifying the CO_2 generated in 96 h. Soil active C is measured following the 0.02 M $KMnO_4$ oxidation methods. The soil pH is determined in a 1:2 soil–water slurry with a pH meter. Standard nutrient analysis is conducted by extracting air-dry soil with a modified Morgan solution (100 g L^{-1} ammonium acetic solution adjusted to pH 4.8 by acetic acid) and analyzing the extracts on an inductively coupled plasma (ICP) emission spectrometer for P, K, Mg, Fe, Mn, Zn, and other nutrient concentrations [13]. These 12 soil health indicators are then scored (0–100 points) by comparing them to the established scoring curves. The mean of the 12 individual indicator scores is the overall soil health score, indicating "very low," "low," "medium," "high," and "very high" in the ranges of 0–20, 20–40, 40–60, 60–80, and 80–100, respectively.

A standard CASH report is shown in Figure 4. The analytical results of the soil texture are presented, followed by the results and the corresponding rating score of the 12 health indicators. Different colors are used to denote the individual soil health ratings, with red, orange, yellow, light green, and dark green indicating very low, low, medium, high, and very high, respectively. The major constraints are specified when the health rating falls in the "very low" (red color) class. Effective soil management practices can be recommended accordingly for improving the "very low" soil health rating.

The overarching challenge to adopting CASH is constructing a robust soil health rating system that involves substantial amounts of funds, time, and effort. Such a rating system consists of a suite of reliable, locality-specific soil health scoring curves. To establish a soil health scoring curve, numerous soil samples need to be collected to represent a geographic and climate region. The samples are divided into different soil texture groups and analyzed for indicator values by qualified research laboratories. The measurement results of each soil health indicator are then examined by developing a histogram (frequency distribution curve) to confirm the normal distribution. A cumulative normal distribution curve is created for the individual indicators using the mean and standard deviations of the measured samples. A scoring function is eventually established for each soil health indicator by transforming the range of the measured values along the cumulative normal distribution curve into an interpretive rating that assigns a score from 0 to 100 [43]. A higher measured value may give a higher or a lower score for a physical and biological indicator, whereas a measurement in the optimum range yields a higher value for chemical indicators [13].

Similar soil health assessment systems exist, such as SMAF and SHAPE. In SMAF, the soil health indicator selection is refined by climate, soil, crop species, slope, and other factors from 19 suggested soil properties [43]. Veum et al. (2020) selected, for example, seven soil health indicators, including soil bulk density, organic C, β-glucosidase activity, pH, EC, and extractable P and K, to assess the health of farmland soils in central Missouri, USA, using the SMAF tool [44]. Congreves et al. (2015) improved the local adaptation of CASH in Ontario, Canada, by incorporating principal component analysis-based weights of individual indicators in the final soil health index calculation. The localized model Ontario Soil Health Assessment (OSHA) demonstrated higher sensitivity in evaluating the long-term effects of tillage and crop rotation on the soil health of temperate agroecosystems [69]. Ye et al. (2021) used both CASH and SMAF to investigate the effects of 40-year conservation tillage and four-year cover crop planting on the health of U.S. Southern

Coastal Plain soils [70]. Both models predicted no changes in the overall soil health. The CASH index, however, suggested the management priority of improving soil organic C and structure to enhance soil health. Nunes et al. (2020) commented that "both SMAF and CASH were developed using a relatively small dataset and their interpretation curves were not validated at the nationwide scale" [40]. The authors proposed SHAPE as an expanded, improved version of CASH by accounting for soil, geographic, and climate factors at the continental scale and incorporating Bayesian model-based scoring functions [40].



Comprehensive Assessment of Soil Health

From the Cornell Soil Health Laboratory, Department of Soil and Crop Sciences, School of Integrative Plant Science, Cornell University, Ithaca, NY 14853. http://soilhealth.cals.cornell.edu

Grower:
Mr. T Organic Grains
556 Loamy Haven
Hardwork, PA 12435

Agricultural Service Provider:
Mr. Bob Consulting

Sample ID:	LL6
Field ID:	Deep six
Date Sampled:	10/16/2015
Crops Grown:	COG/COG/COG
Tillage:	more than 9 inches

Test Report

Measured Soil Textural Class: **sandy loam**

Sand: **59%** - Silt: **36%** - Clay: **5%**

Group	Indicator	Value	Rating	Constraints
physical	Available Water Capacity	0.09	28	
physical	Surface Hardness	255	14	Rooting, Water Transmission
physical	Subsurface Hardness	400	18	Subsurface Pan/Deep Compaction, Deep Rooting, Water and Nutrient Access
physical	Aggregate Stability	56.4	76	
biological	Organic Matter	2.1	54	
biological	ACE Soil Protein Index	6.9	44	
biological	Soil Respiration	0.6	55	
biological	Active Carbon	359	32	
chemical	Soil pH	5.9	54	
chemical	Extractable Phosphorus	2.3	66	
chemical	Extractable Potassium	175.3	100	
chemical	Minor Elements Mg: 134.0 / Fe: 3.4 / Mn: 2.7 / Zn: 1.3		100	

Overall Quality Score: **53** / Medium

Figure 4. A comprehensive soil health assessment report example illustrating the assessment score, overall health, and main constraints of a cropland soil [13]. Red, orange, yellow, light green, and dark green indicate very low, low, medium, high, and very high in soil health rating, respectively.

4. Soil Health Management

Improper land use, crop cultivation, animal grazing, and fertilization lead to soil health degradation and soil function losses. Effective soil management practices are necessary to maintain and enhance the soil health of agricultural land.

4.1. Soil Health Principles

The USDA-NRCS defined five basic land and soil management principles to maintain and improve soil health [71] (Figure 2).

Principle 1—soil armor: to keep the soil covered as much as possible with living plants, crop residues, compost, or synthetic tarps. A soil cover helps control soil erosion, check weeds, mitigate soil temperature fluctuation, reduce soil compaction, and provide improved habitats to soil organisms;

Principle 2—minimizing soil disturbance: to reduce the introduction of mechanical disturbance (e.g., tillage), chemical disturbance (e.g., pesticide application), and biological disturbance (e.g., overgrazing) to soil. Conservation tillage, integrated pest management, and rotational animal grazing are effective management practices to minimize soil disturbance, reduce soil erosion, and enhance soil biodiversity;

Principle 3—plant diversity: to grow different crops on farmland in order to suppress disease and pest incidences and sustain a fully functioning soil food web;

Principle 4—continual live plant/root: to keep a living root growing throughout the year is critical to increasing soil biodiversity, achieving high microbial activity, and controlling soil erosion; and

Principle 5—livestock integration: to include animal grazing in cover crop, crop residue, and weed management is effective for improving animal welfare, reducing herbicide uses, promoting nutrient cycling, and decreasing cropland nutrient export.

4.2. Best Soil Health Management Practices

The USDA-NRCS has been developing, implementing, and extending effective soil management practices since the 1940s to conserve soil and enhance soil ecosystem services, in particular crop productivity. One original mission of the USDA-NRCS was to "maintain healthy and productive working landscapes" [72]. A suite of best soil management practices was identified to maximize the crop productivity while minimizing the negative environmental impacts of modern agriculture, including proper land use, appropriate cropping systems, conservation tillage, land application of organic residues, agronomic fertilization, and engineering soil conservation structures [73] (Figure 2). These practices are a precise translation in action of the five basic soil health principles and have demonstrated high effectiveness in sustaining and enhancing soil health. Most of the practices were initially developed for controlling soil erosion and solidifying soil conservation. Accelerated soil erosion is the primary cause for soil health degradation [74]. Inappropriate agricultural operations may entail significant losses of healthy, fertile topsoil in water and wind, leading to land productivity decreases and environmental quality deterioration.

4.2.1. Proper Land Use

Proper land use is the first element to consider in soil health management. The ways human beings use the land are determined by its soil capability, and in turn, influence the soil health. The agricultural land use capabilities of natural soils are typically divided into eight classes based on the land topography and soil characteristics, with Class I having no limitations for intensive crop production, Class III demonstrating severe limitations (e.g., risk of erosion, water interference, or unfavorable climate), and Class VI being unsuitable for cultivation [73]. Appropriate management practices (e.g., terracing, artificial drainage, and irrigation) become necessary to rectify the limitations when land use capability Class III–V soils are used for crop production. Class VI-VIII lands are not suitable for cultivation and usually used for range, forestry, wildlife habitat, or recreational purposes. Lands with coarse textured soils (e.g., sandy loam) should not be used as rice paddies because of the low water retention capability. Lands with heavy textured soils (e.g., clay and clay loam), on the other hand, are not desirable as septic tank sites [73]. Improper land use results generally in significant soil erosion losses and subsequently, soil health degradation.

4.2.2. Crop Rotation

An appropriate cropping system always involves crop rotation as two or more different crops are grown alternatingly on the same land at different times. Corn–soybean, winter wheat–alfalfa, and corn–soybean–winter wheat, for example, are the three crop rotation systems commonly practiced in the northeastern region of the U.S. [73]. The major benefit of crop rotation is to suppress pests and diseases in agricultural soils. Different crops host different pests and soil microbes. Therefore, changing crop species helps break the disease cycle in a given farmland and thus helps control pests and soil-borne diseases [74,75]. Different crops vary in the root system, root exudates, nutrient requirements, and nutrient cycling ability. Crop rotation, therefore, increases crop yields and improves soil structure, erosion resistance, biodiversity, C sequestration, and the overall soil health [76,77]. Research has indicated that long-term crop rotations, especially with leguminous plants (e.g., alfalfa, soybean, and pea), greatly improve cropland soil health [70,77].

4.2.3. Cover Crops

Planting a cover crop on fallow agricultural land is highly efficient to maintain the soil health of cropland. Hartwig and Ammon (2002) defined a cover crop as "any living ground cover that is planted into or after a main crop and then commonly killed before the next crop is planted" [78]. Cover crops have been used in agricultural cultivation for centuries. They are frequently found on between-tree row-strips of orchards, in greenhouses and high tunnel nurseries between soil beds, and in crop fields during the winter season. Common cover crop species include grasses (e.g., rye, barley, oats, ryegrass, Sudangrass, millet, and sorghum); annual, biennial, and perennial legumes (e.g., peas, beans, alfalfa, hairy vetch, and clovers); and other broadleaf species (e.g., buckwheat, radish, canola, mustard, marigold, and kale) [79]. An array of farming tools and approaches has been invented to reduce the costs associated with cover-crop planting (e.g., aerial seeding, drill planting, and interseeding) and termination (e.g., winter kill, roller crimping, mowing, tillage, and herbicide treatment). The successful establishment of a cover crop also needs to consider seed formulation, seeding rate, and planting and termination dates and methods [80].

The inclusion of cover crops in a cropping system expands and strengthens the practice of crop rotation. It is critically important to control soil erosion, maintain soil microbial pollution and diversity, and enhance soil health [81]. Other benefits of cover crops extend to adding OM to soil, suppressing weeds and pests, reducing soil compaction, improving soil structure, enhancing water infiltration, promoting nutrient retention and cycling, and providing emergency forage [73]. In general, cover crops are a practical implementation of USDA-NRCS soil health principles 1, 3, 4, and potentially 5 (if animal grazing is integrated). Sharma et al. (2018) conducted a comprehensive review on the role of cover crops toward soil health and sustainable agriculture [82]. Though the short-term effects of cover crops on the overall soil health may not be detected by the existing assessment methods [70], living cover crops have been evident in reducing soil erosion losses and enhancing the microbial community structure and function [83]. In a winter wheat–fallow cropping system, planting oat as a cover crop reduced soil inorganic N by >41% and noticeably increased the levels of soil total N, total organic C, and biomass residues [83].

4.2.4. Conservation Tillage

Conservation tillage refers to any reduced tillage or planting systems in which ≥ 30% of the soil surface is covered by crop residues after planting to reduce erosion by water; if wind erosion is the primary concern, >1120 kg ha^{-1} of flat small-grain residue equivalent are on the surface during the critical erosion period [73]. Strip till, ridge till, stubble mulch till, reduced till, and no-till are exemplified conservation tillage practices if the land surface coverage by plant residues meets the criteria [84].

A brief description of the various conservation tillage systems is given in Table 3. A recent meta-analysis of the U.S. research data suggested that tillage intensity influences soil health [85]. Relative to conventional tillage, conservation tillage greatly reduces the mechanical disturbance of cropland soil. Conservation tillage is a chief measure through which USDA-NRCS soil health principle 2 can be achieved. It greatly helps conserve soil OM, improve soil structure (aggregation), and reduce soil erosion losses and greenhouse gas emissions [73,86]. Additional benefits of conservation tillage extend to reductions in tillage costs and subsurface soil compaction, and improvements in water infiltration and soil water conservation. The predominant disadvantages of the conservation tillage systems, in particular no-till, include higher costs for weed and pest control, increased nutrient runoff risks from surface fertilizer application, restricted root growth and development, and potential delays in spring planting owing to soil being too wet or cold compared to conventional tillage systems [73]. Pieper et al. (2015) noticed significant increases in soil aggregate stability, active organic C, potentially mineralizable N, and microbial activity of vegetable plots under strip tillage instead of conventional tillage [87]. A recent study in Pakistan reported notable improvements in soil health (i.e., soil water-holding capacity; pH; and total N, available P and K, and OM contents) in a rice-wheat cropping system by practicing conservation tillage [88]. The efficacy of conservation tillage for improving the cropland soil health, however, may not be readily revealed by the existing assessment methods [70,89].

Table 3. Existing conservation tillage systems for controlling soil erosion and enhancing soil health.

Tillage System	Soil Conditions Prior to Planting	Operation	Weed Control Methods
Ridge till	Undisturbed; ridge scalp at planting	Till land using a sweep cultivator to form 10–15 cm height ridges; seeds are planted in ridges	Combined herbicide application and soil cultivation
Strip till	Undisturbed; strip till at planting	Narrow and shallow tillage using a rotary tiller or an in-row chisel planter; ~1/3 surface tilled at planting	Combined herbicide application and soil cultivation
Stubble mulch till	Tilled—residues ≥ 30%	Use a chisel tiller, a blade plow, or a sweep cultivator to till stubble-covered land	Combined herbicide application and soil cultivation
Reduced till	Tilled—residues ≥ 30%	Reduce till of cropland using a chisel tiller, a disc plow, or a blade plow to prepare seed beds	Combined herbicide application and soil cultivation
No till	Undisturbed	Use a drill planter (no-till seeder) to sow seeds	Herbicides

4.2.5. Soil Organic Amendment

Organic matter is the single core factor that influences most of the soil health indicators. The predominant component of soil OM is humic substances (60–80% by weight), a brown to black, amorphous, recalcitrant organic product resulting from the microbial decomposition and synthesis of plant and other biomass residues [1]. Humic substances tend to form stable complexes with clay minerals, enhancing the resistance to microbial mineralization. The composition and content of OM in a soil is largely controlled by the local climate and influenced by soil texture, mineralogy, land use, and soil management. Tillage and artificial drainage, for instance, promote soil OM decomposition via introducing more oxygen into soil. Organic amendment, on the contrary, increases soil OM contents by applying additional organic residues to soil [1].

Land application of organic residues or soil amendment with plant debris, animal manures, biosolids, composts, food processing refuses, agro-industrial wastes, and biochar is an effective method to increase soil OM content and improve soil biological properties. A field trial in Ireland demonstrated that soil amendments separately with a spent mushroom substrate and a forced aeration compost at 25, 50, and 100 ton ha^{-1} generated barley grain yields correlated with the amendment rate and remarkably higher than the control and comparable inorganic NPK fertilization treatments. The soil bulk density and acidity were notably reduced whereas organic C, total N, and available P contents increased [90]. Many organic amendments such as spent mushroom substrate, poultry litter, biosolids, and solid animal manures and the derived biochars contain substantial levels of plant nutrients (e.g., N, P, K, Ca, Mg, and S) in addition to organic C [8,91–94]. Continuous, repeated land application of these organic amendments at sufficient rates would efficiently improve soil health. Scientific land application programs designed with careful considerations of organic amendment quality, application rate, application timing, and application method are necessary to achieve the desirable soil health improvements while minimizing potential environmental impacts like nutrient runoff losses, odor emissions, and air and water pollution. Surface broadcasting followed by immediate soil incorporation is commonly practiced to apply solid organic residues, whereas subsurface soil injection is used to apply slurry organic wastes.

4.2.6. Crop-Range-Livestock Integration and Rotational Grazing

In a crop-range-livestock integrated system, land is used to produce crops from spring through fall and the resulting stubbles and other plant residues remain in the field for livestock animals such as cattle, goats, and sheep to graze in winter. Winter cover crops are another feed source to support animal grazing. Livestock animals are raised on the rangeland during the crop-growing seasons. Integration of livestock grazing into the routine cropping system is promising to improve farm resource utilization efficiency, reduce the demanding use of chemical fertilizers and pesticides, and enhance soil health [40,95]. These benefits may be voided if overgrazing occurs (e.g., cropland with limited amounts of crop residues and cover crop biomass is overloaded with animal weight and grazing time). Soil health deterioration may be induced by excessive animal trampling and the consequent soil compaction, aggregate breakdown, and water infiltration decrease [40]. Such deterioration may also arise from animal grazing on wet soil. Overgrazing is more common for larger animals like cattle. Rotational grazing can be exercised to avoid overgrazing.

Rotational grazing refers to the practice of subdividing a pasture into a number (e.g., 2–30) of smaller paddocks and only selected paddocks are grazed by animals at a given time while the remaining paddocks are un-grazed to allow for forage restoration [96]. Successful rotational grazing demands a proper rotation schedule with timing of animal paddock shifts matching the growth stage of forage plants. A rigid, regular animal paddock shifting schedule without considering the plant growth rate decreases the benefits of rotational grazing. A shorter grazing period and a longer “rest” time promote the forage productivity of individual paddocks [96]. A well-managed rotational grazing program helps reduce soil erosion from perennial pastures and improve the water quality as well as animal production.

5. Summary and Conclusions

Natural soil is a living ecosystem and therefore, can be healthy or unhealthy. The health of a soil reflects its capacity to function and provide desirable ecosystem services, such as sustaining crop productivity. Healthy soil is the foundation of sustainable agriculture. Soil health, however, can be deteriorated by improper land use and management practices. Worldwide, soil health degradation has become an overarching challenge of the agricultural production system, threatening global food security and social, environmental, and economic sustainability. To restore, sustain, and enhance the soil health of agricultural land, effective soil health assessment and management methods and approaches are warranted.

The concept of soil health evolved from soil quality, a previous soil science discipline that was intensively studied before the new millennium. In the past decade, the science of soil health has rapidly developed, in particular in terms of the three focal aspects: concept, assessment, and management (as illustrated in Figure 2). The understanding and interpretation of soil health by researchers, farmers, policymakers, and other stakeholders are diverse, covering soil ecosystem services, functions, processes, and properties. Intensive research has been conducted to establish a viable soil health index system. Numerous soil physical, chemical, and biological parameters were evaluated for the feasibility of soil health indication. Realizing the criticality of biological processes in delivering soil ecosystem services, scientists have created an array of new biological parameters as potential soil health indicators. Currently, 19 Tier 1 soil health indicators, mainly soil physical and chemical attributes, are recommended. Most of the new soil biological properties need further scientific validation and applicability improvements. A suite of soil health assessment methods has been developed. Nevertheless, nearly all the assessment methods need additional substantiation and enhancement in relevance, scientific validity, practicality, and local adaptation. To maintain and boost the soil health of agricultural production systems, five basic principles and a variety of management practices have been advocated for. These principles and practices, designed primarily for soil erosion control, have been shown to be effective in improving soil health if appropriately and continuously implemented. Other well-established soil management strategies and approaches, such as agronomic fertilization, desalinization, liming, and vegetated buffer strips, should also be included as best soil health management practices. Intensified research, education, and outreach efforts are necessary to improve localized adaptation, adoption, and implementation of soil health assessment and management.

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