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The concept and future prospects of soil health

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Abstract

Soil health is the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans, and connects agricultural and soil science to policy, stakeholder needs and sustainable supply chain management. Historically, soil assessments focused on crop production, but today soil health also includes the role of soil in water quality, climate change and human health. However, quantifying soil health is still dominated by chemical indicators, despite growing appreciation of the importance of soil biodiversity, due to limited functional knowledge and lack of effective methods. In this Perspective, the definition and history of soil health are described and compared to other soil concepts. We outline ecosystem services provided by soils, the indicators used to measure soil functionality, and their integration into informative soil health indices. Scientists should embrace soil health as an overarching principle that contributes to sustainability goals, rather than only a property to measure.

TOC blurb—Soil health is essential to crop production, but is also key to many ecosystem services. In this Perspective, the definition, impact and quantification of soil health are examined, and the needs in soil health research are outlined.

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Publisher's note

Introduction

Soil is a complex system[1] at the intersection of the atmosphere, lithosphere, hydrosphere and biosphere[2] that is critical to food production and key to sustainability through its support of important societal and ecosystem services[3,4]. It is in this context that the concept of soil health emerged in the early 2000s (Box 1), and today has linkages to the emerging 'One Health' concept[5], in which the health of humans, animals, and the environment are all connected.

The terminology, concept, and operationalization of soil health are still evolving (Box 1). It is now defined by most agencies, such as the US Department of Agriculture, as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." (https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/) Several other related concepts exist, including soil fertility, soil quality, and soil security[6] (Fig. 1), which also emphasize the role or functioning of soil in society, ecosystems and/or agriculture[4]. The narrowest of these terms is soil fertility, which refers to soil's role in crop production[6]. Soil fertility is managed by farmers at the field scale for the purpose of cost-effective crop production and entirely focuses on growing food, fuel, and fibre for human use[7].

Soil quality is the historic origin of the term soil health, and describes a soil's ability to function for agriculture and its immediate environmental context. Soil quality therefore includes soil effects on water quality, plant and animal health within entire ecosystems[8]. Although the terms are often used synonymously, we argue that soil health is distinct from soil quality, as the scope of soil health extends beyond human health to broader sustainability goals that include planetary health, whereas the scope of soil quality usually focuses on ecosystem services with reference to humans[6,8,9].

Soil security, introduced in 2012, is the most recent and broadest term of the four, and encompasses soil health, using the term soil 'condition' to describe the manageable properties of soil[10]. Soil security relates to the need for access to soil ecosystem services to be on the same level as other human rights[11], and is therefore often used in a policy context, encompassing human culture, capital, and legal aspects of soil management. Importantly, soil security allows for productive conversation about soil as a common good, similar to water and air[12], rather than only as private property (as in soil fertility and quality). We believe this view must be moved to the centre of the debate about the role of soils in sustainability and governance[13].

Soil health encompasses scales, stakeholders, functions and assessment tools relevant to soil quality and fertility, and shares some of the policy dimension of soil security (Fig. 1), going beyond a focus on only crop production or other explicitly human benefits. The multi-dimensionality of the soil health concept allows for soil management goals to be aligned with sustainability goals, and should provide the foundation to consider a large number of stakeholders, functions, and spatial and temporal scales. One of the most important achievements of the soil health framework (initially under the term soil quality[6]) is the addition of an urgently needed biological perspective to soil management in order to address longer-term sustainability challenges for crop production. A biological perspective is also critical to expanding soil assessment and management to addressing concerns over biodiversity, water quality, climate, recreation, and human and planetary health beyond humans.

The historical uneasiness with which scientists have embraced the concept of soil health is due to challenges of defining soil health in a way that allows for a universal quantitative assessment that encompasses all of its ecosystem services, including human health. Reasons for this challenge include soil heterogeneity, the site-specific nature of soil management, and the varying ecosystem services that have sometimes conflicting or competing needs. Nevertheless, there has been widespread interest amongst researchers, policymakers, and stakeholders in the use of the soil health concept.

In this Perspective, we describe the relationship between soil health management and sustainable plant production, water quality, human health, and climate change mitigation. Biological, chemical and physical indicators and their integration into a comprehensive approach to soil health are outlined, and we argue for a greater inclusion of biological indicators in soil health assessments. Finally, we discuss recent technology developments that should be leveraged in measuring and monitoring soil health, and future directions for soil health research and management.

Soil health and ecosystem services

Soils provide multiple ecosystem services (Fig. 2), and as such, soil health management in support of sustainability must consider three points: that enhancing many soil ecosystem services requires multi-functional management; that managing soil to improve one service can have positive (synergistic) or negative effects (tradeoffs) on another service; and that soil health management should sustain soil services over the long term. Here, we briefly highlight four main soil ecosystem services—sustainable plant production, water quality control, human health advancement, and climate change mitigation—that are considered during soil health management.

Sustainable plant production

Plant production, the main goal of intensive agriculture, is an important focus of soil health management[14,15], as it affects water use and quality, human health, animal health, climate and biodiversity (Fig. 2). A foundation of soil health, though, is the recognition that managing nutrient availability alone, such as through the use of agrochemicals (mainly fertilizers), is not sufficient for optimizing plant growth[6]. Furthermore, there is increased recognition that some management practices used in intensive agriculture to increase total plant production are detrimental to soil health[16]. For example, rooting depth—critical in plant production—depends to a large extent on soil structure, which is determined in part by organic matter content[17] and soil preparation[18]. Tillage can negatively impact soil structure through soil compaction[19], and the use solely of inorganic fertilizers (as opposed to organic rich fertilizers such as compost and manure, or the use of cover crops) is often not sufficient to restore or retain adequate levels of soil organic matter[20]. Focusing on soil health will therefore expand soil management from a reliance on inorganic fertilizers to employing organic amendments and crop residue return, reducing mechanical impact by tillage, increasing plant diversity in both time and space, or reducing erosion with contour ploughing (ploughing along elevation contours) or grass strips[15,17,18].

In addition to managing physicochemical soil properties for plant production, soil health considers the interactions between plants and soil microbial communities around roots, which can promote or reduce plant growth[21]. Promoting a soil microbiome for high plant production requires management of microbial abundance and activity, community composition and specific functions[22,23]. For example, organic amendments (such as compost) can foster increased resilience to plant pathogens through promotion of beneficial microorganisms[23]. In many cases, higher organic matter contents through higher amendments or reduced tillage increase biodiversity that is expected to improve crop resilience[24]. However, there are exceptions to these trends, as for example reducing tillage may reduce crop yields in some instances[25] with follow-on reductions of soil organic carbon[26].

Water quality

Soils can be a source and/or sink of pollutants[27] as rainwater and snowmelt moves through it (Fig. 2). These pollutants include herbicides, pesticides, heavy metals, antibiotics, hormones, microplastics, pathogens, polycyclic aromatic hydrocarbons (PAH), per- and poly-fluoroalkyl substances (PFAS)[28]. Moreover, nutrient pollution from agricultural fertilizer use is a global problem, leading to eutrophication and/or anoxia of waterways, promoting harmful algal blooms, and negatively impacting drinking water quality[29]. Thus, there is a trade-off between soil management to support crop growth and water quality, which requires careful consideration and multiple management strategies.

Managing soil health to promote good water quality includes retaining pollutants and others in the soil, buffering against them, and biotically transforming them. Increasing soil organic matter will retain heavy metals and organic toxins, some of which show nearly irreversible adsorption to organic matter[30]. Using buffer zones, such as vegetative filter strips near agricultural areas or constructed wetlands, can slow the migration of nitrate, phosphate or pesticide contamination to water[31]. Soil biota can transform organic pollutants, such as the common hydrocarbon toluene, to harmless compounds[32]. Therefore, both organic matter content and microbial activity, key properties of soil health, improve the quality of the water that is draining soil.

Soil health of urban soils have not yet received sufficient recognition[33], but can contain an even wider range of contaminants than agricultural soils, and many urban soils have also been modified to an extent that water can drain either very quickly or not at all[34]. Soil health management in urban soils must therefore balance eliminating surface runoff against retaining water and pollutants by reduced drainage. A combination of managing physical retention with biological transformation of pollutants through high soil biodiversity[35] is the goal of bioretention[34] and constructed soils[36] to provide clean drinking water.

Human health

Human health depends to a great extent on soil health, including and going beyond the obvious connection between soil and human health through crop production (Fig. 2): similarly important is the type of crop and its nutritional content[37]; soils with greater micronutrient availability are related to lower malnutrition[38] and higher soil organic matter improves the nutritional value of crops[39]. In addition to these relatively well-known properties, nutritional value of crops can also depend on robust soil biodiversity[40], which can enhance micronutrient bioavailability to crops[41] and suppress soil-borne plant disease[42], as well as taste, food storage and preparation[43].

Soils can also negatively impact human health. For examples, soil pollutants can contaminate produce through direct contact or dust, suspension, or rainsplash. Some compounds, such as arsenic[44] as with most inorganic pollutants, can also be taken up through the root system and accumulate in grain or fruit. In addition to abiotic contaminants, soils can contain pathogenic fungi that produce mycotoxins, contaminating plant products and causing acute and chronic diseases[45] in animals and humans. Furthermore, soils are also the source of parasitic worms (helminthiasis) that can live for years in the human gastrointestinal tract, cause malnutrition, and result in stunted development[46].

Although soil hosts pathogens, it has also historically been the source of organisms that produce antibiotics used in the medical industry, such as streptomycin[47]. Most of the soil microbiome remains to be identified, and important discoveries for human medical applications may still be made[48]. Quantifying and managing soil biodiversity, part of the goals of soil health management, is needed to arrest extinction of microbial species[49] and preserving opportunities for future bioprospecting.

Climate change

Soil management can mitigate or exacerbate climate change and its effects on other soil ecosystem services such as water quality or plant production.[50,51] For example, climate change mitigation strategies, such as sequestering carbon in soil as organic matter, can benefit agriculture by improving crop productivity and resilience to drought and flooding[50]. Furthermore, increased soil organic matter contents can be achieved by increasing the use of organic fertilizers or soil amendments, as well as by reducing tillage[15] to increase aggregation and control microbial mineralization to carbon dioxide (Table 1), which can also promote plant growth. However, there are trade-offs between managing soil health for climate change versus for food production. For instance, use of nitrogen fertilizers, which are commonly used to increase crop production, can lead to increased emissions of nitrous oxide, which is a powerful greenhouse gas[51]. These examples highlight the difficulty in balancing the various uses of soils, and why it is important to provide context and goals for soil health management.

Quantifying soil health

Quantification is important in managing soil health and soil ecosystem services, and the multi-functionality (Fig. 2) and diversity of soil requires multiple indicators to be quantified and integrated into an index. Broadly, soil health indicators can be classified as physical, chemical, or biological[6], although these categories are not always clearly delineated, as many properties are a reflection of multiple processes. For example, soil aggregation is the result of chemical parameters (such as organic matter content), mineral type, and/or biological activities[52]. Similarly, plant-available phosphate falls under chemical indicators, but is largely a result of biological processes of microbial mineralization and plant uptake. The present classification (chemical-physical-biological) is therefore in many respects less a reflection of causality (for example, as plant availability of phosphate is also a result of a biological process) than the object of inquiry (for instance, phosphate is a chemical indicator) that can be readily analysed.

To be used as a soil health indicator, a parameter should satisfy several criteria, which include being: relevant to soil health, its ecosystem functions and services (Table 1, Fig. 3); sensitive, by changing detectably and quickly without being reflective of merely short-term oscillations; practical, by being conducted cheaply and with a short turnaround; and informative for management[53] (Fig. 4). Approximately half of the indicators currently used in more than 20% of 65 soil health analysis schemes (comprising a mixture of declaring to be soil quality or soil health schemes[6]) satisfy all four criteria (Fig. 4), but some important indicators do not. Total organic carbon, for example, satisfies three criteria, but typically does not change very quickly (is not sensitive), requiring additional indicators such as organic carbon fractions that are more sensitive[54]. Other indicators, such as soil texture or depth, do not readily change, cannot be easily managed (in other words, are not ‘informative’, Fig. 4), even though they are highly relevant for soil health[6,53,55], and in many schemes still require time-intensive analyses or in-field measurements[56]. However, these unmanageable indicators provide context for soil health and can be understood as mapping a soil’s potential or capability[55], without which the manageable attributes cannot be understood. Importantly, and problematically, none of the listed biological indicators are currently effective in allowing cheap, reliable and quick information to be obtained.

Soil health assessments for plant production often include total organic carbon, plant-available nutrients, pH, CEC, EC, penetration resistance, N mineralization, and microbial biomass (Table 1). A smaller number of these tests (less than 20%) include aggregation, water storage, and OC fractions. Managing soil health for climate change mitigation should include testing similar parameters, with a small portion of tests already examining soil nitrogen forms that should be adapted to provide information about potential greenhouse gas emissions including nitrous oxide. Soil health assessments relevant for water quality should include microbial biomass and activity, mobile nutrients, heavy metal toxins, and total organic carbon already part of many soil health testing schemes, yet should also encompass aggregation and infiltration that are only occasionally included. Many of these indicators should also be used in soil health assessment for human health.

In total, more than two thirds of soil health test frameworks currently include the traditional quantification of soil organic matter, pH, and plant-available phosphorus and potassium, and more than half include water storage and bulk density[6]. A third of tests also recommend measurements of soil respiration, microbial biomass or nitrogen mineralization to characterize biological properties, as well as structural stability[6]. Chemical indicators make up at least 40% of the indicators in 90% of the soil health assessment schemes (Fig. 5), underscoring the continued importance of chemical properties in soil health quantification and the long-standing emphasis on plant production. Indeed, the most advanced analytical schemes currently, such as the Soil Management Assessment Framework, focus on indicators for sustainable crop production[57–60]. However, the EU Commission recently recommended inclusion of soil biodiversity as one of six indicators of soil health[61].

Biological indicators typically still constitute less than 20% of the indicators (Fig. 4), even when the total number of indicators used by a particular scheme increases. Furthermore, the development of soil health assessment schemes over the last decade has not yet lead to an inclusion of a greater proportion of biological indicators, despite their declared importance for soil health management (Fig. 4). One reason for the low representation of biological indices is, we posit, the lack of mechanistic understanding of how soil biota relate to soil functions (meeting the ‘relevant’ criteria, Fig. 4), how that understanding relates to management decisions (‘informative’) and the inability to easily quantify biological indicators (‘effective’). This lack of understanding is even the case for soil ecosystem services that would benefit from biological indicators, such as crop production[18,21,22,62], water quality[27], or biodiversity[49]. In a Swiss grassland soil, for example, a loss in soil biodiversity (microbes and fauna) was associated with lower plant diversity, a three-fold higher phosphorus leaching, and six-fold higher gaseous losses of nitrous oxide[35]. Advancing both the information about causality between biological indicators and soil health as well as those assessment tools that satisfy all four criteria is therefore critically needed and is the next frontier in soil health research.

A new generation of indicators

Each soil health goal requires a different set of parameters be monitored, compared to reference states when appropriate, and managed. For indicators included in more than 20% of already proposed methods, we recommend these be the minimum set of indicators for that management goal (Table 1). Furthermore, we suggest additional measurements, especially biological assessments, be added for when assessing soil for each of the management goals. For example, we suggest that aggregation, infiltration, earthworm abundance, organic C and N fractions should be more widely adopted in soil health testing (Table 1), and N-mineralizing enzyme activity be added for soil health assessments for plant production. We further propose several new indicators that are mainly geared towards non-agricultural soil services, such as human health and water quality, need to become part of routine soil health testing. These indicators include pathogens, parasites, biodiversity, bioavailable and mobile toxins (such as dioxin, PAH, and microplastics), and compound and pore-size diversity.

Importantly, development of soil health indicators related to the climate change functions of soils, such as greenhouse gas emissions and carbon sequestration, has largely been ignored. This neglect is largely due to GHG emissions depending on fluctuating conditions (such as moisture and temperature)[63], so the magnitude of GHG fluxes for a given field or region cannot be assessed by one-time soil measurements. However, soil carbon fractions of both unprotected and mineral-protected organic matter[64] already allow assessment of soil organic matter vulnerability with respect to soil carbon sequestration, and are indispensable indicators for soil's climate change function[65]. Such fractions capture changes in soil organic matter properties very sensitively, yet are less variable than mineralization or microbial biomass assays, allow unambiguous interpretation[66], and can be quantified using rapid infrared technology[64] (Table 1). In-field methods for measuring greenhouse gas emissions will need to provide integrated information about the highly temporally dynamic processes, requiring a new generation of sensors based on autonomous gas and solute detection powered by bioreactors[67] and a range of energy-harvesting technologies[68] in wireless networks[69].

Diversity indicators, whether organismal (biological), molecular (chemical), or structural (physical), are not adequately included in or integrated into analytical frameworks of soil health. Biological diversity in particular has been recognized as important for soil and human health[40], yet appropriate soil health indicators and practical quantification methods for soil biota diversity are lacking[6]. Similarly, molecular or soil structural diversity are not yet explored yet are important for soil organic carbon persistence and sequestration[70]. Next-generation sensor technology for plant and climate functions could provide the much-needed platform to monitor changes in soil health over time[67,68,69]. Recent global mapping of biodiversity[71,72] and similar efforts will potentially provide context and reference sites for biodiversity calibration. Rapid screening techniques using near- and mid-infrared[64,65], beyond infrared energies, sound[73], lab-on-a-chip technology[74]—technologies generally underdeveloped for soil[75]—should be adapted to make existing soil health analyses cheaper and faster. Further promising tools or techniques for observing biological properties including electrochemistry[76] and biosensors[77] are promising avenues that speak to the rapid emergence of new approaches. Similarly, passive samplers[78] can and should be used to quantify the small portion of organic toxins that is harmful to organisms, rather than assessments relying on total contents that are not sufficiently sensitive to changes in management or reflect the ecologically relevant fraction. Altogether, such technologies could expand the suite of assessed biological properties to include soil organic matter vulnerability[54,64] and microbial or faunal community or functional gene information[79].

Advances in soil health monitoring over the coming decade should also include development of remote sensing techniques[80]. Remote sensing should not only include spatial information of soil properties, such as seen with successes measuring soil moisture using microwave[81], but also assess soil management practices that can be related to soil functions via mathematical modelling, as is already in development for soil organic carbon monitoring[82]. Such rapid and large-scale soil health screening through remote sensing should be complemented by exploring the use of guided small-scale robotics[83] to assess soil hotspots and sensitive flowpaths (such as soil cracks and earthworm holes) that are typically undetected through remote or bulk assessments. Next-generation electronics should be applied to enable cheap and distributed sensor deployment, fast data transmission, storage and handling, and need to make use of the rapid development in the computing and smart-grid sector to develop internet-of-things sensor networks for soil health monitoring. Rapid screening and in situ and remote monitoring technologies discussed here would substantially advance our ability to measure and manage soil health, ultimately improving soil ecosystem services.

Soil health indices

As there is a multitude of soil health indicators, an appropriate desire exists by scientists and stakeholders to integrate them into one single test score or ‘soil health index’ (note the difference between ‘indicator’ and ‘index’). However, relatively few indices exist; in the 2020 database compiled on soil health, *SoilHealthDB,* which assessed over 500 studies on soil health and quality[14], only five studies included a single soil health index. We discuss some of the challenges in creating integrated indices, and needs that must be overcome when developing and using them.

Challenges

Creating a soil health index is difficult, as indicated by the relatively low number of published indices, because it requires quantitative transformation and weighting of multiple indicators, including categorical properties, in order to integrate them into a final single score. Indicator values are necessarily transformed using non-linear relationships, because a higher value does not always indicate better soil health[84,85,86]. A ‘high’ organic carbon value might indeed indicate a desirable property for many soil functions, but pH should be within an intermediate range, and the force needed to penetrate the soil should be relatively low. In the Comprehensive Assessment of Soil Health, for example, these three categories are described as ‘More is better’, ‘Optimum curve’, and ‘Less is better’[86]. In most existing frameworks, the conversion of measured values to scores are based on the distribution of the actual measurements within a reference dataset[85]. To determine the final soil health score, often all indicators are treated as equally important[84,85]. For instance, the Comprehensive Assessment of Soil Health assigns values between 0-100 (where 100 is highest) to each indicator based on a comparison to reference values of all available data in the region[87].

Although these indices can provide useful information on large scales[86], regional comparisons are not appropriate in situations with bias resulting from inherent differences between soil types[88] and require careful calibration to regional conditions and needs[89]. In temperate arable soils in England and Wales, for example, an organic carbon value of 1.5% is considered a lower limit for soils with 40% clay, but would be considered high in soils that have less than 10% clay[90]. Therefore, identifying soil organic carbon as high or low in this region depends on clay contents, and soils should be compared to references with a similar clay content. Changes of soil health over time can generate more robust comparisons, which relates to the definition of soil health as a “continued capacity”. For example, the formation or maintenance of aggregates over time can indicate better soil health[84], as particles are bound into aggregates mainly by microbial products from organic amendments[91]. However, aggregates can form even without organic matter, and the formation of aggregates differs between soils—within weeks and without organic amendments, aggregates formed in a kaolinitic Oxisol from Brazil, whereas no aggregates formed in an illitic Mollisol from the US[52]. Considering inherent differences between soils is particularly important when using biological indices. For example, bacterial diversity was as much affected by soil type, soil texture and pH, as by whether soils were located under forests or grasslands across a north-south gradient in Germany[92]. At the same sites, changes in bacterial diversity as a result of fertilization, mowing, and grazing in grasslands or of various silvicultural management in forests were only discernible within a given site.

Despite these caveats, appropriately comparing changes in soil health indicators and indices over time or to a suitable reference dataset, can be used to assess whether, for example, a reduction in tillage or addition of compost improve aggregation and total soil health scores[62]. Indeed, it is standard practice to identify whether a soil has high or low amounts of extractable nutrients or converting nutrient indicators into amounts of fertilizer for a certain crop while recognizing differences in texture, mineral types and even utilizes information from fertilizer responses for a specific soil[93].

Needs

Development of a soil health index that includes all soil functions (Figs 1 & 2) requires engagement of a broader set of stakeholders than an index focused on crop production. A comprehensive soil health framework will need to include and allow weighting trade-offs to lead to optimum overall function, as it must balance the sometimes competing functions of soil, for example, the need to minimize water pollution by fertilizers versus the need to optimize nutrient availability for crop growth[94]. Such trade-offs also mean that the effects of non-crop ecosystem services such as water quality, have to be valued against crop growth effects on human health, which has rarely been done in a quantitative way[95] even in comprehensive ecosystem services assessments[96]. For example, soil effects on human health need to be assessed as they affect humans both through production of nutritious food as well as through clean water, with unclear quantitative criteria whether water is more important than food or vice versa.

Holistic soil health indices should therefore include multi-criteria decision analysis[97] to quantify and prioritize sustainability outcomes of soil health management. Societal demands for different soil functions such as water quality and food production may vary by stakeholders and region; for example, in an analysis of societal demands in Europe water quality and food production was on average mentioned by the same groups, though densely populated countries such as The Netherlands and Belgium put more value on water quality and nutrient management than countries such as Romania or Finland[98]. Soil health data should be presented using interactive data visualizations[99] that reconfigure according to the desired focus. Such interactive tools will benefit researchers[100] as well as stakeholders[101] to prioritize soil functions and take decisions. Emerging data analysis tools such as machine learning[6], deep learning, artificial neural networks[102], or game theory[103] should be explored more fully in order to quantify the effect of soil health indicators as well as prioritize soil functions such as water quality or food production.

In parallel, new analytical and conceptual approaches need to be developed that capture systems characteristics of soil health, in order to operationalize both monitoring soil health itself but also understanding soil health effects on soil functions. Precision or digital agriculture[104] are expanding avenues to leverage for quantification of soil health with its multiple ecosystem functions and services. There must be greater engagement between soil science and engineering whereby both instrument and computational technology is jointly developed with stakeholders. For example, soil-engineering collaborations through colabs[105] will need to advance scientific discovery of new detector technology as well as data analysis tools that can adapt complex data structures into simple apps for stakeholder use. Water science, medicine, psychology, philosophy and other fields need to engage for metrics and management to reflect the full range of soil health functions, including climate change, water quality, biodiversity, and human health. Fostering discussions at professional and trade meetings as well as cross-training of the next generation of scientists may help to promote mutual understanding and joint problem-solving.

Future perspectives

The soil health concept fills an important stakeholder need in sustainable development[61] by elevating the recognition for soil's role in modern society and is developing into an attractive and actionable platform for farmers, land managers, municipalities and policy makers. The versatility of the concept allows many stakeholders to adopt soil health and to make it work for their context. By providing an illustrative link to broader sustainability goals that can motivate innovative soil management, soil health meets universal agreement in the eye of the public as a goal to work towards.

Scientists are converging on a definition of soil health, and are developing or refining methods to quantify its various facets, albeit mainly with respect to its crop productivity function and with inadequate consideration of biotic and abiotic diversity. Researchers should embrace soil health as an overarching principle to which to contribute knowledge, rather than as only a property to measure. In this way, soil health could become better established as a scientific field to which many disciplines can contribute, for example by listing their specific discipline's research also under the keyword 'soil health'. Making the soil health concept live up to its potential as a unifying concept that integrates soil functions requires engagement by all involved parties, and particularly a common understanding between stakeholders and scientists.

Because of soils' broad environmental and societal functions, soil health should be legally recognized as a common good. The development of soil health quantification standards should be spearheaded by governmental or intergovernmental organizations such as the Global Soil Partnership. International standards have to be developed for suitable type of indicators, their methodological details[106] and their integration into indices. Such a comprehensive soil health index should then be referenced by local, regional or national jurisdictions and organizations to guide decisions that impact soil and its functions to benefit sustainability goals.

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History of the Soil Health Concept

The burgeoning broad public interest in the soil health concept is largely grounded in historical development. Even though the term ‘soil health’ has been more regularly used in the scientific and popular literature only since the early 2000s[107,108,109], the analogy of the soil ecosystem to an organism reaches far into the past. Soil is frequently part of creation myths[110] and humans have always had deep spiritual connections with soil, as shown in songs[111], fine and performing arts[112,113].

Since the 1700s, scientists have introduced the notion of biological processes in the formation of soil[114], and that soil ecosystems are endangered as much as any other ecosystem[115] provided a foundation for soil health. The 1979 Gaia concept[116] popularized the view of nature as a planetary-scale self-regulation system, explicitly including soil ecosystem concepts and going beyond soil services solely for humans. Appreciation for soil biological processes was largely enabled by significant advances in analytical capabilities since the 1980s, including global mapping of soil biodiversity[71,72] during the 2010s. The formulation of the UN’s Sustainability Development Goals in 2015 provided a need to align soil functions with sustainability[117] that makes soil health a suitable platform.

The soil health concept emerged from soil quality in the 1990s,[8,118] and initially met with considerable criticism[119]. More recently, policy makers have embraced the concept, exemplified by India distributing soil health cards to 100 million farmers[120] and major companies starting programs on soil health to manage their supply chains more sustainably[121]. Including carbon sequestration in soils as a main approach in the UNFCCC process to withdraw atmospheric carbon dioxide enhanced the political urgency to implement suitable soil health practices on a global scale[122]. The rapid adoption of the soil health concept after 2010 may partly be rooted in its flexibility and thereby the ability by different stakeholder to use it in their own way[123].

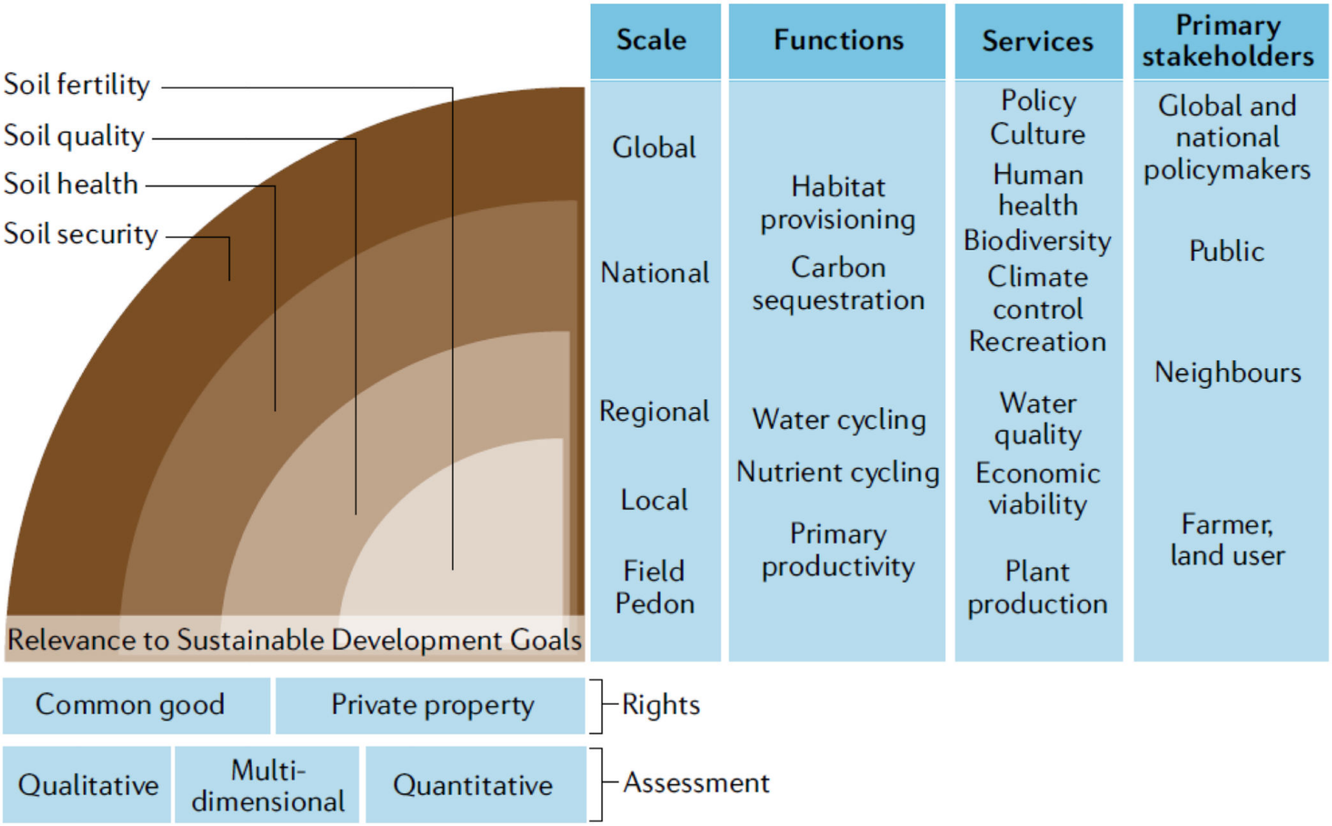


Figure 1. Soil fertility, quality, health, and security.

The concepts vary by what relevant spatial scales, functions, ecosystem services, and stakeholders they capture (listed as nested concepts on the right of the figure). The concepts also differ in the view of soil rights and assessments. Soil health encompasses a broad range of ecosystem functions, services and actors, impacting a wide array of sustainability goals. The five functions listed here impact overall soil ecosystem services[3,4,6].

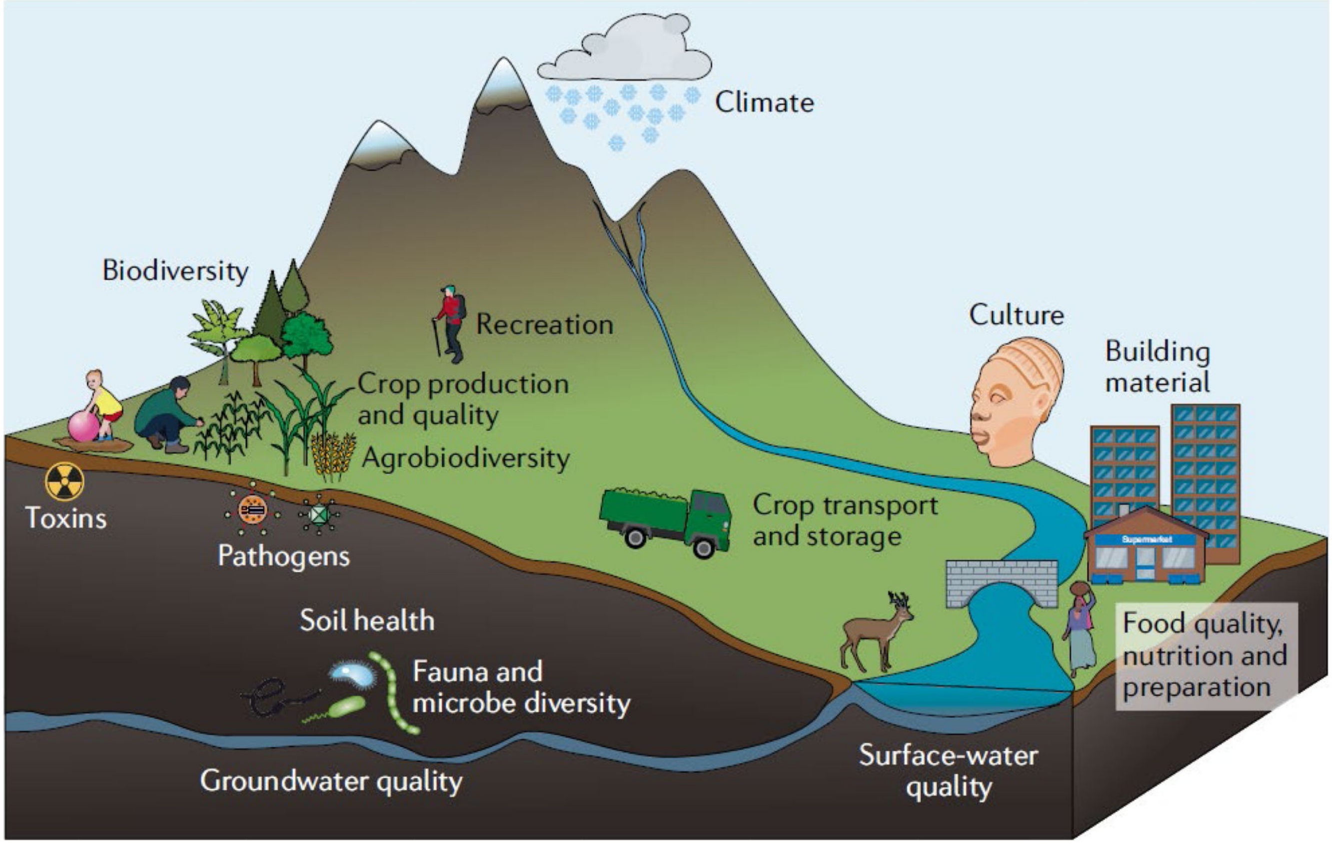
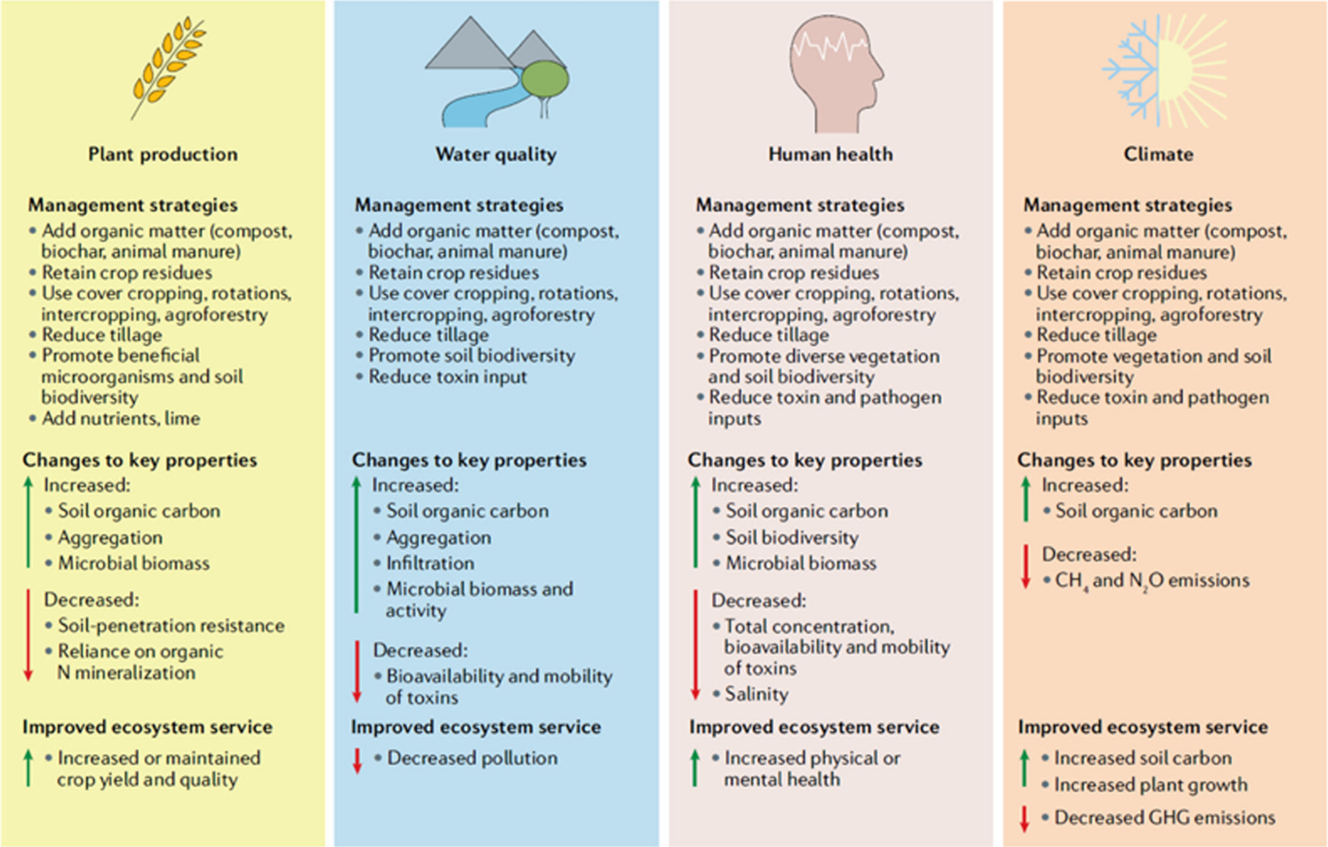


Figure 2. Soil health and global ecosystem services.

Soil health affects human and planetary health through crop production, quality, storage and transportation; food quality and taste; soil contamination, or through climate change, recreation, and culture. Immediacy of soil health effects on plants and soil biota facilitates assessment of causality (for example, soil nutrient availability affects crop production). Cascading effects (such as soil nutrient availability affecting human health indirectly through crop quality and food storage) require causalities to be demonstrated for which in some cases science still needs to be established.



Plant production

Management strategies
- Add organic matter (compost, biochar, animal manure)
- Retain crop residues
- Use cover cropping, rotations, intercropping, agroforestry
- Reduce tillage
- Promote beneficial microorganisms and soil biodiversity
- Add nutrients, lime

Changes to key properties

↑ Increased:
- Soil organic carbon
- Aggregation
- Microbial biomass

↓ Decreased:
- Soil-penetration resistance
- Reliance on organic N mineralization

Improved ecosystem service

↑
- Increased or maintained crop yield and quality

Water quality

Management strategies
- Add organic matter (compost, biochar, animal manure)
- Retain crop residues
- Use cover cropping, rotations, intercropping, agroforestry
- Reduce tillage
- Promote soil biodiversity
- Reduce toxin input

Changes to key properties

↑ Increased:
- Soil organic carbon
- Aggregation
- Infiltration
- Microbial biomass and activity

↓ Decreased:
- Bioavailability and mobility of toxins

Improved ecosystem service

↓
- Decreased pollution

Human health

Management strategies
- Add organic matter (compost, biochar, animal manure)
- Retain crop residues
- Use cover cropping, rotations, intercropping, agroforestry
- Reduce tillage
- Promote diverse vegetation and soil biodiversity
- Reduce toxin and pathogen inputs

Changes to key properties

↑ Increased:
- Soil organic carbon
- Soil biodiversity
- Microbial biomass

↓ Decreased:
- Total concentration, bioavailability and mobility of toxins
- Salinity

Improved ecosystem service

↑
- Increased physical or mental health

Climate

Management strategies
- Add organic matter (compost, biochar, animal manure)
- Retain crop residues
- Use cover cropping, rotations, intercropping, agroforestry
- Reduce tillage
- Promote vegetation and soil biodiversity
- Reduce toxin and pathogen inputs

Changes to key properties

↑ Increased:
- Soil organic carbon

↓ Decreased:
- CH_4 and N_2O emissions

Improved ecosystem service

↑
- Increased soil carbon
- Increased plant growth

↓
- Decreased GHG emissions

Figure 3. Soil ecosystem services management.

Four important roles of soil (plant production, water quality, human health, and climate mitigation) are listed at the top of the figure. Various management strategies, and their impacts on key soil properties and ecosystem services, are listed below.

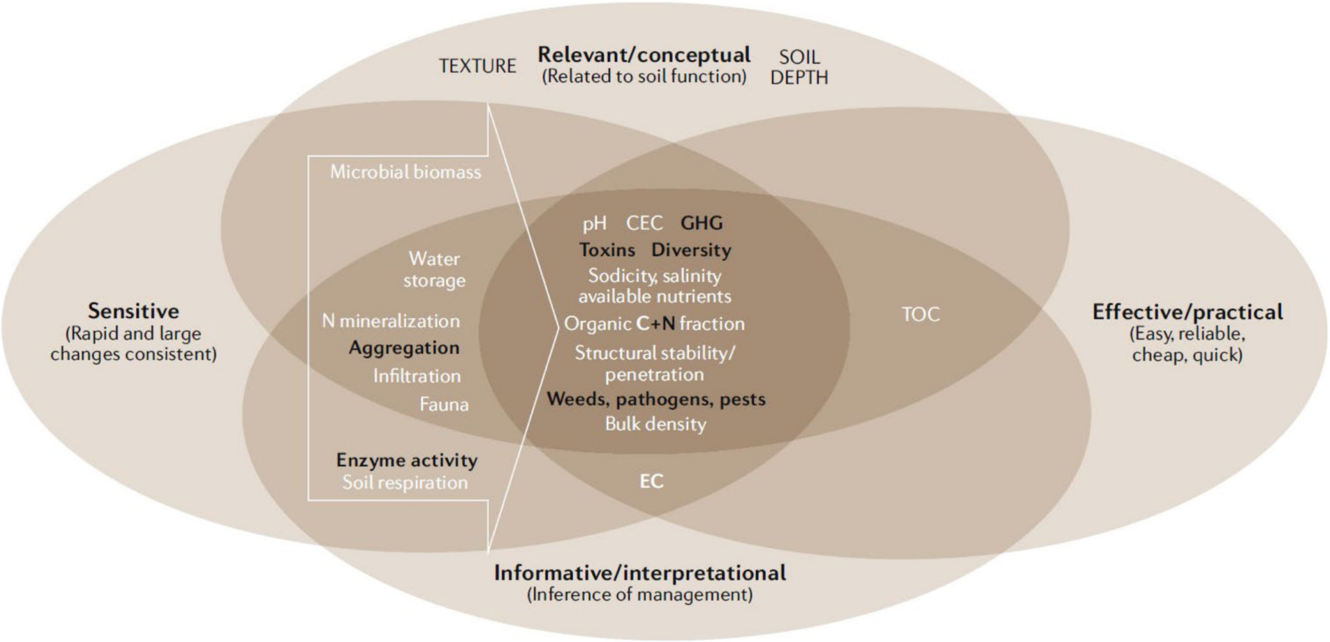


Figure 4. Soil health indicators and relevance to assessments.

Soil health indicators ideally are informative, sensitive, effective and relevant[6,53]. Some do not fulfill all criteria but are still relevant (such as TEXTURE or SOIL DEPTH that do not change readily and are not managed, therefore also called capability indicators[55]). Bold black text denotes indicators that expand the utility of soil health quantification beyond crop production towards sustainability and planetary health; the white arrow outline encompasses indicators that should be further developed to be effective and practical. Note, diversity includes biota in soil, diversity of soil types in landscape, molecular/structural in soil organic matter and plants growing in soil, some of which may not be readily quantified through analytical or modeling approaches. C, carbon; CEC, cation exchange capacity; EC, electric conductivity; GHG, greenhouse gases; N, nitrogen; TOC, total organic carbon

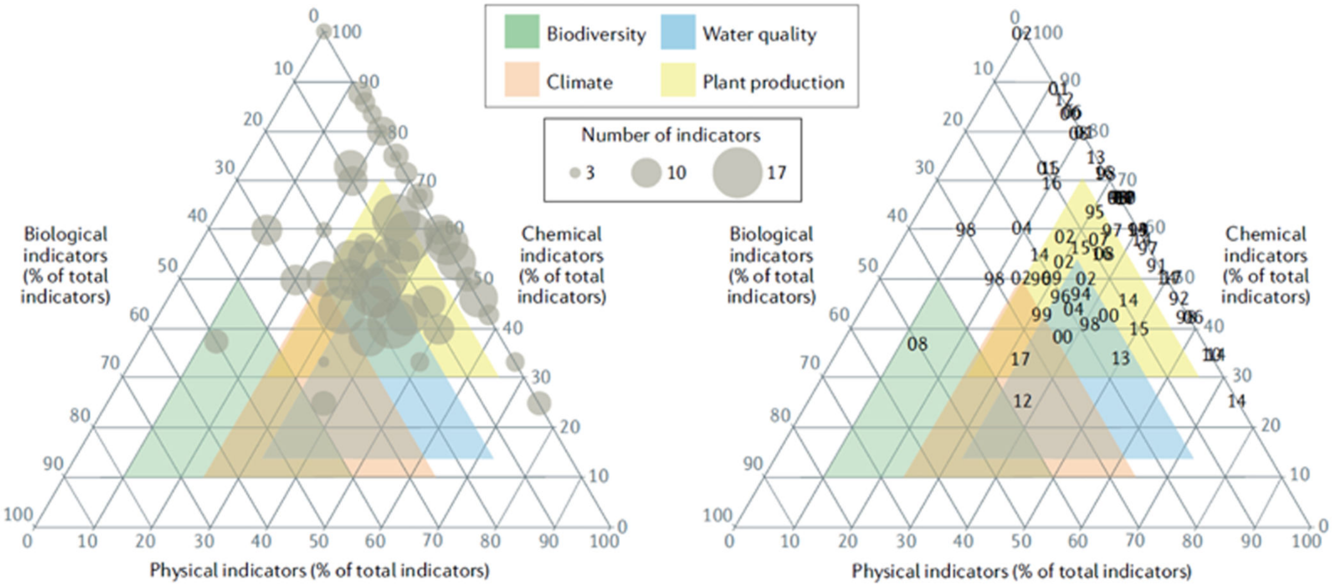


Figure 5. Biological, chemical and physical indicators included in soil health assessment schemes[6]

a| Number of indicators and proportion of each type (biological, chemical or physical). Size of the circle represents the number of indicators in the assessment scheme. **b|** Year of each soil health assessment scheme. Only the last two digits of the year are shown (values in the 80's and 90's are from the 1980s and 1990s, values from 00 to 20 represent years 2000 onwards). Currently proposed soil health indices utilize mostly chemical and physical indicators. The proportion of biological indicators is typically lower than either chemical or physical indicators, which did not change over time as the methods were published, likely reflecting the historic focus of soil health indices on crop growth. The number of indicators in the proposed schemes does not relate to the proportion of biological indicators. A comprehensive soil health index may consider a balanced set of indicators that represent at least 20% biological, physical and chemical measurements (dashed red triangle). However, indices designed to quantify different services may require a different set of indicators: a soil health index for crops may require more chemical indicators (inside the yellow 'Plant' triangle), for water more physical (blue triangle), for biodiversity more biological (green triangle), and for climate more physical and biological indicators (orange triangle).

Table 1

Soil indicators, inclusion in ecosystem service assessments, indicator type and assessment methods.

Indicators included in more than 20% of soil health assessments are labelled as ‘>20%’. Those included in at least one but less than 20% of assessment methods are labelled as ‘<20%’. Those that are typically not included, but recommended to be included, are labelled as ‘proposed’. Those indicators less directly relevant for a certain ecosystem service are marked as ‘-‘, those that are more relevant with ‘+’.

		Ecosystem service					
Indicator	**Inclusion**†	**Plant production**	**Water quality**	**Human health**	**Climate control**	**Type of indicator**	**Methods to assess**‡
N/S/P-mineralizing enzyme activity	<20%	+	+	-	+	B	Colorimetry, extraction; lab-on-a-chip; electrochemistry
N mineralization	> 20%	+	+	-	+	B	Incubation; extractions; lab-on-a-chip; electrochemistry
Microbial biomass	> 20%	+	+	-	+	B	Incubation; extractions; lab-on-a-chip; electrochemistry
Pathogens	Proposed	+	+	+	-	B	Extractions; optical analyses; lab-on-a-chip; color reactions; DNA probes; electrochemistry
Biodiversity	Proposed	+	+	+	+	B	Extractions; bioassays; metagenomics; high-throughput sequencing; Phospholipid fatty acid; lab-on-a-chip
Microbial activity	> 20%	+	+	+	+	B	Incubation; lab-on-a-chip; electrochemistry; biosensors
Parasites	Proposed	-	-	+	-	B	Extractions; bioassays; metagenomics; high-throughput sequencing; screening for pathogenicity genes; lab-on-a-chip; electrochemistry; ultrasound
Fauna	Proposed	+	+	+	+	B	Extractions; bioassays; metagenomics; high-throughput sequencing; lab-on-a-chip; electrochemistry; sound
Earthworms	< 20%	+	-	+	-	B	Extractions; lab-on-a-chip; sound
GHG emissions	Proposed	-	-	-	+	B	In-field and laboratory GHG sensors; robots; lab-on-a-chip; biosensors
Organic toxins	Proposed	+	+	+	-	C	Extractions; passive samplers; lab-on-a-chip; electrochemistry
Organic C fractions	< 20%	+	+	-	+	C	Near/mid infrared spectroscopy; density & size fractionation; oxidation
Norg fractions	< 20%	+	+	-	+	C	Protein assay; near/mid infrared spectroscopy; density & size fractionation
Organic carbon	> 20%	+	+	+	+	C	Near/mid infrared spectroscopy; combustion; ultrasound
Bio-available nutrients	> 20%	+	+	+	+	C	Near/mid infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
pH	> 20%	+	+	+	+	C	Near/mid infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry

		Ecosystem service					
Indicator	**Inclusion**[†]	**Plant production**	**Water quality**	**Human health**	**Climate control**	**Type of indicator**	**Methods to assess**[‡]
CEC	> 20%	+	+	-	-	C	Near/mid infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
EC	> 20%	+	+	+	-	C	Near/mid infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
Compound diversity	Proposed	-	+	-	+	C	Spectroscopy
Mobile nutrients	> 20%	-	+	-	+	C	Near/mid infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
Heavy metal toxins	> 20%	+	+	+	-	C	Near/mid infrared spectroscopy; extractions; passive samplers; bioassays; lab-on-a-chip; biosensors; electrochemistry
Pore size diversity	Proposed	-	+	-	+	P	Near/mid infrared spectroscopy; ultrasound
Aggregation	< 20%	+	+	-	+	P	Sieving; near/mid infrared spectroscopy; ultrasound; visible imaging; infiltrometry
Water storage	< 20%	+	+	+	+	P	Near/mid infrared spectroscopy; pressure plate
Penetration resistance	> 20%	+	+	-	+	P	Penetrometry; mid infrared spectroscopy
Infiltration	< 20%	+	+	+	+	P	Near/mid infrared spectroscopy; ultrasound; visible imaging; infiltrometer

B: biological; C: chemical; P: physical; N: nitrogen; OC: organic carbon; CEC: cation exchange capacity; EC: electrical conductivity; N_{org} : organic nitrogen

[†] proportion from ref. 6

[‡] broad categories are given; for some detailed methods have been proposed (see ref. 106), others are suggestion for future exploration