The concept and future prospects of soil health

Johannes Lehmann, Deborah A. Bossio, Ingrid Kögel-Knabner and Matthias C. Rillig

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, owing to limited functional knowledge and lack of effective methods. In this Perspective, the definition and history of soil health are described and compared with 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.

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 the role of soil 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 the ability of a soil 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 that 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 multidimensionality 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 address 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 the 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

Box 1 | **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[106–108], the analogy of the soil ecosystem to an organism reaches far into the past. Soil is frequently part of creation myths[109] and humans have always had deep spiritual connections with soil, as shown in songs[110], fine and performing arts[111,112].

Since the 1700s, scientists have introduced the notion of biological processes in the formation of soil[113], and that soil ecosystems are endangered as much as any other ecosystem[114] provided a foundation for soil health. The 1979 Gaia concept[115] 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 of soil biological processes has been 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 United Nations' Sustainable Development Goals in 2015 provided a need to align soil functions with sustainability[116], which makes soil health a suitable platform.

The soil-health concept emerged from soil quality in the 1990s[8,117] and was initially met with considerable criticism[118]. More recently, policymakers have embraced the concept, exemplified by India distributing soil health cards to 100 million farmers[119] and major companies starting programmes on soil health to manage their supply chains more sustainably[120]. Including carbon sequestration in soils as a main approach in the United Nations Framework Convention on Climate Change (UNFCCC) process to withdraw atmospheric carbon dioxide enhanced the political urgency to implement suitable soil-health practices on a global scale[121]. The rapid adoption of the soil-health concept after 2010 could partly be rooted in its flexibility and, thereby, the ability of different stakeholders to use it in their own way[122].

that should be leveraged in measuring and monitoring soil health, and future directions for soil-health research and management.

Soil-health and soil-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 multifunctional management; that managing soil to improve one service can have positive (synergistic) or negative effects (trade-offs) 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 physico-chemical 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 content through higher amendments or reduced tillage increases biodiversity, which is expected to improve crop resilience[24]. However, there are exceptions to these trends — reducing tillage, for example, can reduce crop yields in some instances[25], with follow-on reductions of soil organic carbon[26].

Water quality. Soil can be a source and/or sink of pollutants[27] as rainwater and snowmelt move through it (FIG. 2). These pollutants include herbicides, pesticides, heavy metals, antibiotics, hormones, microplastics, pathogens, polycyclic aromatic hydrocarbons, perfluoroalkyl and polyfluoroalkyl substances[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, into 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 has 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 run-off 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, the 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 affecting taste, food storage and food preparation[43].

Soils can also negatively impact human health. For example, soil pollutants can contaminate produce through direct contact or dust, suspension or rainsplash. Some compounds, such as arsenic[44] and 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 could 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 preserve 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 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, the 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 multifunctionality (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 enquiry (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 time; 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 those declaring themselves 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 is 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,

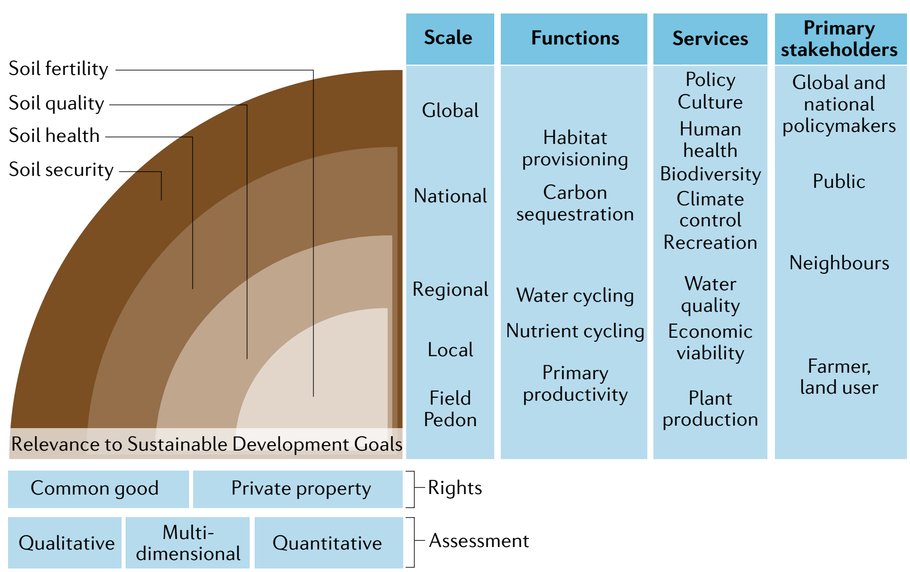

Fig. 1 | **Soil fertility, quality, health and security.** The concepts vary by what relevant spatial scales, functions, ecosystem services and stakeholders they capture (listed as nested concepts on the right of the figure). The concepts also differ in the view of soil rights and assessments. Soil health 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].

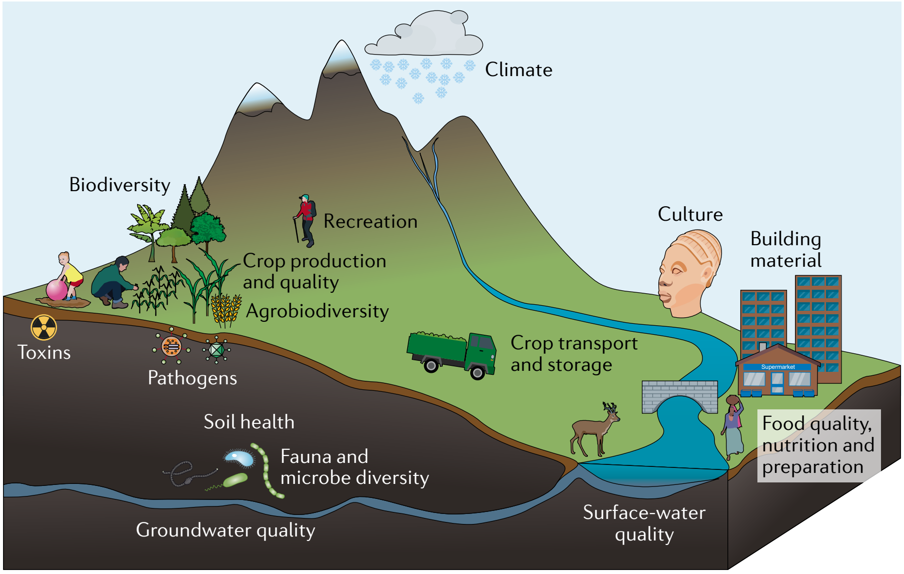

Fig. 2 | **Soil-health and global-ecosystem services.** Soil health affects human and planetary health through crop production, quality, storage and transportation; food quality and taste; soil contamination; or through climate change, recreation and culture. Immediacy of soil-health effects on plants 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, the science still needs to be established.

cation-exchange capacity, electrical conductivity, penetration resistance, nitrogen mineralization and microbial biomass (TABLE 1). A smaller number of these tests (fewer than 20%) include aggregation, water storage and organic-carbon 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, which 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 European Commission recently recommended the inclusion of soil biodiversity as one of six indicators of soil health[61].

Biological indicators typically still constitute fewer than 20% of the indicators (FIGS 4,5), even when the total number of indicators used by a particular scheme increases. Furthermore, the development of soil-health-assessment schemes over the past decade has not yet led to inclusion of a greater proportion of biological indicators, despite their declared importance for soil-health management (FIG. 5). 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 decrease in soil biodiversity (microbes and fauna) was associated with lower plant diversity, a threefold higher phosphorus leaching and sixfold higher gaseous losses of nitrous oxide[35]. Advancing both the information about causality between biological indicators and soil health, and 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 with reference states when appropriate and managed. For indicators included in more than 20% of already-proposed methods, we recommend that these be the minimum set of indicators for that management goal (TABLE 1). Furthermore, we suggest that additional measurements, especially biological assessments, be added when assessing soil for each of the management goals. For example, we suggest that aggregation, infiltration, earthworm abundance and 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 that 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, polycyclic aromatic hydrocarbons 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 greenhouse gas emissions depending on fluctuating conditions (such as moisture and temperature)[63], so the magnitude of greenhouse gas 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

Table 1 | **Soil indicators, inclusion in ecosystem-service assessments, indicator type and assessment methods**

Indicator	Inclusion[a]	Ecosystem service				Type of indicator	Methods to assess[b]
		Plant production	Water quality	Human health	Climate control		
Nitrogen-/sulfur-/phosphorus-mineralizing enzyme activity	<20%	+	+	–	+	B	Colorimetry, extraction; lab-on-a-chip; electrochemistry
Nitrogen 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; colour 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 chemical fractions	<20%	+	+	–	+	C	Near-/mid-infrared spectroscopy; density and size fractionation; oxidation
Organic nitrogen fractions	<20%	+	+	–	+	C	Protein assay; near-/mid-infrared spectroscopy; density and size fractionation
Organic carbon	>20%	+	+	+	+	C	Near-/mid-infrared spectroscopy; combustion; ultrasound
Bioavailable nutrients	>20%	+	+	+	+	C	Near-/mid-infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
pH	>20%	+	+	+	+	C	Near-/mid-infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
Cation-exchange capacity	>20%	+	+	–	–	C	Near-/mid-infrared spectroscopy; extractions; passive samplers; colorimetry; electrochemistry
Electrical conductivity	>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; infiltrometry

Indicators included in more than 20% of soil-health assessments are labelled as '>20%'. Those included in at least one but fewer 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 '–', while those that are more relevant are marked with '+'. B, biological; C, chemical; GHG, greenhouse gas; P, physical. [a]Proportion from REF.[6]. [b]Broad categories are given; for some, detailed methods have been proposed (see REF.[105]), while others are suggestions for future exploration.

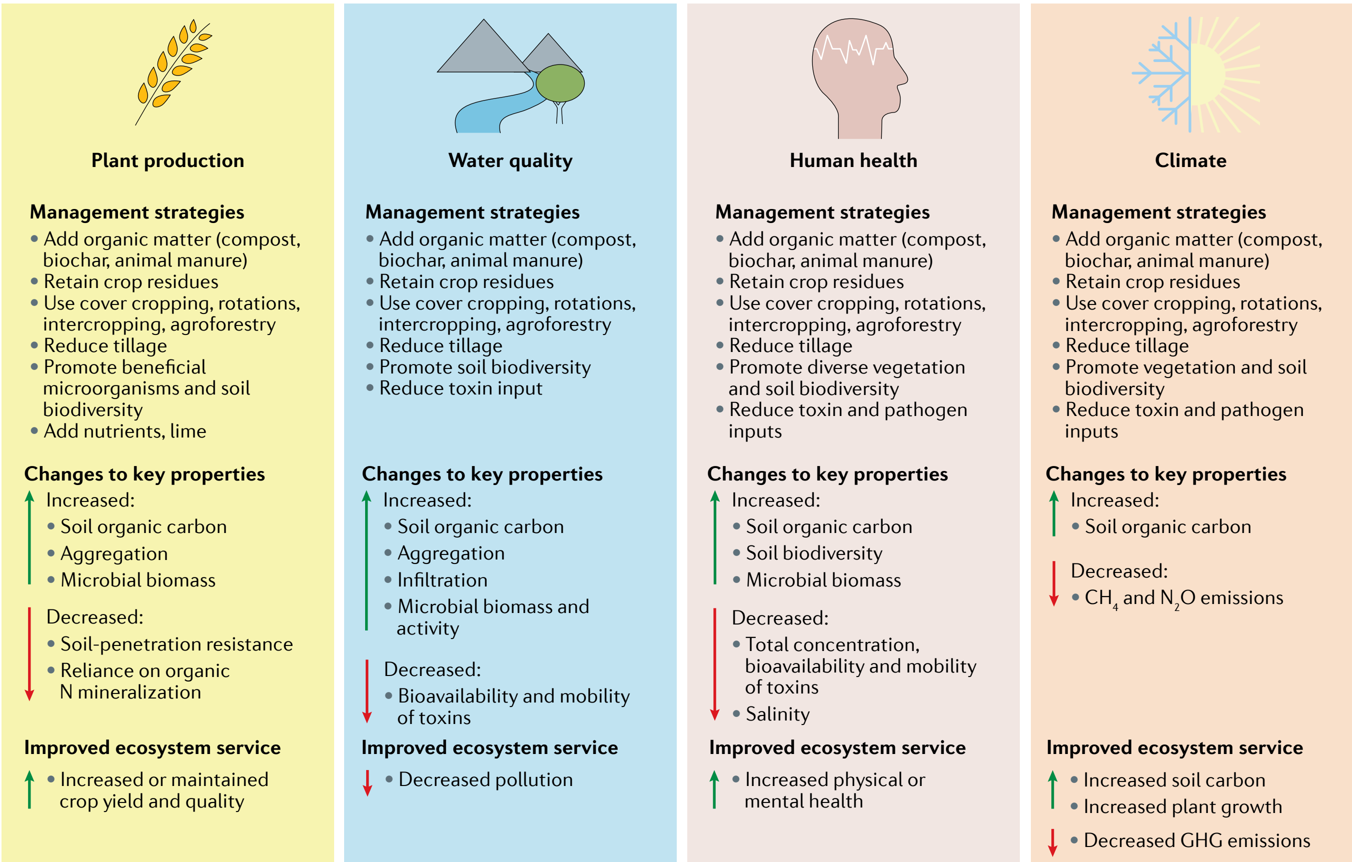

Fig. 3 | **Soil-ecosystem-services management.** Four important roles of soil (plant production, water quality, human health and climate mitigation) are listed at the top of the figure. Various management strategies, and their impacts on key soil properties and ecosystem services, are listed underneath. GHG, greenhouse gas; N, nitrogen.

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 and soil structural diversity are not yet explored but 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[67–69]. 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-infrared 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[67], are promising avenues that speak to the rapid emergence of new approaches. Similarly, passive samplers[77] can and should be used to quantify the small proportion of organic toxins that are harmful to organisms, rather than assessments relying on total content that are not sufficiently sensitive to changes in management nor 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[78].

Advances in soil-health monitoring over the coming decade should also include development of remote-sensing techniques[79]. Remote sensing should not only include spatial information of soil properties, such as seen with successes measuring soil moisture using microwave[80], 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[81]. Such rapid and large-scale soil-health screening through remote sensing should be complemented by exploring the use of guided small-scale robotics[82] 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 among 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 nonlinear relationships, because a higher value does not always indicate better soil health[83–85]. 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' (REF.[85]). In most existing frameworks, the conversion of measured values to scores is based on the distribution of the actual measurements within a reference dataset[84]. To determine the final soil-health score, often, all indicators are treated as equally important[83,84]. For instance, the Comprehensive Assessment of Soil Health assigns values between 0 and 100 (where 100 is the highest) to each indicator based on a comparison with reference values of all available data in the region[86].

Although these indices can provide useful information on large scales[85], regional comparisons are not appropriate in situations with bias resulting from inherent differences between soil types[87] and require careful calibration to regional conditions and needs[88]. 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[89]. Therefore, identifying soil organic carbon as high or low in this region depends on clay content, and soils should be compared with 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 instance, the formation or maintenance of aggregates over time can indicate better soil health[83], as particles are bound into aggregates mainly by microbial products from organic amendments[90]. 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 USA[52]. Considering inherent differences between soils is particularly important when using biological indices. In one 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[91]. 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.

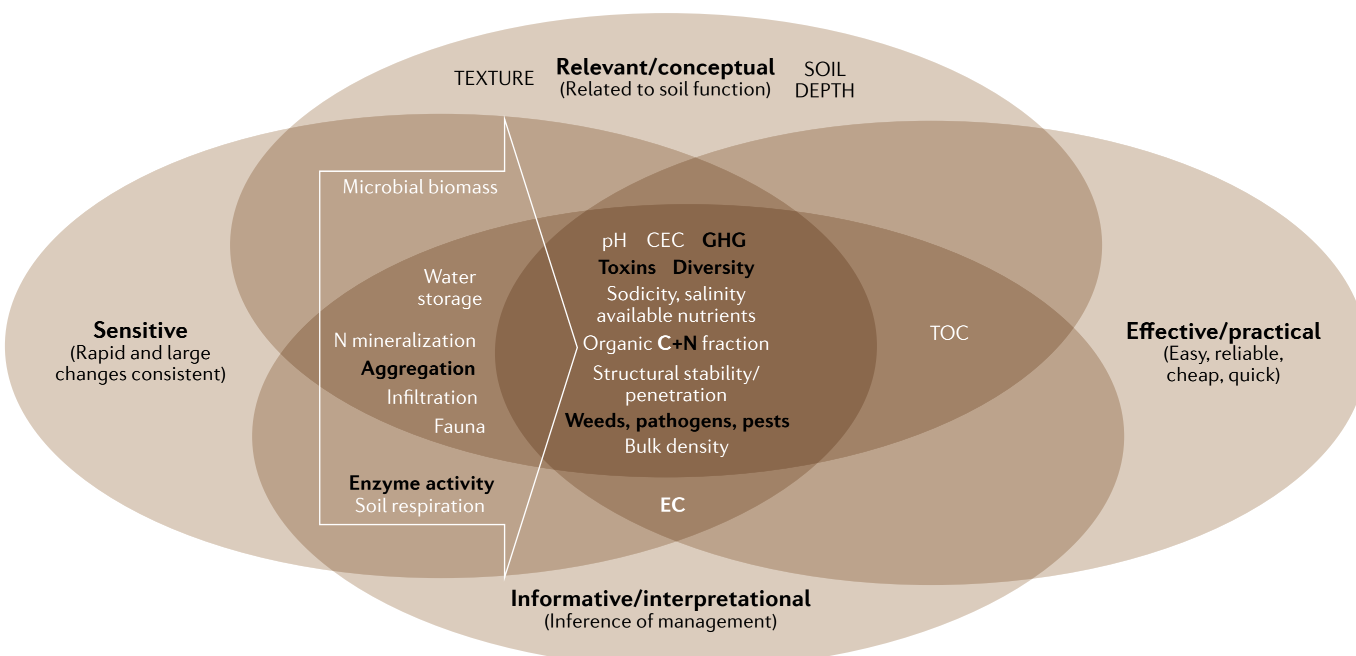

Fig. 4 | **Soil-health indicators and relevance to assessments.** Soil-health indicators ideally are informative, sensitive, effective and relevant[6,53]. Some do not fulfil all criteria but are still relevant (such as texture or soil depth, which do not change readily and are not managed and, therefore, also called capability indicators[55]). Bold 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 diversity in soil organic matter and plants growing in soil, some of which might not be readily quantified through analytical or modelling approaches. C, carbon; CEC, cation-exchange capacity; EC, electrical conductivity; GHG, greenhouse gases; N, nitrogen; TOC, total organic carbon.

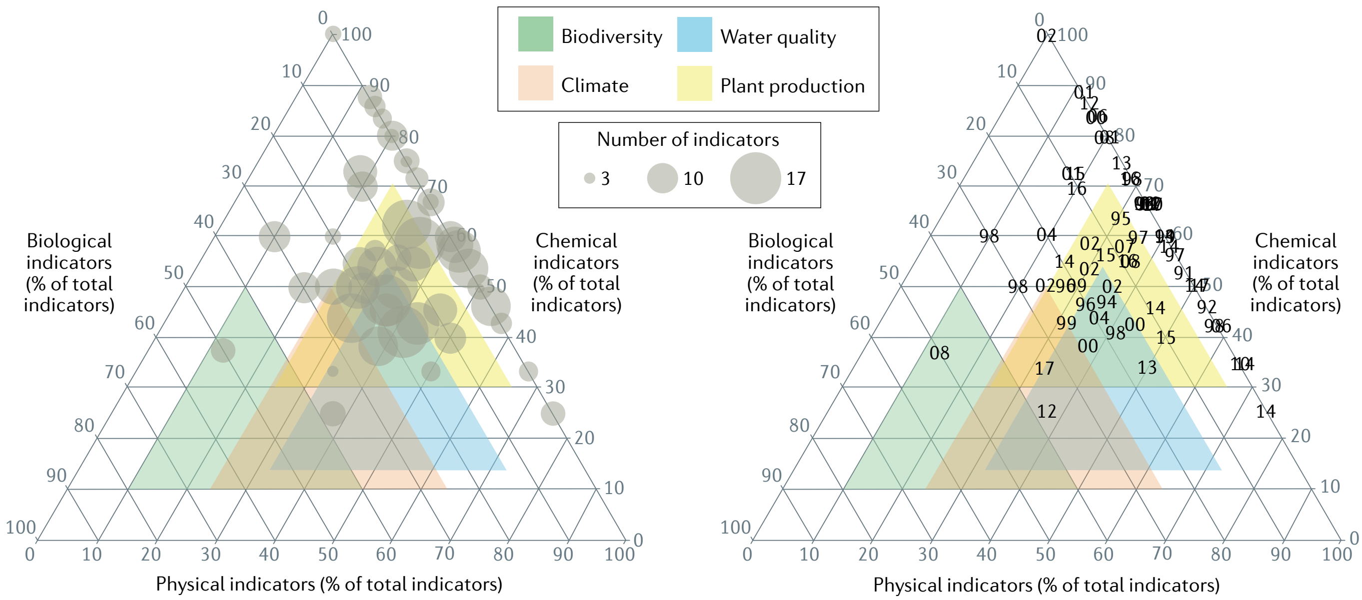

Fig. 5 | **Biological, chemical and physical indicators included in soil-health-assessment schemes[6].** The left panel shows the number of indicators and proportion of each type (biological, chemical or physical). Each circle represents one assessment scheme, and the size of the circle represents the number of indicators in the scheme. The right panel shows the year of each soil-health-assessment scheme from the left panel. Only the last two digits of the year are shown (values in the 80s and 90s are from the 1980s and 1990s, and 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 might consider a balanced set of indicators that represents at least 20% biological, physical and chemical measurements. However, indices designed to quantify different services could require a different set of indicators: a soil-health index for plant production might require more chemical indicators (inside the yellow triangle), for water quality more physical (blue triangle), for biodiversity more biological (green triangle) and for climate more physical and biological indicators (orange triangle).

Despite these caveats, appropriately comparing changes in soil-health indicators and indices over time or with a suitable reference dataset can be used to assess whether, for example, a reduction in tillage or addition of compost improves 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 to convert nutrient indicators into amounts of fertilizer to apply to a certain crop while recognizing differences in texture and mineral types, which even utilizes information from fertilizer responses for a specific soil[92].

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[93]. 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[94], even in comprehensive ecosystem-services assessments[95]. Soil effects on human health need to be assessed as they affect humans both through production of nutritious food and through clean water, with unclear quantitative criteria on whether water is more important than food or vice versa.

Holistic soil-health indices should, therefore, include multi-criteria decision analysis[96] to quantify and prioritize sustainability outcomes of soil-health management. Societal demands for different soil functions such as water quality and food production can vary by stakeholder and region. In an analysis of societal demands in Europe, water quality and food production was, on average, mentioned by the same groups, although 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[97]. Soil-health data should be presented using interactive data visualizations[98] that reconfigure according to the desired focus. Such interactive tools will benefit researchers[99] as well as stakeholders[100] to prioritize soil functions and make decisions. Emerging data-analysis tools such as machine learning[6], deep learning, artificial neural networks[101] or game theory[102] 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 and understanding soil-health effects on soil functions. Precision and digital agriculture[103] 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 co-labs[104] 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, will 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 of the role of soil in modern society and is developing into an attractive and actionable platform for farmers, land managers, municipalities and policymakers. 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 soil's 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 types of indicator, their methodological details[105] 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.

Johannes Lehmann[1,2,3✉], *Deborah A. Bossio*[4], *Ingrid Kögel-Knabner*[3,5] *and Matthias C. Rillig*[6,7]

[1]*School of Integrative Plant Science, Cornell University, Ithaca, NY, USA.*

[2]*Cornell Atkinson Center for Sustainability, Cornell University, Ithaca, NY, USA.*

[3]*Institute for Advanced Study, Technical University of Munich, Garching, Germany.*

[4]*The Nature Conservancy, Arlington, VA, USA.*

[5]*Chair of Soil Science, Technical University of Munich, Freising, Germany.*

[6]*Institut für Biologie, Freie Universität Berlin, Berlin, Germany.*

[7]*Berlin-Brandenburg Institute of Advanced Biodiversity Research (BBIB), Berlin, Germany.*

✉*e-mail: cl273@cornell.edu*

https://doi.org/10.1038/s43017-020-0080-8

Published online 25 August 2020

1. Ladyman, J., Lambert, J. & Wiesner, K. What is a complex system? *Eur. J. Philos. Sci.* **3**, 33–67 (2013).
2. Brevik, E. C. et al. The interdisciplinary nature of SOIL. *Soil* **1**, 117–129 (2015).
3. Blum, W. E. Functions of soil for society and the environment. *Rev. Environ. Sci. Biotechnol.* **4**, 75–79 (2005).
4. Baveye, P. C., Baveye, J. & Gowdy, J. Soil "ecosystem" services and natural capital: critical appraisal of research on uncertain ground. *Front. Environ. Sci.* **4**, 41 (2016).
5. Keith, A. M., Schmidt, O. & McMahon, B. J. Soil stewardship as a nexus between ecosystem services and one health. *Ecosyst. Serv.* **17**, 40–42 (2016).
6. Bünemann, E. K. et al. Soil quality–a critical review. *Soil Biol. Biochem.* **120**, 105–125 (2018).
7. Patzel, N., Sticher, H. & Karlen, D. L. Soil fertility - phenomenon and concept. *J. Plant Nutr. Soil Sci.* **163**, 129–142 (2000).
8. Doran, J. W. & Parkin, T. B. in *Defining Soil Quality for a Sustainable Environment* Vol. 32 (eds Doran, J. W., Coleman, D. C., Bezdicek, D. F. & Stewart, B. A.) 1–21 (Soil Science Society of America, 1994).
9. Pankhurst, C. E., Doube, B. M. & Gupta, V. V. S. R. in *Biological Indicators of Soil Health* (eds Pankhurst, C., Doube, B. & Gupta, V.) 419–435 (CAB International, 1997).
10. McBratney, A., Field, D. J. & Koch, A. The dimensions of soil security. *Geoderma* **213**, 203–213 (2014).
11. Koch, A. et al. Soil security: solving the global soil crisis. *Glob. Policy* **4**, 434–441 (2013).
12. Stankovics, P., Tóth, G. & Tóth, Z. Identifying gaps between the legislative tools of soil protection in the EU member states for a common European soil protection legislation. *Sustainability* **10**, 2886 (2018).
13. Montanarella, L. Agricultural policy: govern our soils. *Nature* **528**, 32–33 (2015).
14. Jian, J., Du, X. & Stewart, R. D. A database for global soil health assessment. *Sci. Data* **7**, 16 (2020).
15. Karlen, D. L., Veum, K. S., Sudduth, K. A., Obrycki, J. F. & Nunes, M. R. Soil health assessment: past accomplishments, current activities, and future opportunities. *Soil Tillage Res.* **195**, 104365 (2019).
16. Norris, C. E. & Congreves, K. A. Alternative management practices improve soil health indices in intensive vegetable cropping systems: a review. *Front. Environ. Sci.* **6**, 50 (2018).
17. O'Dell, R. E. & Claassen, V. P. Vertical distribution of organic amendment influences the rooting depth of revegetation species on barren, subgrade serpentine substrate. *Plant Soil* **285**, 19–29 (2006).
18. Congreves, K. A., Hayes, A., Verhallen, E. A. & Van Eerd, L. L. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. *Soil Tillage Res.* **152**, 17–28 (2015).
19. Hamza, M. A. & Anderson, W. K. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. *Soil Tillage Res.* **82**, 121–145 (2005).
20. Jenkinson, D. S. The Rothamsted long-term experiments: Are they still of use? *Agron. J.* **83**, 2–10 (1991).
21. Berendsen, R. L., Pieterse, C. M. & Bakker, P. A. The rhizosphere microbiome and plant health. *Trends Plant Sci.* **17**, 478–486 (2012).
22. Chaparro, J. M., Sheflin, A. M., Manter, D. K. & Vivanco, J. M. Manipulating the soil microbiome to increase soil health and plant fertility. *Biol. Fertil. Soils* **48**, 489–499 (2012).
23. Bonanomi, G., Lorito, M., Vinale, F. & Woo, S. L. Organic amendments, beneficial microbes, and soil microbiota: toward a unified framework for disease suppression. *Annu. Rev. Phytopathol.* **56**, 1–20 (2018).
24. Chen, X. D. et al. Soil biodiversity and biogeochemical function in managed ecosystems. *Soil Res.* **58**, 1–20 (2020).
25. Pittelkow, C. M. et al. Productivity limits and potentials of the principles of conservation agriculture. *Nature* **517**, 365–368 (2015).
26. Ogle, S. M., Swan, A. & Paustian, K. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. *Agric. Ecosyst. Environ.* **149**, 37–49 (2012).
27. Zimnicki, T. et al. On quantifying water quality benefits of healthy soils. *BioScience* **70**, 343–352 (2020).
28. Evans, A. E., Mateo-Sagasta, J., Qadir, M., Boelee, E. & Ippolito, A. Agricultural water pollution: key knowledge gaps and research needs. *Curr. Opin. Environ. Sustain.* **36**, 20–27 (2019).
29. Carpenter, S. R. et al. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecol. Appl.* **8**, 559–568 (1998).
30. Lamichhane, S., Krishna, K. B. & Sarukkalige, R. Polycyclic aromatic hydrocarbons (PAHs) removal by sorption: a review. *Chemosphere* **148**, 336–353 (2016).
31. Tournebize, J., Chaumont, C. & Mander, Ü. Implications for constructed wetlands to mitigate nitrate and pesticide pollution in agricultural drained watersheds. *Ecol. Eng.* **103**, 415–425 (2017).
32. Hanson, J. R., Macalady, J. L., Harris, D. & Scow, K. M. Linking toluene degradation with specific microbial populations in soil. *Appl. Environ. Microbiol.* **65**, 5403–5408 (1999).
33. Li, G., Sun, G. X., Ren, Y., Luo, X. S. & Zhu, Y. G. Urban soil and human health: a review. *Eur. J. Soil Sci.* **69**, 196–215 (2018).
34. Laurenson, G., Laurenson, S., Bolan, N., Beecham, S. & Clark, I. The role of bioretention systems in the treatment of stormwater. *Adv. Agron.* **120**, 223–274 (2013).
35. Wagg, C., Bender, S. F., Widmer, F. & van der Heijden, M. G. Soil biodiversity and soil community composition determine ecosystem multifunctionality. *Proc. Natl Acad. Sci. USA* **111**, 5266–5270 (2014).
36. Kadam, A. M., Oza, G. H., Nemade, P. D. & Shankar, H. S. Pathogen removal from municipal wastewater in constructed soil filter. *Ecol. Eng.* **33**, 37–44 (2008).
37. Welch, R. M. & Graham, R. D. Breeding for micronutrients in staple food crops from a human nutrition perspective. *J. Exp. Bot.* **55**, 353–364 (2004).
38. Barrett, C. B. & Bevis, L. E. The self-reinforcing feedback between low soil fertility and chronic poverty. *Nat. Geosci.* **8**, 907–912 (2015).
39. Wood, S. A., Tirfessa, D. & Baudron, F. Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agric. Ecosyst. Environ.* **266**, 100–108 (2018).
40. Wall, D. H., Nielsen, U. N. & Six, J. Soil biodiversity and human health. *Nature* **528**, 69–76 (2015).
41. Jacoby, R., Peukert, M., Succurro, A., Koprivova, A. & Kopriva, S. The role of soil microorganisms in plant mineral nutrition—current knowledge and future directions. *Front. Plant Sci.* **8**, 1617 (2017).
42. Schlatter, D., Kinkel, L., Thomashow, L., Weller, D. & Paulitz, T. Disease suppressive soils: new insights from the soil microbiome. *Phytopathology* **107**, 1284–1297 (2017).
43. Rillig, M. C., Lehmann, A., Lehmann, J., Camenzind, T. & Rauh, C. Soil biodiversity effects from field to fork. *Trends Plant Sci.* **23**, 17–24 (2018).
44. Oliver, M. A. & Gregory, P. J. Soil, food security and human health: a review. *Eur. J. Soil Sci.* **66**, 257–276 (2015).
45. Hussein, H. S. & Brasel, J. M. Toxicity, metabolism, and impact of mycotoxins on humans and animals. *Toxicology* **167**, 101–134 (2001).
46. Bethony, J. et al. Soil-transmitted helminth infections: ascariasis, trichuriasis, and hookworm. *Lancet* **367**, 1521–1532 (2006).
47. Schatz, A., Bugle, E. & Waksman, S. A. Streptomycin, a substance exhibiting antibiotic activity against gram-positive and gram-negative bacteria. *Proc. Soc. Exp. Biol. Med.* **55**, 66–69 (1944).
48. Ling, L. L. et al. A new antibiotic kills pathogens without detectable resistance. *Nature* **517**, 455–459 (2015).
49. Veresoglou, S. D., Halley, J. M. & Rillig, M. C. Extinction risk of soil biota. *Nat. Commun.* **6**, 8862 (2015).
50. Lal, R. Soil carbon sequestration impacts on global climate change and food security. *Science* **304**, 1623–1627 (2004).
51. Paustian, K. et al. Climate-smart soils. *Nature* **532**, 49–57 (2016).

52. Denef, K. & Six, J. Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. *Eur. J. Soil Sci.* **56**, 469–479 (2005).
53. Rinot, O., Levy, G. J., Steinberger, Y., Svoray, T. & Eshel, G. Soil health assessment: A critical review of current methodologies and a proposed new approach. *Sci. Total. Environ.* **648**, 1484–1491 (2019).
54. Van Wesemael, B. et al. An indicator for organic matter dynamics in temperate agricultural soils. *Agric. Ecosyst. Environ.* **274**, 62–75 (2019).
55. Bouma, J. et al. in *Global Soil Security* (eds Field, D. J., Morgan, C. L. S. & McBratney, A. B.) 27–44 (Springer, 2017).
56. Schoenholtz, S. H., Van Miegroet, H. & Burger, J. A. A review of chemical and physical properties as indicators of forest soil quality: challenges and opportunities. *For. Ecol. Manag.* **138**, 335–356 (2000).
57. Andrews, S. S. & Carroll, C. R. Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecol. Appl.* **11**, 1573–1585 (2001).
58. Lilburne, L. R., Hewitt, A. E., Sparling, G. P. & Selvarajah, N. Soil quality in New Zealand: policy and the science response. *J. Environ. Qual.* **31**, 1768–1773 (2002).
59. Idowu, O. J. et al. Use of an integrative soil health test for evaluation of soil management impacts. *Renew. Agric. Food Syst.* **24**, 214–224 (2009).
60. Cherubin, M. R. et al. A Soil Management Assessment Framework (SMAF) evaluation of Brazilian sugarcane expansion on soil quality. *Soil Sci. Soc. Am. J.* **80**, 215–226 (2016).
61. E.U. Mission Board Soil Health and Food. *Caring for Soil is Caring for Life*. *The Publications Office of the European Union* https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/32d5d312-b689-11ea-bb7a-01aa75ed71a1 (European Commission, 2020).
62. Nunes, M. R., Karlen, D. L., Veum, K. S., Moorman, T. B. & Cambardella, C. A. Biological soil health indicators respond to tillage intensity: a US meta-analysis. *Geoderma* **369**, 114335 (2020).
63. Kaiser, E. A. et al. Nitrous oxide release from arable soil: importance of N-fertilization, crops and temporal variation. *Soil Biol. Biochem.* **30**, 1553–1563 (1998).
64. Baldock, J. A., Beare, M. H., Curtin, D. & Hawke, B. Stocks, composition and vulnerability to loss of soil organic carbon predicted using mid-infrared spectroscopy. *Soil Res.* **56**, 468–480 (2018).
65. Rossel, R. V. et al. Continental-scale soil carbon composition and vulnerability modulated by regional environmental controls. *Nat. Geosci.* **12**, 547–552 (2019).
66. Six, J., Bossuyt, H., Degryze, S. & Denef, K. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* **79**, 7–31 (2004).
67. Pietrelli, A., Bavasso, I., Lovecchio, N., Ferrara, V. & Allard, B. in *8th IEEE International Workshop on Advances in Sensors and Interfaces (IWASI)* 302–306 (IEEE, 2019).
68. Shaikh, F. K. & Zeadally, S. Energy harvesting in wireless sensor networks: a comprehensive review. *Renew. Sustain. Energy Rev.* **55**, 1041–1054 (2016).
69. Tan, X., Sun, Z., Wang, P. & Sun, Y. Environment-aware localization for wireless sensor networks using magnetic induction. *Ad Hoc Netw.* **98**, 102030 (2020).
70. Lehmann, J. et al. Persistence of soil organic carbon caused by functional complexity. *Nat. Geosci.* **13**, 529–534 (2020).
71. Tedersoo, L. et al. Global diversity and geography of soil fungi. *Science* **346**, 1078 (2014).
72. Van Den Hoogen, J. et al. Soil nematode abundance and functional group composition at a global scale. *Nature* **572**, 194–198 (2019).
73. Rillig, M. C., Bonneval, K. & Lehmann, J. Sounds of soil: a new world of interactions under our feet? *Soil Syst.* **3**, 45 (2019).
74. Smolka, M. et al. A mobile lab-on-a-chip device for on-site soil nutrient analysis. *Precision Agric.* **18**, 152–168 (2017).
75. Rossel, R. A. V. & Bouma, J. Soil sensing: a new paradigm for agriculture. *Agric. Syst.* **148**, 71–74 (2016).
76. Ali, M. A., Dong, L., Dhau, J., Khosla, A. & Kaushik, A. Perspective — electrochemical sensors for soil quality assessment. *J. Electrochem. Soc.* **167**, 037550 (2020).
77. Enell, A. et al. Combining leaching and passive sampling to measure the mobility and distribution between porewater, DOC, and colloids of native oxy-PAHs, N-PACs, and PAHs in historically contaminated soil. *Environ. Sci. Technol.* **50**, 11797–11805 (2016).
78. Sismaet, H. J. & Goluch, E. D. Electrochemical probes of microbial community behaviour. *Annu. Rev. Anal. Chem.* **11**, 441–461 (2018).
79. Chabrillat, S. et al. Imaging spectroscopy for soil mapping and monitoring. *Surv. Geophys.* **40**, 361–399 (2019).
80. Mohanty, B. P., Cosh, M. H., Lakshmi, V. & Montzka, C. Soil moisture remote sensing: state-of-the-science. *Vadose Zone J.* **16**, 1–9 (2017).
81. Paustian, K. et al. Quantifying carbon for agricultural soil management: from the current status toward a global soil information system. *Carbon Manage.* **10**, 567–587 (2019).
82. Duckett, T. et al. Agricultural robotics: the future of robotic agriculture. Preprint *arXiv* https://arxiv.org/abs/1806.06762 (2018).
83. Hussain, I., Olson, K. R., Wander, M. M. & Karlen, D. L. Adaptation of soil quality indices and application to three tillage systems in southern Illinois. *Soil Tillage Res.* **50**, 237–249 (1999).
84. Fine, A. K., van Es, H. M. & Schindelbeck, R. R. Statistics, scoring functions, and regional analysis of a comprehensive soil health database. *Soil Sci. Soc. Am. J.* **81**, 589–601 (2017).
85. Svoray, T., Hassid, I., Atkinson, P. M., Moebius-Clune, B. N. & van Es, H. M. Mapping soil health over large agriculturally important areas. *Soil Sci. Soc. Am. J.* **79**, 1420–1434 (2015).
86. Moebius-Clune, B. N. et al. *Comprehensive Assessment of Soil Health – The Cornell Framework, Edition 3.1* (Cornell Univ. Press, 2016).
87. Wiesmeier, M. et al. Soil organic carbon storage as a key function of soils-a review of drivers and indicators at various scales. *Geoderma* **333**, 149–162 (2019).
88. Lima, A. C. R., Brussaard, L., Totola, M. R., Hoogmoed, W. B. & de Goede, R. G. M. A functional evaluation of three indicator sets for assessing soil quality. *Appl. Soil Ecol.* **64**, 194–200 (2013).
89. Verheijen, F. G., Bellamy, P. H., Kibblewhite, M. G. & Gaunt, J. L. Organic carbon ranges in arable soils of England and Wales. *Soil Use Manage.* **21**, 2–9 (2005).
90. Bucka, F. B., Kölbl, A., Uteau, D., Peth, S. & Kögel-Knabner, I. Organic matter input determines structure development and aggregate formation in artificial soils. *Geoderma* **354**, 113881 (2019).
91. Kaiser, K. et al. Driving forces of soil bacterial community structure, diversity, and function in temperate grasslands and forests. *Sci. Rep.* **6**, 33696 (2016).
92. Jordan-Meille, L. et al. An overview of fertilizer-P recommendations in Europe: soil testing, calibration and fertilizer recommendations. *Soil Use Manage.* **28**, 419–435 (2012).
93. McLellan, E. L. et al. The nitrogen balancing act: tracking the environmental performance of food production. *Bioscience* **68**, 194–203 (2018).
94. Brevik, E. C. & Sauer, T. J. The past, present, and future of soils and human health studies. *Soil* **1**, 35–46 (2015).
95. Pereira, P., Bogunovic, I., Muñoz-Rojas, M. & Brevik, E. C. Soil ecosystem services, sustainability, valuation and management. *Curr. Opin. Environ. Sci. Health* **5**, 7–13 (2018).
96. Bampa, F. et al. Harvesting European knowledge on soil functions and land management using multi-criteria decision analysis. *Soil Use Manage.* **35**, 6–20 (2019).
97. Schulte, R. P. et al. Demands on land: mapping competing societal expectations for the functionality of agricultural soils in Europe. *Environ. Sci. Policy* **100**, 113–125 (2019).
98. Ward, M. O., Grinstein, G. & Keim, D. *Interactive Data Visualization: Foundations, Techniques, and Applications* (AK Peters/CRC Press, 2015).
99. Villamil, M. B., Miguez, F. E. & Bollero, G. A. Multivariate analysis and visualization of soil quality data for no-till systems. *J. Environ. Qual.* **37**, 2063–2069 (2008).
100. Börner, K., Bueckle, A. & Ginda, M. Data visualization literacy: definitions, conceptual frameworks, exercises, and assessments. *Proc. Natl Acad. Sci. USA* **116**, 1857–1864 (2019).
101. Reichstein, M. et al. Deep learning and process understanding for data-driven Earth system science. *Nature* **566**, 195–204 (2019).
102. Tian, R. & Wu, J. Groundwater quality appraisal by improved set pair analysis with game theory weightage and health risk estimation of contaminants for Xuecha drinking water source in a loess area in Northwest China. *Hum. Ecol. Risk Assess. Int. J.* **25**, 132–157 (2019).
103. Finger, R., Swinton, S. M., Benni, N. E. & Walter, A. Precision farming at the nexus of agricultural production and the environment. *Annu. Rev. Resour. Econ.* **11**, 313–335 (2019).
104. van Joolingen, W. R., de Jong, T., Lazonder, A. W., Savelsbergh, E. R. & Manlove, S. Co-Lab: research and development of an online learning environment for collaborative scientific discovery learning. *Comput. Hum. Behav.* **21**, 671–688 (2005).
105. Stott, D. E. *Recommended Soil Health Indicators and Associated Laboratory Procedures. Soil Health Technical Note No. 450-03* (U.S. Department of Agriculture, Natural Resources Conservation Service, 2019).
106. Haberern, J. A soil health index. *J. Soil Water Conserv.* **47**, 6 (1992).
107. Pankhurst, C. E. et al. Evaluation of soil biological properties as potential bioindicators of soil health. *Austr. J. Exp. Agric.* **35**, 1015–1028 (1995).
108. Doran, J. W. & Zeiss, M. R. Soil health and sustainability: managing the biotic component of soil quality. *Appl. Soil Ecol.* **15**, 3–11 (2000).
109. Winiwarter, V. & Blum, W. E. in *Footprints in the Soil. People and Ideas in Soil History* (ed. Warkentin, B.) 107–122 (Elsevier, 2006).
110. Capra, G. F., Ganga, A. & Moore, A. F. Songs for our soils. How soil themes have been represented in popular song. *Soil Sci. Plant Nutr.* **63**, 517–525 (2017).
111. Jenny, H. in *Study Week on Organic Matter and Soil Fertility*. Pontificiae Academiae Scientarium Scripta, Varia 32. 947–979 (North Holland Publ. Co and Wiley Interscience Division, 1968).
112. Feller, C., Landa, E. R., Toland, A. & Wessolek, G. Case studies of soil in art. *Soil* **1**, 543–559 (2015).
113. Brevik, E. C. & Hartemink, A. E. Early soil knowledge and the birth and development of soil science. *Catena* **83**, 23–33 (2010).
114. Carson, R. *Silent Spring* (Houghton Mifflin, 1962).
115. Lovelock, J. E. *Gaia, a New Look at Life on Earth* (Oxford Univ. Press, 1979).
116. Keesstra, S. D. et al. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil* **2**, 111–128 (2016).
117. Mausel, P. W. Soil quality in Illinois — an example of a soils geography resource analysis. *Prof. Geogr.* **23**, 127–136 (1971).
118. Sojka, R. E. & Upchurch, D. R. Reservations regarding the soil quality concept. *Soil Sci. Soc. Am. J.* **63**, 1039–1054 (1999).
119. Rumpel, C. et al. Put more carbon in soils to meet Paris climate pledges. *Nature* **564**, 32–34 (2018).
120. Freidberg, S. Assembled but unrehearsed: corporate food power and the 'dance' of supply chain sustainability. *J. Peasant Stud.* **47**, 383–400 (2020).
121. Chabbi, A. et al. Aligning agriculture and climate policy. *Nat. Clim. Change* **7**, 307–309 (2017).
122. Puig de la Bellacasa, M. Re-animating soils: transforming human–soil affections through science, culture and community. *Sociol. Rev.* **67**, 391–407 (2019).

Acknowledgements
J.L. acknowledges the Hans Fischer Senior Fellowship of the Institute for Advanced Study (Technical University Munich) and a TNC-ACSF project (Cornell University), D.A.B. the support by the Craig and Susan McCaw Foundation, I.K.-K. the support by the German Federal Ministry of Education and Research (BMBF) in the framework of the funding measure 'Soil as a Sustainable Resource for the Bioeconomy' (BonaRes project), BonaRes Centre for Soil Research (FKZ 031B0516A; BonaRes, Module A) and M.C.R. an ERC Advanced Grant (694368) and the BMBF for the project 'Bridging in Biodiversity Science (BIBS)' (01LC1501A). Sincere thanks to Else Bünemann-König for sharing raw data.

Author contributions
All authors contributed substantial discussion of content, edited the manuscript and its revisions.

Competing interests
The authors declare no competing interests.

Peer review information
Nature Reviews Earth & Environment thanks Hailin Zhang, Nanthi Bolan and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Publisher's note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.