Healthy soil for healthy humans and a healthy planet

Peter M Kopittke, Budiman Minasny, Elise Pendall, Cornelia Rumpel, Brigid A Mckenna

To cite this version:

Peter M Kopittke, Budiman Minasny, Elise Pendall, Cornelia Rumpel, Brigid A Mckenna. Healthy soil for healthy humans and a healthy planet. Critical Reviews in Environmental Science and Technology, 2023, 54 (3), pp.210 - 221. 10.1080/10643389.2023.2228651 . hal-04660559

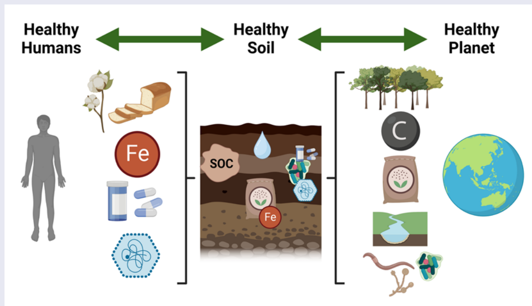
CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
2024, VOL. 54, NO. 3, 210–221
https://doi.org/10.1080/10643389.2023.2228651

Healthy soil for healthy humans and a healthy planet

Peter M. Kopittke[a], Budiman Minasny[b], Elise Pendall[c], Cornelia Rumpel[d] and Brigid A. McKenna[a]

[a]School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Queensland, Australia; [b]School of Life & Environmental Sciences, Sydney Institute of Agriculture, Faculty of Science, The University of Sydney, Sydney, New South Wales, Australia; [c]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, New South Wales, Australia; [d]Sorbonne Université, INRAE, CNRS, Institute for Ecology and Ecological Sciences, (iEES Paris, UMR Sorbonne Université, CNRS, INRAE, UPEC, IRD), Paris, France

ABSTRACT



Soil provides multiple, diverse functions, with these underpinning both planetary and human health. For planetary health, soil contributes to multiple critical processes, including through biomass production, by regulating the carbon pool, providing a habitat for 25% of global biodiversity, cycling the nutrients upon which terrestrial systems depend, and cycling water. Soil also underpins human health; humans use soil to provide 98.8% of our food and sustain our nutrition, regulate pathogens, and supply medicines. However, humans have tended to focus on soil almost solely for producing biomass (food, fiber, and energy) through intensive agriculture, and this narrow focus now causes rapid soil degradation, including through loss of soil organic matter, erosion, and salinization. This degradation directly harms planetary health and reduces the ability of soil to support health of future human generations. We argue that a healthy soil is a soil that is multifunctional and is capable of underpinning human and planetary health. Using this definition, a broad conceptual framework is provided for quantifying soil health, with such an approach enabling a shift in the way that we think about, plan, and manage systems to ensure ongoing planetary and human health.

KEYWORDS Human health; planetary health; soil degradation; soil health

HANDLING EDITORS Binoy Sarkar and Lena Q. Ma

1. Introduction

Soil is an extremely thin layer, accounting for only one ten-millionth of the earth's total radius (6,371 km compared to 1 m depth). This thin layer is the interface between the living and the non-living and is critical for the health of both the planet and humans. However, at times, humans have historically shown little regard for soil and its criticality for our survival—whether it be in the Dust Bowl of the USA in which an estimated 20 million hectares of land became "mobile" (Heathcote, 1980), through contamination resulting in 19% of surveyed agricultural soils in China exceeding environmental limits (Wang et al., 2019), or by the construction of infrastructure on the most fertile soils. Indeed, soil is often taken for granted—"We know more

CONTACT Peter M. Kopittke p.kopittke@uq.edu.au School of Agriculture and Food Sciences, The University of Queensland, St Lucia, Queensland 4072, Australia

about the movement of celestial bodies than about the soil underfoot" (Leonardo da Vinci, sixteenth Century).

Several concepts have developed over time as an approach for recognizing the value and importance of soil, including the concepts of soil fertility, soil quality, and soil health. Initially, these tended to focus more on the ability of soil to produce biomass in agricultural systems (soil fertility), but over time, the focus has become broader, taking into account the role of soil in global ecosystems (soil health) (Bünemann et al., 2018, Lehmann et al., 2020a). But despite this critical progress, we still do not have a well-accepted framework for defining, measuring, and quantifying soil health, as is required for its inclusion in models and decision-making processes.

This review reexamines 'soil health', first by better defining this term, and second by providing a broad conceptual framework for its quantification. Initially, we broadly consider the mechanisms by which soil sustains both planetary health and human health, as this is fundamental to subsequently define soil health. Next, we consider how soil is degraded, and how this degradation is jeopardizes the health of the planet and that of future human generations. Then, by giving consideration to the mechanisms by which soil underpins planetary and human health, we develop a fundamental framework for measuring and quantifying soil health. The ideas argued here build upon the excellent work of others (Lehmann et al., 2020a, Rinot et al., 2019). Developing an approach that enables us to maintain soil health is critical for ensuring the long-term hospitability and survivability of our planet.

2. Role of soil in planetary health: the multifunctional nature of soil

Various approaches have been used to identify, value, and quantify the multiple contributions that soil makes to the environment and to human society. Over the last couple of decades, the term 'functions' has been developed, with the functions provided by soil determining its ability to contribute to broader environmental services (Greiner et al., 2017). Accordingly, soil functions are defined as "bundles of soil processes that underpin the delivery of ecosystem services" (Bünemann et al., 2018). Importantly, soil is 'multifunctional' because it does many things simultaneously. Indeed, soil provides numerous functions, including biomass production, nutrient cycling, water cycling, carbon storage and cycling, protecting biodiversity, providing recreation, store of history, and providing building materials (Evangelista et al., 2023, Greiner et al., 2017, Vogel et al., 2019, Zwetsloot et al., 2021). Furthermore, it is because of this multifunctional nature that soil is critical for planetary health—soil underpins multiple vital planetary processes (Evangelista et al., 2023). Indeed, the multifunctional nature of soil enables it to play a central role across multiple, and extremely diverse, planetary processes and provide a range of ecosystem services. It has recently been noted that ecosystem service provision by soils is the result of multiple interactions, leading to emergent system properties (Harris et al., 2022).

Here, we highlight five of the key functions of soil that underpin planetary health: biomass production, regulation of the carbon (C) pool, provision of habitat for biodiversity, nutrient cycling, and water cycling (Figure 1). Whilst soil has more than five functions, it is known that these five soil functions are of central importance for the earth system and for sustainable development of human societies (Kopittke et al., 2022, Vogel et al., 2019, Zwetsloot et al., 2021).

The first critical function of soil is the provision of biomass, with soil supporting the 470 Pg C of terrestrial biomass (Bar-On et al., 2018). However, humans have increasingly appropriated biomass production through intensive agricultural systems, with soil providing 98.8% of the calories consumed by humans worldwide (see later). The second function of soil is regulation of the C pool—soil stores ca. 3,012 Pg of organic C within the surface 2 m (Sanderman et al., 2017), with 61 Pg of C entering soil through plants each year and a similar amount lost from soil to the atmosphere under steady-state conditions. In other words, the soil C pool is dynamic, with 7% of the atmospheric C pool cycled through soil annually. Thirdly, soil provides habitat

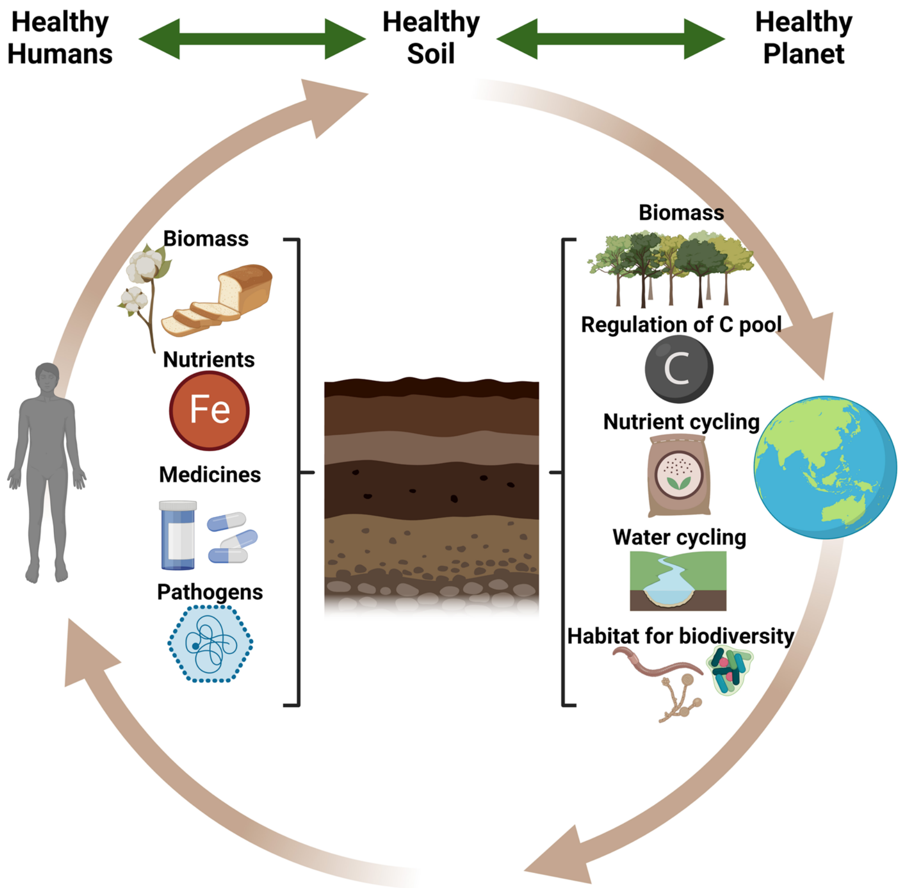


Figure 1. A healthy planet and healthy humans rely upon the multifunctional capacity of healthy soil.

for 25% of global biodiversity (Bach & Wall, 2017), with more than 40% of living organisms in the terrestrial environment directly associated with soil—this makes soil the most biologically diverse habitat on Earth. The fourth function of soil is nutrient cycling. Without the nutrients cycled by soil, plant growth in terrestrial systems would be almost non-existent—soil accounts for 94% of nitrogen (N) in the terrestrial environment and 98% of the phosphorus (P) (Wang et al., 2010). The fifth and final of these central soil functions is water cycling. Soil is the largest store of water in the terrestrial ecosystem, storing up to a maximum of 121,800 km^3 of water, averaging 17,000 km^3 at any given time (Webb et al., 1993).

3. Direct role of soil in human health

Not only does soil underpin planetary health, it also underpins human health—humans depend upon soil for our survival. In a similar manner to planetary health, the contribution of soil to human health is related to its multifunctional nature, with soil making broad and diverse contributions (Figure 1). Indeed, this is recognized through the concept of 'one health', the soil-plant-animal-human-planetary health continuum (Singh et al., 2017).

First and foremost, soil provides 98.8% of the calories consumed by humans worldwide, with human health and survival therefore entirely dependent upon soil. Historically, this food was obtained through hunting and gathering, but more recently, this has been achieved through the clearing of native vegetation and the use of industrialized agricultural practices. Given the rapidly increasing human population coupled with dietary changes, demand for the calories provided by soil is increasing rapidly. This increases the stress placed on soil by humans—food production must increase by 50% between 2012 and 2050 (FAO, 2021). Not only does soil provide food, it also provides humans with biomass in the forms of fiber and energy. For example, it has been estimated that 32 million ha are used for the production of biofuels (Langeveld et al., 2014).

In addition to supplying biomass for calories, soil supplies the majority of the essential human nutrients, with this being related to both the biomass production function of soil as well as the nutrient cycling function of soil. Of the 29 elements that are essential for humans, 13 are also essential plant nutrients that are obtained from soil, and five are elements obtained from soil that are required by some plants but not all (Brevik, 2012). As an example of the role of soil in contributing to human nutrition, ca. 50% of the world's most important agricultural soils have inadequate levels of Zn (Alloway et al., 2008), and as a result, it is estimated that 1.1 billion people suffer from a dietary deficiency of Zn (Kumssa et al., 2015). Indeed, most regions in the world where Zn deficiency in humans is of greatest concern (including South Asia and Africa) are also the regions with low concentrations of plant-available Zn in the soil (Cakmak et al., 2017). Whilst the inadequate supply of nutrients from soil into human diets is problematic, in a similar manner, elevated concentrations of inorganic and organic pollutants that are present in soil also impact adversely upon human health (with this also related to the biomass production and nutrient cycling functions of soil). For example, Europe contains 2.5 million potentially contaminated sites, in the USA the Office of Solid Waste and Emergency Response (OSWER) has cleaned up over 540,000 sites, whilst in China it is estimated that nearly 20 million ha of farmland (ca. one-fifth of total farmland) is contaminated by heavy metals (FAO & ITPS, 2015). As a result, market basket surveys in China have shown that 2-10% of the rice samples surveyed exceeded the maximum permissible level of Cd in rice (Wang et al., 2019).

Soil also contributes to human health by the provision of medicines through soil biodiversity, with most clinically-relevant antibiotics coming from soil (Brevik, 2012). Indeed, it has been estimated that ca. 40% of prescription drugs are derived from soil (Pepper et al., 2009). Finally, soil also plays a role in human health through soil-borne pathogens, including viruses, bacteria, fungi, protozoa, and a range of worms. These pathogens can infect humans by passing through the skin, through a skin abrasion, through ingestion, or through inhalation (Brevik et al., 2020). These soil-borne pathogens cause many well-known diseases in humans, including Hepatitis A and E, Poliovirus Types 1 and 2, *E. coli*, anthrax, tetanus, botulism, and tuberculosis, ringworm, and tapeworm (Brevik et al., 2020).

4. Humans have a unifunctional focus and it is causing degradation of soil and loss of multifunctionality

Although soil is multifunctional, with this underpinning both planetary and human health, humans have historically tended to have a unifunctional focus (i.e., focus almost exclusively on a single function)—the provision of biomass for human consumption through agricultural production. Indeed, although soil has at least five key functions (biomass production, regulation of the C pool, provision of habitat for biodiversity, nutrient cycling, and water cycling), there has been widespread global land-use change to increase human-appropriation of only one of these functions—biomass production. To illustrate this point, whilst humans currently use 1,600 million ha (12% of the ice-free land) of productive land for crops and 3,200 million ha (25%) for permanent grassland and pasture (FAO., 2023), there is comparatively little widespread global use of soils for the other key soil functions.

The rapidly growing population, in addition to shifts in consumptions patterns, are profoundly increasing the stresses placed on soil to provide this biomass through agricultural production. Indeed, this use of soil by humans to produce biomass through intensive agriculture is now causing degradation and is decreasing the ability of soil to provide its other multiple functions.

Accordingly, it is estimated that 33% of soil globally is moderately to highly degraded, and that 52% of agricultural land is moderately to severely degraded costing US$400 billion per year (ELD, 2015, FAO & ITPS, 2015). According to the United Nations Convention to Combat Desertification (UNCCD), the global economy will lose US$23.2 trillion by 2050 due to land degradation (UNCCD, 2018). Soil degradation disproportionately occurs in cropping soil—although cropland covers 13% of global land-cover, it accounts for 29% of all degraded areas (FAO, 2021).

One important form of soil degradation is the loss of soil organic matter (SOM) and the concomitant release of carbon dioxide to the atmosphere as a greenhouse gas. As already noted, soil stores ca. 3,012 Pg of organic C within the surface 2 m, but it is known that long-term cropping of soil reduces these SOM stocks by 30-60% by decreasing inputs of organic materials to soil as well as by increasing outputs (losses) of SOM from the soil. Indeed, it is estimated that 116 Pg of C has been lost from SOM stocks globally due to land-use change (Sanderman et al., 2017). This loss of SOM causes both a decrease in inherent soil fertility, decreasing the ability to produce biomass (including food), as well as the release of C to the atmosphere as carbon dioxide which contributes markedly to global warming and may thus affect human health (Rumpel et al., 2022). Erosion following loss of organic matter is also an important mechanism resulting in degradation of soil, with an estimated 20-37 Gt of soil lost annually (FAO, 2021). This is equivalent to up to ca. 4 t of soil per person globally. Not only does this erosion have adverse off-site effects due to issues with sedimentation, but it is generally the most fertile surface soil that is eroded and lost. This results in the direct loss of the nutrients required for plant growth, including an estimated 23-42 Mt of N and 15-26 Mt of P annually, with a replacement value of $33-60 billion for N and $77-140 billion for P (FAO & ITPS, 2015). The over-application and inefficient use of fertilizers also contributes to soil degradation—although the application of fertilizers to soil is now essential for providing food for ca. half of the world's population (Erisman et al., 2008), their over-application is causing the release of greenhouse gases (especially nitrous oxide), acidifying soil, and causing eutrophication of water bodies (Snyder et al., 2009). Indeed, global N use efficiency is estimated to be 47% (Lassaletta et al., 2014), meaning less than half of all N fertilizer applied is taken up by crops. Soil can also be degraded through salinization, with this occurring through multiple mechanisms, including the irrigation with poor quality waters, elevation of the groundwater table due to over-irrigation, and the clearing of deep-rooted native vegetation, causing increased recharge and elevation of the groundwater table. Salinization is estimated to lead to loss of 1.5 million ha of productive cropland annually (FAO, 2021).

This soil degradation, whether it be from SOM loss, erosion, salinization, over-application of fertilizers, acidification, or from other factors (including contamination with toxic compounds), results in a marked decrease in ecosystem services derived from soil due to decline of its multifunctionality. For example, the substantial loss of SOM due to agricultural practices decreases all five functions of soil given that SOM is an integral component of the soil C pool, it drives biomass production, it is central for cycling of nutrients, it is the energy source for soil biodiversity, and it is important for water cycling in soil given SOM's role in regulating soil structure. In a similar manner, the other forms of degradation (such as erosion and salinization) also decrease soil multifunctionality through one or more mechanisms.

5. This loss of soil multifunctionality is already causing planetary harm

This degradation of the soil that results from the intensive anthropogenic use of the soil, together with the associated loss of its multifunctionality, is causing substantial harm to planetary health. With humans increasing demand for biomass production from soil, the anthropogenic pressures being placed on soil are causing changes in critical Earth-system processes and pushing the planet into a less hospitable state. Applying the planetary boundaries concept (Steffen et al., 2015), soil is considered a master variable for the regulation of critical Earth-system processes. Indeed, of the seven Earth-system processes that have been quantified (Steffen et al., 2015), unsustainable soil use plays a critical role in modifying the Earth-systems in at least two and smaller contributions for a further three (Kopittke et al., 2021).

Importantly, unsustainable human use of soil makes it an important contributor to climate change, with climate change considered as one of the two 'core' planetary boundaries (Steffen et al., 2015). Indeed, anthropogenic emissions from soil account for ca. 15% of the entire global increase in climate warming (radiative forcing) due to the well-mixed greenhouse gases, primarily due to carbon dioxide from loss of soil organic matter (74% of soil-derived warming), but also due to nitrous oxide (17%) and methane (9%).

Another critical Earth-system process where anthropogenic use of soil degrades planetary health is through land-system change (Steffen et al., 2015). This is because the primary driver of land-system change is agriculture, with soil therefore being the indirect driver of deforestation to clear soil for cultivation of crops and livestock to produce the food by supplying nutrients and water. For example, it is estimated that agriculture, and its reliance on soil, has accounted for 80% of deforestation (Hosonuma et al., 2012), with global land cover change causing annual topsoil SOC losses of 1.9 Pg SOC yr^{-1} (Padarian et al., 2022).

Not only does anthropogenic use of soil contribute to climate change and land-system change, but it is also a major contributor to biogeochemical flows of N and P. Excess losses of these nutrients are of concern for planetary health as they can lead to eutrophication of water bodies, even potentially causing an ocean anoxic event severe enough to result in large-scale extinction of marine life (Watson et al., 2017). The application of N and P to soil, primarily for agricultural production, accounts for at least 66% of anthropogenic N and 38% of the P (Kopittke et al., 2021). Thus, the anthropogenic use of soil results in it being a major global contributor to the biogeochemical flows of N and P that have already exceeded the planetary boundary.

Finally, anthropogenic use of soil is also threatening planetary health by disrupting biosphere integrity (genetic diversity). Although soil accounts for 25% of global biodiversity (Bach & Wall, 2017), intensive agriculture profoundly decreases the complexity of the soil food web and reducing the mass of soil fauna (Geisen et al., 2019, Tsiafouli et al., 2015). However, this impact is far from being understood due to the complexity of soil systems. Given that we are only in our infancy of understanding the role of soil biodiversity in environmental health (van Bruggen et al., 2019), it is not currently possible to quantify the effect of anthropogenic land-use change on broader biosphere integrity and the loss of genetic diversity.

6. Will the loss of soil multifunctionality also harm future human health?

6.1. Future biomass production for human use

If soil underpins human health and planetary survivability, then what are the implications of ongoing degradation of soil, and the loss of its multifunctionality, on human health? The continued degradation of soil through human activities, especially intensive agricultural production, will have increasingly adverse effects on the biomass production that humans rely upon through multiple mechanisms.

The first is through a direct effect, with the loss of multifunctionality directly decreasing biomass production for humans. This is because biomass production is one of the five key soil functions—in other words, intensive agricultural practices are already degrading soil and decreasing its inherent production capacity, thereby decreasing the long-term ability of soil to supply biomass to future generations. For example, the profound loss of SOM caused by intensive agricultural practices is critical in reducing future productivity—it is well-known that the loss of SOM decreases biomass production (Bot & Benites, 2005), with increases in the SOM content to regionally-specific targets potentially increasing global yields by 23% for wheat and 10% for maize (Oldfield et al., 2019). In a similar manner, the ongoing erosion of soil is predicted to reduce crop yield by up to 10% by 2050.

The second, highly interconnected, long-term effect of a decrease in soil multifunctionality on human health is an indirect effect, by contributing to climate change and the loss of biodiversity. This not only has long-term effects on the hospitability of our planet, but it also expected to indirectly decrease the ability of humans to produce our food from soil. For example, it is thought that climate change has already decreased consumable calorie production by 1% (Ray et al., 2019) and that by 2050 it is expected that climate change will have decreased per-person global food availability by 3.2% (Springmann et al., 2016). In a similar manner, the loss of soil biodiversity that occurs in intensive agricultural systems is known to decrease overall soil productivity given the critical role of soil biodiversity in suppressing disease-causing organisms and improving nutrient cycling and fertility. Indeed, it has been shown that increasing biodiversity complexity in soil can increase resilience, nutrient-use efficiency, and crop yield (Wall et al., 2015).

The long-term ability of humans to produce adequate food and other biomass depends upon our ability to decrease soil degradation and maximize soil multifunctionality, thereby maintaining food production and helping maintain planetary health. Sustaining human health in the future will be a challenge—we will require 50% more food with 44% of cropland already degraded, a further 18% deteriorated (FAO, 2021), and up to 90% of soil predicted to be degraded by 2050.

6.2. Loss of soil multifunctionality also contributes to social and political instability

Not only will ongoing soil degradation and the associated loss of multifunctionality decrease the ability of humans to produce food (biomass) for our survival, but it is expected that this will increase social and political instability. Indeed, there is considerable interest in the causal relationship between food security and conflict, with both violent conflict leading to food insecurity and with food insecurity also leading to violent conflict (FAO, 2018). In this regard, it has been found that in areas with conflict, cropland increases the frequency of violence against civilians given that combatants must turn to local agricultural resources for sustenance (Koren & Bagozzi, 2017). Growing competition for land due to soil degradation leads to the loss of productivity and increased conflict (Bora et al., 2010).

7. Healthy humans and a healthy planet require healthy soil

Given the critical role of soil in underpinning both human health and planetary health, it is imperative that we minimize the degradation of soil so that it can continue to provide its multifunctionality to secure human and planetary health for future generations. The term 'soil health', however, is itself not clear. As with human health, measurement is not easy and no single measurement adequately covers all aspects of health.

For 'soil health', the first issue is finding a suitable definition—over the last couple of decades, the focus has shifted from productivity to a definition encompassing the broader role of soil in ecosystems. For example, soil health has been defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans" (Lehmann et al., 2020a), although this definition is perhaps too narrow given that the ability of soil to sustain other organisms is also of central importance, such as bacteria and fungi. In a somewhat similar manner, the United Nations Intergovernmental Technical Group on Soils (ITPS) define healthy soil as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems" (ITPS., 2020). However, this definition from the ITPS is somewhat unclear as it is uncertain how "productivity", "diversity", and "environmental services" differ from each other (or the underlying basis for selecting these specific terms) and a conceptual framework is not provided to allow for the assessment of soil health using this definition. Finally, we note that frameworks have recently been developed for assessing soil health. For example, in the framework of Rinot et al. (2019), soil health is related to its ability to provide the three broad types of ecosystem services—regulating, provisioning, and supporting services, whilst in the framework of Li et al. (2021), soil health is estimated by using both the natural soil productivity and the human management productivity. Harris et al. (2022) defined soil health based on system complexity and emergent properties, arguing that soil health measurements require the discovery and identification of system properties and their dependence on complexity and connectivity. In a similar manner, Evangelista et al. (2023) proposed a framework for assessing soil security that integrates six existential challenges to sustainable development through five dimensions: capacity, condition, capital, connectivity, and codification. Their proposed assessment framework involves evaluating soil functions, soil services, and threats to soil using potential indicators for each dimension.

We propose a somewhat different approach whereby we define a 'healthy soil' as one that provides the multifunctionality that underpins planetary and human health. In other words, soil health is the ability of the soil to produce biomass, regulate the C pool, provide habitat for biodiversity, cycle nutrients, and cycle water. Although some soils inherently have a lower multifunctional capacity than others (for example, compare a sandy soil in an arid climate to a clayey soil in a humid environment), this is not to say that some natural soils are inherently healthier than others—soil health should not be compared to an average or idealized value. Rather, the health of a soil is related to human impacts, and soil health is determined by comparing the decreased multifunctional capacity of a soil impacted upon by humans to that of the comparable natural soil—a 'reference state' (Román Dobarco et al., 2021). For example, by examining how changes in land use (such as intensive cropping) has decreased the ability of soil to provide its broad multifunctionality (for example, its ability to provide C pool regulation) compared to the corresponding value for the natural soil, this provides quantification of the effect of land management practices on soil health (Figure 2).

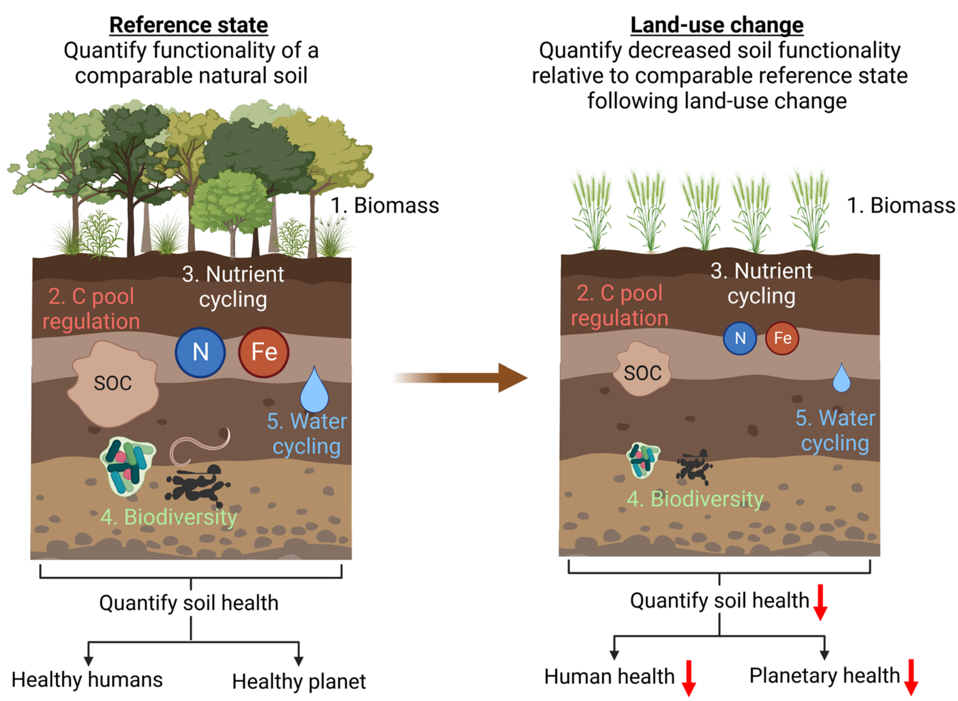


Figure 2. Quantifying the magnitude of the decrease in the five key soil functions that underpin a healthy planet and healthy humans (Figure 1) used to calculate the change in soil health caused by land-use change relative to a comparable natural soil (reference state).

According to our conceptual approach, an assessment of soil health requires quantification of soil functions and comparison to the corresponding reference state (Figure 2). Whilst quantifying soil multifunctionality is not straight-forward, considerable progress has already been made in developing a framework and multiple studies have provided approaches (Jónsson & Davíðsdóttir, 2016, Vogel et al., 2019, Zwetsloot et al., 2021). For example, approaches have been developed for the quantitative evaluation of soil multifunctionality, both in terms of the soil's potential state and actual state (Kibblewhite et al., 2008), based upon the measurement of soil attributes as indicators to assess the ability of soil to fulfill its functions (Vogel et al., 2019). For example, the biofunctool was developed to assess four major functions needed to maintain soil health with simple methods, which can be directly applied in the field (Thoumazeau et al., 2019). Most importantly, frameworks have been developed for assessing changes in soil condition and capability over large areas using appropriate reference states (Román Dobarco et al., 2021).

In our conceptual framework, we have first considered here the core functions by which soil underpins planetary and human health, with soil health then measured by quantifying this multifunctionality and comparing to the reference state for a corresponding natural system (Román Dobarco et al., 2021). In the previous approach (Rinot et al., 2019), the three types of soil ecosystem services (regulating, provisioning, and supporting) are each quantified and normalized to a uniform scale (0-100), with the relative performance of each of these three ecosystem services being the difference between the maximum and minimum value.

Regardless, the development of approaches for measuring and quantifying soil health, such as the broad conceptual framework presented here, will allow development of models to enable the spatial assessment of soil health, identification of the least healthy soils where interventions are required, and development of predictive tools to enable their better management and optimization. Quantification of soil health, and changes in soil health, would also enable the degradation of soil to be adequately accounted for in economic decision-making models. These approaches, underpinned by soil health, would not only enable appropriate policy interventions, but would also assist with decision-making at local levels (Lehmann et al., 2020b). Indeed, this would facilitate the strategic implementation of sustainable soil management strategies (Kopittke et al., 2019) to maintain and improve the soil-plant-animal-human-planetary health continuum (Yan et al., 2022). Such an approach is imperative if we are to maintain and improve future human and planetary health.

Author contributions

Peter Kopittke: Conceptualization, Writing—original draft, Writing—review & editing. Budiman Minasny: Writing—original draft, Writing—review & editing. Elise Pendall: Writing—original draft, Writing—review & editing. Cornelia Rumpel: Writing—original draft, Writing—review & editing. Brigid A. McKenna: Conceptualization, Writing—original draft, Writing—review & editing.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Peter M. Kopittke http://orcid.org/0000-0003-4948-1880

References

Alloway, B., Graham, R., & Stacey, S. (2008). Micronutrient deficiencies in Australian field crops. In B. Alloway (Ed.), *Micronutrient deficiencies in global crop production* (pp. 63–92). Springer Netherlands.

Bach, E. M., & Wall, D. H. (2017). Trends in global biodiversity: Soil biota and processes. In D. A. Dellasala & M. I. Goldstein (Eds.), *Encyclopedia of the anthropocene* (pp. 125–130). Elsevier.

Bar-On, Y. M., Phillips, R., & Milo, R. (2018). The biomass distribution on Earth. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(25), 6506–6511.

Bora, S., Ceccacci, I., Delgado, C., & Townsend, R. (2010). Food security and conflict. World Bank (Agriculture and Rural Development Department), p. 27.

Bot, A., & Benites, J. (2005). *The importance of soil organic matter: Key to drought-resistant soil and sustained food production*. Food & Agriculture Organization of United Nations.

Brevik, E. C. (2012). Soils and human health: An overview. In E. C. Brevik & L. C. Burgess (Eds.), *Soils and human health* (pp. 29–56). CRC Press.

Brevik, E. C., Slaughter, L., Singh, B. R., Steffan, J. J., Collier, D., Barnhart, P., & Pereira, P. (2020). Soil and human health: Current status and future needs. *Air, Soil and Water Research*, *13*, 117862212093444.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., Fleskens, L., Geissen, V., Kuyper, T. W., Mäder, P., Pulleman, M., Sukkel, W., van Groenigen, J. W., & Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125.

Cakmak, I., McLaughlin, M. J., & White, P. (2017). Zinc for better crop production and human health. *Plant and Soil*, *411*(1–2), 1–4.

ELD. (2015). *Report for policy and decision makers: Reaping economic and environmental benefits from sustainable land management*. Economics of Land Degradation (ELD) Initiative, Bonn, Germany, p. 4.

Erisman, J. W., Sutton, M. A., Galloway, J., Klimont, Z., & Winiwarter, W. (2008). How a century of ammonia synthesis changed the world. *Nature Geoscience*, *1*(10), 636–639.

Evangelista, S. J., Field, D. J., McBratney, A. B., Minasny, B., Ng, W., Padarian, J., Román Dobarco, M., & Wadoux, A. M. J. C. (2023). A proposal for the assessment of soil security: Soil functions, soil services and threats to soil. *Soil Security*, *10*, 100086.

FAO and ITPS. (2015). *Status of the world's soils*. FAO and ITPS.

FAO. (2018). *Food security and conflict: Empirical challenges and future opportunities for research and policy making on food security and conflict*. Food and Agriculture Organization of the United Nations.

FAO. (2021). *The state of the world's land and water resources for food and agriculture – Systems at breaking point: Synthesis report*. FAO.

FAO. (2023). FAO statistical databases. http://www.fao.org/faostat/.

Geisen, S., Wall, D. H., & van der Putten, W. H. (2019). Challenges and opportunities for soil biodiversity in the anthropocene. *Current Biology: CB*, *29*(19), R1036–R1044.

Greiner, L., Keller, A., Grêt-Regamey, A., & Papritz, A. (2017). Soil function assessment: Review of methods for quantifying the contributions of soils to ecosystem services. *Land Use Policy*, *69*, 224–237.

Harris, J. A., Evans, D. L., & Mooney, S. J. (2022). A new theory for soil health. *European Journal of Soil Science*, *73*(4), e13292.

Heathcote, R. L. (1980). Perception of desertification on the Southern Great Plains: A preliminary enquiry. In R. L. Heathcote (Ed.), *Perception of desertification* (pp. 34–59). United Nations University.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R. S., Brockhaus, M., Verchot, L., Angelsen, A., & Romijn, E. (2012). An assessment of deforestation and forest degradation drivers in developing countries. *Environmental Research Letters*, *7*(4), 044009.

ITPS. (2020). Towards a definition of soil health. (Soil Letters, September 2020). Intergovernmental Technical Panel on Soils (ITPS), Food and Agriculture Organization of the United Nations, p. 2.

Jónsson, J. Ö. G., & Davíðsdóttir, B. (2016). Classification and valuation of soil ecosystem services. *Agricultural Systems*, *145*, 24–38.

Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *363*(1492), 685–701.

Kopittke, P. M., Berhe, A. A., Carrillo, Y., Cavagnaro, T. R., Chen, D., Chen, Q.-L., Román Dobarco, M., Dijkstra, F. A., Field, D. J., Grundy, M. J., He, J.-Z., Hoyle, F. C., Kögel-Knabner, I., Lam, S. K., Marschner, P., Martinez, C., McBratney, A. B., McDonald-Madden, E., Menzies, N. W., … Minasny, B. (2022). Ensuring planetary survival: The centrality of organic carbon in balancing the multifunctional nature of soils. *Critical Reviews in Environmental Science and Technology*, *52*(23), 4308–4324.

Kopittke, P. M., Menzies, N. W., Dalal, R. C., McKenna, B. A., Husted, S., Wang, P., & Lombi, E. (2021). The role of soil in defining planetary boundaries and the safe operating space for humanity. *Environment International*, *146*, 106245.

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A., & Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International*, *132*, 105078.

Koren, O., & Bagozzi, B. E. (2017). Living off the land: The connection between cropland, food security, and violence against civilians. *Journal of Peace Research*, *54*(3), 351–364.

Kumssa, D. B., Joy, E. J. M., Ander, E. L., Watts, M. J., Young, S. D., Walker, S., & Broadley, M. R. (2015). Dietary calcium and zinc deficiency risks are decreasing but remain prevalent. *Scientific Reports*, *5*, 10974.

Langeveld, J. W. A., Dixon, J., van Keulen, H., & Quist-Wessel, P. M. F. (2014). Analyzing the effect of biofuel expansion on land use in major producing countries: Evidence of increased multiple cropping. *Biofuels, Bioproducts and Biorefining*, *8*(1), 49–58.

Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland. *Environmental Research Letters*, *9*(10), 105011.

Lehmann, J., Bossio, D. A., Kögel-Knabner, I., & Rillig, M. C. (2020a). The concept and future prospects of soil health. *Nature Reviews. Earth & Environment*, *1*(10), 544–553.

Lehmann, J., Hansel, C. M., Kaiser, C., Kleber, M., Maher, K., Manzoni, S., Nunan, N., Reichstein, M., Schimel, J. P., Torn, M. S., Wieder, W. R., & Kögel-Knabner, I. (2020b). Persistence of soil organic carbon caused by functional complexity. *Nature Geoscience*, *13*(8), 529–534.

Li, Z., Lun, F., Liu, M., Xiao, X., Wang, C., Wang, L., Xu, Y., Qi, W., & Sun, D. (2021). Rapid diagnosis of agricultural soil health: A novel soil health index based on natural soil productivity and human management. *Journal of Environmental Management*, *277*, 111402.

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *SOIL*, *5*(1), 15–32.

Padarian, J., Stockmann, U., Minasny, B., & McBratney, A. B. (2022). Monitoring changes in global soil organic carbon stocks from space. *Remote Sensing of Environment*, *281*, 113260.

Pepper, I. L., Gerba, C. P., Newby, D. T., & Rice, C. W. (2009). Soil: A public health threat or savior? *Critical Reviews in Environmental Science and Technology*, *39*(5), 416–432.

Ray, D. K., West, P. C., Clark, M., Gerber, J. S., Prishchepov, A. V., & Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS One*, *14*(5), e0217148.

Rinot, O., Levy, G. J., Steinberger, Y., Svoray, T., & Eshel, G. (2019). Soil health assessment: A critical review of current methodologies and a proposed new approach. *The Science of the Total Environment*, *648*, 1484–1491.

Román Dobarco, M., McBratney, A., Minasny, B., & Malone, B. (2021). A framework to assess changes in soil condition and capability over large areas. *Soil Security*, *4*, 100011.

Rumpel, C., Amiraslani, F., Bossio, D., Chenu, C., Henry, B., Espinoza, A. F., Koutika, L.-S., Ladha, J., Madari, B., Minasny, B., Olaleye, A. O., Shirato, Y., Sall, S. N., Soussana, J.-F., & Varela-Ortega, C. (2022). The role of soil carbon sequestration in enhancing human resilience in tackling global crises including pandemics. *Soil Security*, *8*, 100069.

Sanderman, J., Hengl, T., & Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(36), 9575–9580.

Singh, B. R., McLaughlin, M. J., & Brevik, E. (2017). *The nexus of soils, plants, animals and human health*. Schweizerbart Science Publishers.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, *133*(3–4), 247–266.

Springmann, M., Mason-D'Croz, D., Robinson, S., Garnett, T., Godfray, H. C. J., Gollin, D., Rayner, M., Ballon, P., & Scarborough, P. (2016). Global and regional health effects of future food production under climate change: A modelling study. *Lancet (London, England)*, *387*(10031), 1937–1946.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L. M., Ramanathan, V., Reyers, B., & Sörlin, S. (2015). Planetary boundaries: Guiding human development on a changing planet. *Science (New York, NY)*, *347*(6223), 1259855.

Thoumazeau, A., Bessou, C., Renevier, M.-S., Trap, J., Marichal, R., Mareschal, L., Decaëns, T., Bottinelli, N., Jaillard, B., Chevallier, T., Suvannang, N., Sajjaphan, K., Thaler, P., Gay, F., & Brauman, A. (2019). Biofunctool®: a new framework to assess the impact of land management on soil quality. Part A: Concept and validation of the set of indicators. *Ecological Indicators*, *97*, 100–110.

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., de Ruiter, P. C., van der Putten, W. H., Birkhofer, K., Hemerik, L., de Vries, F. T., Bardgett, R. D., Brady, M. V., Bjornlund, L., Jørgensen, H. B., Christensen, S., Hertefeldt, T. D., Hotes, S., Gera Hol, W. H., Frouz, J., Liiri, M., Mortimer, S. R., … Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global Change Biology*, *21*(2), 973–985.

UNCCD. (2018). Investing in land degradation neutrality: Making the case. An overview of indicators and assessments. United Nations.

van Bruggen, A. H. C., Goss, E. M., Havelaar, A., van Diepeningen, A. D., Finckh, M. R., & Morris, J. G. (2019). One Health - Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. *The Science of the Total Environment*, *664*, 927–937.

Vogel, H.-J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., Wiesmeier, M., & Wollschläger, U. (2019). Quantitative evaluation of soil functions: Potential and state. *Frontiers in Environmental Science*, *7*, 164.

Wall, D. H., Nielsen, U. N., & Six, J. (2015). Soil biodiversity and human health. *Nature*, *528*(7580), 69–76.

Wang, P., Chen, H., Kopittke, P. M., & Zhao, F.-J. (2019). Cadmium contamination in agricultural soils of China and the impact on food safety. *Environmental Pollution (Barking, Essex: 1987)*, *249*, 1038–1048.

Wang, Y. P., Law, R. M., & Pak, B. (2010). A global model of carbon, nitrogen and phosphorus cycles for the terrestrial biosphere. *Biogeosciences*, *7*(7), 2261–2282.

Watson, A. J., Lenton, T. M., & Mills, B. J. W. (2017). Ocean deoxygenation, the global phosphorus cycle and the possibility of human-caused large-scale ocean anoxia. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*(2102), 20160318.

Webb, R. S., Rosenzweig, C. E., & Levine, E. R. (1993). Specifying land surface characteristics in general circulation models: Soil profile data set and derived water-holding capacities. *Global Biogeochemical Cycles*, *7*(1), 97–108.

Yan, Z., Xiong, C., Liu, H., & Singh, B. K. (2022). Sustainable agricultural practices contribute significantly to One Health. *Journal of Sustainable Agriculture and Environment*, *1*(3), 165–176.

Zwetsloot, M. J., Leeuwen, J., Hemerik, L., Martens, H., Simó Josa, I., Broek, M., Debeljak, M., Rutgers, M., Sandén, T., Wall, D. P., Jones, A., & Creamer, R. E. (2021). Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. *European Journal of Soil Science*, *72*(4), 1640–1654.