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Ensuring planetary survival: Balancing the multifunctional nature of soils

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Abstract

Not only do soils provide 98.7% of the calories consumed by humans, they also provide numerous other functions upon which planetary survivability closely depends. However, our continuously-increasing focus on soils for biomass provision (food, fiber, and energy) through intensive agriculture is rapidly degrading soils and diminishing their capacity to deliver other vital functions, including climate regulation, nutrient cycling, biodiversity protection, and water cycling. These trade-offs in soil functionality – the increased provision of one function at the expense of other critical planetary functions – are the focus of this review. We examine how land-use change for biomass provision in the spiral of ever increasing economic growth has decreased the ability of soils to provide regulating services including global climate, biodiversity, the cycling of water and nutrients, which sustain plant growth and ecosystem health, and protection of the Earth's freshwater supplies. Given the existential threats facing humanity and their economies, it is imperative that we increase our focus on the multiple functions that soils provide for long-term human welfare and survival of the planet rather than focusing almost blindly on the short-term provision of biomass for economic profit. For this, there is an urgent need for predictive, multiscale models that quantify soil functional complexity and its link to economic models that can be used to guide policy and decision-making processes.

Keywords:

1 Introduction

Seven global existential cornerstones for the sustainable development of human societies are threatened, namely: Food Security, Water Security, Energy Security, Health, and Climate, Biodiversity, and Ecosystem Service Delivery. Although threats to these seven existential cornerstones are all global, complex, inter-related, and difficult to resolve, soil is related to all of them – soil is the single most important common variable in sustaining life on our planet (Kopittke et al. 2021; McBratney et al. 2014).

Soils are diverse and multifunctional –they contribute to provisioning functions that are as basis of human life and economies easily tangible such as the provision of food, fiber, and energy. Moreover, they also provide less tangible regulating and support functions with longer-term benefits such as regulation of climate, and biogeochemical cycles, and biodiversity protection supporting human health and the quality of life on our planet. Because of their critical importance, soils contribute to at least 12 of the sustainable development goals (SDGs) of the United Nations (Figure 2). Despite the multiple benefits of soils, society has historically focused almost exclusively on one single function – the provision of biomass (food, fiber and energy). The reason is that societal development is intimately linked to agricultural production, which is the basis of economic growth (Dethier and Effenberger, 2012; Davis, 2017). However, by prioritizing biomass production, the capacity for soils to deliver the remaining functions has been compromised. Whilst agricultural production is clearly essential, society's narrow recognition of the soils' production function at the expense of its other functions, is limiting our understanding of how soil can be best managed to secure and capitalize on its multifunctionality. This is however imperative to address the global challenges, threatening the hospitability and survivability of our planet by worsening the existential challenges.

Here, we address the multifunctionality of soil and consider trade-offs in these functions, focusing on how the constant, global demand for productive agriculture is profoundly decreasing the ability of soil to provide other functions critical for planetary health (Vazquez et al. 2021; Zwetsloot et al. 2021). Indeed, it is increasingly clear globally that soil management to increase delivery of one function (especially food and fibre production) has substantially reduced the soils' capacity to deliver other functions (such as nutrient cycling, biodiversity protection, and climate regulation), as shown in Europe by Zwetsloot et al. (2021). To better inform policy and guide decision-making processes, there is an urgent need to develop predictive, multiscale models that quantify soil functional complexity and their contribution to ecosystem services (Lehmann et al. 2020) in view of their importance for progress towards stable economies, planetary health and sustainable development goals. Currently, this information is lacking, and the multifunctionality of soils is largely excluded from broader assessments of ecosystem services despite their role as a planetary master variable.

We build on previous reviews, such as that of McBratney et al. (2014) who developed a framework for 'soil security', that of Amundson et al. (2015) who examined the interconnection between soil, climate and food security, and that of Kopittke et al. (2019) who examined how agricultural intensification is degrading soils. First, we examine the multiple functions of soils, considering their importance for the health of both humans and the planet. Next, we examine how land-use changes, driven by the need for increased agricultural production, are causing trade-offs in the ability of soils to deliver its other key functions. We also consider how the decreasing ability of soil to provide these other functions, such as climate regulation, can be halted and reversed. We make the case for soil organic carbon (SOC; for simplicity and brevity, we use the term 'SOC' to also include soil organic matter, SOM) as the integral component of the soil matrix that links and underpins critical soil functions, and argue for a better understanding of carbon (C) fluxes and persistence. Finally, we contend that it is imperative to develop a better understanding of the trade-offs in soil multifunctionality, including approaches to quantify and model these broad trade-offs and their implication to enable more efficient and effective soil management practices that promote sustainable agricultural production to support economies and planetary health to ensure the prosperity and survival of human societies of our planet.

2 Functions of soils

It is first prudent to delineate between soil 'functions' and broader 'ecosystem services' – soil functions provide a soil-related contribution to ecosystem services, with these ecosystem services requiring an inter- and transdisciplinary approach given that soils do not act independently (Bouma 2014). Soil functions can be categorized in multiple ways, including provisioning functions, support functions, regulating functions, and cultural functions. Provisioning functions provide humans with biomass (food, energy, and fiber), raw materials, and a physical environment, with humanity generally focusing on those functions that provide tangible benefits such as food, fibre and energy production to sustain economic growth. Support functions are roles of soils that underpin other functions, and include nutrient cycling, water cycling, and biodiversity. Although support functions are generally not economically evaluated due to double-counting (Jónsson and Davíðsdóttir 2016), we include information in the present review to highlight the importance of soils in this regard. Regulating functions include climate regulation, biological control of pests and diseases, and the recycling of wastes and detoxification, with these being directly economically valued (Jónsson and Davíðsdóttir 2016). Finally, the cultural functions of soil include heritage and recreational functions (Jónsson and Davíðsdóttir 2016).

Here, we focus on (i) biomass production (food, fiber, and energy), (ii) climate regulation, (iii) biodiversity protection and habitat provision, (iv) nutrient cycling, and (v) water cycling as five of the key soil dimensions describing soil multifunctionality (Figure 3) linked to planetary survivability of human societies (Kopittke et al. 2019; Steffen et al. 2015; Vazquez et al. 2021; Vogel et al. 2019; Zwetsloot et al. 2021).

2.1 Production of biomass (food, fiber, and energy) through land-use change

Humans rely almost entirely on soils to provide their biomass: food, fiber, and energy. Indeed, an estimated 98.7% of the daily calories consumed by humans have their origins in soils (2,895 kcal per capita), with only 1.3% from aquatic systems (38 kcal per capita) (FAO 2021). Although soils have sustained humans by providing biomass for millennia through social practices such as hunting and gathering, the establishment of agriculture and the rapidly increasing population growth over the last centuries has let to land-use change and the adoption of intensive production systems to satisfy the increasing demand. To produce their food and other commodities, humans currently use 1,600 million ha (12% of the ice-free land) of productive land for cropland, with a further 3,200 million ha (25%) dedicated to permanent grassland and pasture (FAO 2021). It is often this profound global land-use change, largely for agriculture, that is decreasing the ability of soils to provide the other functions described in later sections.

Of key importance is that the demand for food (plus fiber and energy) has grown markedly over the last one-and-half centuries, and is correlated with an increase in land-use change (Figure 1). For example, the human population increased from 2.5 billion in 1950 to 7.8 billion in 2020, with a concomitant increase in cereal production from 0.74 Gt in 1961 to 2.9 Gt in 2016. The human population will continue to increase even further, reaching a projected 9.8 billion by 2050. Accordingly, demand for food will also continue to increase coupled with changes in diets, with food production required to increase by 70% between 2005 and 2050 (ELD 2015).

As the demand for food increases, there is likely to be a concomitant increase in demand for fiber and energy (biofuels) production from soils. For example, ethanol production, which was 20 GL per year in 2000, is projected to increase to ca. 130 GL per year in 2030 (OECD/FAO 2021), with biofuel production estimated to account for 32 million ha of land globally in 2013 (Langeveld et al. 2013).

Thus, the challenge is how best to increase biomass production whilst maintaining soil resources. To a large extent, this is expected to be achieved by improving production efficiency and yield rather than by increasing the area of land under agriculture (Tillman et al., 2011). Indeed, over the decade to 2030, 87% of the projected increase in global crop production is expected to come from yield improvements, 7% from increased cropping intensity, and only 6% from an expansion of cropland (OECD/FAO 2021). Similarly, increased production in livestock will likely result from intensification, although herd enlargement will contribute significantly to emerging and low-income countries (OECD/FAO 2021). Globally, changing climates already require the adaptation of current farming practices and areas used for agricultural production. There are also other approaches that can be used for increasing food security, such as decreasing food wastage or changing dietary habits, but these and other approaches are beyond the scope of this review.

2.2 Climate regulation

2.2.1 Role of soil in climate regulation

Soils play a critical role in climate regulation, primarily through their importance in the global C cycle. Indeed, soils store more organic C (ca. 2344 Pg of organic C within the surface 3 m, and ca. 1500 Pg C in the surface 1 m) (Scharlemann et al. 2014), than in the atmosphere (875 Pg C in 2019) and vegetation (600 Pg C) combined. Not only is the total SOC stock large, but SOC is highly dynamic – each year, ca. 61 Pg of C enter soils from vegetation with similar amounts being lost from soils to the atmosphere due to mineralization (Lehmann and Kleber 2015). Thus, ca. 7 % of the atmospheric C pool is cycled through soils every year. As such, any human-induced decrease in the quantity of C either entering soils (inputs) or increases in the quantity lost from soils (outputs) can result in marked increases in atmospheric CO_2 concentrations. Furthermore, most productive (and hence C-rich) ecosystems are founded in soils, and thus the loss of soils also results in the loss of the associated biomass C. It has been estimated that the economic value of soil climate regulation is up to US$268 per hectare per year (Jónsson and Davíðsdóttir 2016); on a global scale this roughly equates to US$3.5 trillion per year for the global ice-free land area (13,000 million ha).

2.2.2 Effects of anthropogenic land use change on soil climate regulation

Although SOC stocks are large, it has long been recognized that, for the most part, the use of soils for agricultural production has resulted in a marked loss of this SOC. In global meta-analyses, following conversion of forest to cropping, SOC stocks have reportedly decreased an average of ca. 42% (Guo and Gifford 2002; Kopittke et al. 2017). Associated with the loss of SOC, the release of CO_2 from soils following land-use change is estimated to have resulted in the release of ca. 133 Pg of C, primarily in the last 200 y (Sanderman et al. 2017). This represents ca. 25% of total cumulative global anthropogenic emissions of CO_2 since ? and some 16% of the total increase in radiative forcing due to greenhouse gases (Kopittke et al. 2021).

The need to increase SOC concentrations is recognized through programs such as the ‘4 per mille’ initiative which intends to encourage the introduction of sustainable practices with an aspirational goal to increase global SOC stocks by 0.4% (4 per 1000) per year (Rumpel et al., 2020). There are adjustments to conventional cropping systems that can be used to potentially increase SOC stocks, though highly dependent on environment. For example, the use of conservation agriculture can, in some circumstances, result in a modest increase in SOC stocks, as can the addition of organic materials to the soil. In the meta-analysis of Kopittke et al. (2017), the use of no-till resulted in an average 8% increase in SOC stocks, whilst the addition of organic amendments to the soil resulted in a 25% increase. Whilst such increases in SOC stocks by alternate management practices are critical, the gains in C stocks obtained by improved management remain smaller than the original decrease in C stocks caused by land-use change. Thus, it is clear that consideration could also be given to the conversion of soil used for agricultural production to a system with a higher density of vegetation such as ‘carbon farms’. For example, Guo and Gifford (2002) calculated that the conversion of cropland to secondary forest increased C stocks by 53% whilst conversion to pasture increased C stocks by 19%. For this to occur, there need to be a clear approach for quantifying benefits in terms of increasing climate regulation along with trade-offs in form of greenhouse gas emissions and the value of lost agricultural production.

Brief mention should also be given to the contribution of the soil N cycle in agricultural systems to climate regulation. Globally, 109 Tg of N fertilizers are applied, with the application of these fertilizers to soils contributing to the release of greenhouse gases due to the production of nitrous oxide (N_2O). Indeed, soils account for 60% of total N_2O emissions (Tian et al. 2019), being a total of 3.7% of the global increase in radiative forcing due to anthropogenic greenhouse gas emissions (Kopittke et al. 2021). In this regard, it is imperative to increase the efficiency of N fertilizer usage which has decreased from 68% in 1961 to 47% in 2010 (Lassaletta et al. 2014). This could be achieved through the development of more efficient fertilizers, utilization of other management approaches to increase uptake of N by plants, or increased incorporation of N-fixing legumes in cropping systems.

2.2.3 Quantifying the contribution of soils in climate regulation

For any given soil, the actual (current) contribution to climate regulation can be quantified by measuring the SOC stocks and their change, with SOC being a direct measurement of the primary indicator of this function. For managed systems (such as in soils used for cropping), it is necessary to compare this actual state to its potential value in a restored system or in any other system with alternative management practices. These potential values can be estimated through pedotransfer functions that rely upon various other parameters, including soil texture, bulk density, and climate (Vogel et al. 2019). Hence, for managed systems, the difference between the potential and the actual contribution represents the magnitude of climate regulation which has been lost due to human use of soils, such as clearing land for agricultural production.

2.3 Nutrient cycling

2.3.1 Role of soil in nutrient cycling

The importance of the role that soils play in storing and cycling of nutrients cannot be overstated – without nutrient storage and (re-)cycling in soils, plant growth in both natural ecosystems and agricultural systems would cease almost entirely. For example, global soils contain huge amounts of nitrogen (N) and phosphorus (P), 200 Pg N and 50 Pg P, with this being equivalent to 50% of N in plants and 10% of P (Smil 2000; Stevenson and Cole 1999). To provide context, these soil N stocks (200 Pg N) are ca. 1800-times larger than annual production of reactive N through the Haber-Bosch process for fertilizers (109 Tg N) (FAO 2021), with the annual production of N fertilizers accounting for ca. 1.5% of global energy use. Although soils contain huge reserves of nutrients, only a small fraction is immediately available to plants. In this regard, SOC plays a central role in nutrient storage and cycling in soils – the gradual mobilization of nutrients by mineralization or solubilization, which is critical for nutrient cycling between plants and soil, is mainly mediated by soil microorganisms (Marschner 2012). Accordingly, it has been estimated that the value of this nutrient cycling through soil, using replacement cost, is up to US$180 per hectare per year (Jónsson and Davíðsdóttir 2016), which equates to a value of up to US$2.3 trillion per year for the global, ice-free land.

2.3.2 Effects of anthropogenic land use change on soil nutrient cycling

Through its effect on plant biomass, plant diversity, and soil properties (including changes to microbial diversity), land-use change alters both total stocks of soil nutrients as well as their cycling. This is particularly important for nutrients closely associated with SOC (especially N, P, and S) given both the profound decrease in SOC stocks and concentrations with land-use change (see Section 2.2), as well as the critical role of SOC in soil fertility. For example, it has been reported in a global meta-analysis that upon conversion of forest to cropping land, the median decrease in soil N stocks was 42%, with corresponding decreases being 31% for P and 32% for S (Kopittke et al. 2017). Not only does land use change alter nutrient stocks in soils, but there is a concomitant influence on microbial abundance, diversity and activity (see later), and hence nutrient cycling. Indeed, land use change from natural to agricultural ecosystems can disrupt nutrient cycling by decreasing organic matter and nutrient return to the soil, accelerating SOC decomposition rates through tillage, and also increasing nutrient losses through runoff, erosion, volatilization and leaching (Magdoff et al. 1997). Further, conversion of naturally diverse ecosystems to agricultural use can have detrimental effects on nutrient cycling by reducing the diversity of organic materials entering the soil, which reduces food web diversity and thus nutrient cycling (Kostin et al. 2021; Tsiafouli et al. 2015). This loss of SOC from agricultural systems, together with the coupled decrease in nutrient cycling, has flow-on effects for agricultural production and its economic returns due to a loss of soil fertility. For example, in a meta-analysis, it was found that increases in SOC concentrations would potentially increase yields of wheat by 10% and maize by 23% (Oldfield et al. 2019). The same study showed that lower amounts of N-fertiliser are needed to produce similar yields in SOC rich soils as compared to SOC poor ones.

The deleterious effect of land use change on nutrient stocks and the cycling of these nutrients can be reversed, at least in part, by a range of management strategies. This can be achieved, for example, by using higher plant diversity, such as rotations or mixed cropping, ensuring that the organic materials entering the soil have a wide range of properties which enhance diversity of soil biota and hence nutrient cycling (Kostin et al. 2021; Liu et al. 2020). Cover cropping can also enhance nutrient cycling by increasing microbial activity and mobilizing nutrients, such as N and P (Hallama et al. 2019). Permanent plant cover and the associated minimal soil disturbance also increase the amount of organic materials available for breakdown by soil biota and reduce soil erosion which improves nutrient cycling (Steven et al. 2021). Reduced tillage or no tillage practices can help to retain SOC and improve soil structure, reducing erosion and nutrient loss (Magdoff et al. 1997). Finally, the application of organic amendments can cause marked increases in nutrient cycling and fertility, with Sandhu et al. (2008) reporting that the economic value of nutrient cycling was US$260 per hectare per year in organically managed fields compared to US$142 per hectare per year in conventionally managed fields. At the expense of food production, cropped soils can also be returned to secondary forest, which may substantially increase SOC stocks (see Section 2.2.2), concomitantly increasing the ability of soil to store and cycle nutrients.

If soil is considered solely from the perspective of the short-term goal of biomass production, a number of soil functions can be replaced with the application of readily available inorganic nutrients and other agrochemicals. Indeed, this is the basis of many agricultural production systems that utilise relatively cheap synthetic inputs to mitigate the risk of low yielding crops. The ease and economic benefits of using synthetic fertilisers to optimise yield has also meant that modern plant varieties are typically selected under conditions that select against certain soil biota. This further diminishes the contribution of these species to soil biological fertility and also limits their adaptability to extreme climatic events, such as drought, which may lead to economic losses due to crop failures.

2.3.3 Quantifying the contribution of soils in nutrient cycling

Soil nutrient cycling and storage is determined by a range of mechanisms before their uptake by plants, including their fate as part of SOC and linked to soil cation exchange capacity (CEC, being especially important for storage of nutrients such as Ca, Mg, and K). Hence, quantification of the contribution of soil to nutrient cycling is complex, but generally includes an assessment of SOC as well as the CEC, with the CEC itself depending upon soil texture and mineralogy, as well as the SOC content. However, a range of other factors also influence soil nutrient cycling, including pH, soil depth, and the exogenous application of fertilizers and other amendments. Regardless, given the central role of SOC in nutrient cycling within soils, this parameter is often used when quantifying the contribution of soils to inherent nutrient cycling [for example, see Sandhu et al. (2008)]. As a result, for managed soils, where the nutrient cycling capacity has been degraded, it is possible to estimate the difference between the potential contribution to nutrient cycling and the actual contribution by estimating the loss of SOC.

2.4 Biodiversity protection and habitat provision

2.4.1 Role of soil in biodiversity protection

Soils are the most biologically diverse habitat on Earth with soil biota represented across all three domains in the tree of life, Bacteria, Archaea and Eukaryota, accounting for approximately one-quarter of total biodiversity (Bach and Wall 2017) and with > 40% of living organisms in terrestrial ecosystems associated directly with soils (Decaëns et al. 2006). Microorganisms are the most abundant component of the soil biota with a handful of soil containing billions of individual microbial cells, as well as meters of fungal hyphae and a variety of microfauna. For example, it has been estimated that there are ca. 4.4×10^{20} nematodes (with a total biomass of ca. 3×10^{8} t) in global surface soils (van den Hoogen et al. 2019). These soil fauna contribute to both carbon and nitrogen mineralization, with their contribution often being greater in soils with low fertility. Up to 40% of total net nitrogen mineralized is estimated to be due to soil fauna, with nematodes and protozoa contributing the most (Brussaard et al. 1996). At a global scale, the total mass of soil microorganisms (termed the microbial biomass) is influenced by the soil, climate and plant productivity, with soil biodiversity intricately linked to the SOC providing an energy source for growth and maintenance (Jones et al. 2019).

Within the soil, this biodiversity makes numerous critical contributions, many of which are related to the other functions of soil described in this review. Soil biodiversity contributes to nutrient cycling, food (biomass) production, the provision of water, climate regulation, and human health (FAO 2020). For example, ca. 80% of all antibacterial agents approved between 1983 and 1994 originated from soils, whilst ca. 60% of all drugs approved between 1989 and 1995 originated from soils (Mbila 2013). The total value of soil biodiversity is estimated to be US$2.1 trillion per year (Jónsson and Davíðsdóttir 2016).

Soil biodiversity and the associated ecosystem multifunctionality cannot be ignored when establishing ecosystem protection priorities (Guerra et al. 2021). To protect soil biodiversity, it is imperative to understand the biogeographic patterns and the predictors of soil biodiversity at multiple trophic levels, as well as the role of multiple factors in driving soil functionalities and biodiversity (Rillig et al. 2019). Recent advances in molecular and sequencing technologies have marked the beginning of a new era in exploring the genetic diversity, genetic functions, and ecological preferences of soil organisms at global scales. Indeed, as noted by FAO (2020), “understanding the value of ecosystem services linked to soil organisms is vital for decision-makers when considering soil use and land management changes”.

2.4.2 Effects of anthropogenic land use change on soil biodiversity

Land-use change, including the use of soils for agricultural production, results in a marked decrease in SOC and soil biodiversity (Marques et al. 2019; Newbold et al. 2015) and there are numerous reports showing that intensive agricultural production greatly reduces the complexity of soil food webs and reduces the mass of soil fauna (Geisen et al. 2019; Tsiafouli et al. 2015). For example, pesticides can control target pests and pathogens, but may harm non-target soil organisms and disturb soil food web interactions (Damalas and Eleftherohorinos 2011). Furthermore, excessive applications of fertilizer cause soil degradation and acidification with a negative impact on soil biodiversity (Guo et al. 2010; Savci 2012).

Achieving sustainable agricultural production whilst halting (and reversing) the deleterious effects of agricultural production on soil biodiversity will require various approaches such as crop diversification, regenerative agriculture, organic fertilization, and biological control. For example, agricultural diversification – the intentional addition of functional biodiversity to cropping systems to regenerate biotic interactions underpinning yield-supporting ecosystem services (Kremen et al. 2012), has emerged as a strategy to contribute to the Sustainable Development Goals (SDGs) of the United Nations. Although trade-offs regularly exist between crop yield and multiple ecosystem services (such as discussed throughout this review), a recent meta-analysis has demonstrated that agricultural diversification can actually promote biodiversity and the delivery of ecosystem services without compromising crop yield (Tamburini et al. 2020). Organic, conservation, and regenerative agriculture have distinct impacts on productivity, carbon sequestration, economic performance and ecosystem multifunctionality. A recent study conducted in Europe found that organic and conservation cropping promoted ecosystem multifunctionality including biodiversity preservation, soil and water quality, and climate mitigation, along with economic benefits (Wittwer et al. 2021). In addition, the crop microbiome, as the second genome of its host, promotes the host’s phenotype such as growth and tolerance to pathogens, pests, and environmental stresses. For example, root-associated fungi, such as myccorrhiza and plant growth promoting bacteria are beneficial for nutrient acquisition and cycling (Richardson et al., 2009). This plant-microbiome interaction is largely unexplored but has great potential to achieve sustainable agriculture and ameliorate threats to soil biodiversity (Chen et al. 2021).

2.4.3 Quantifying the contribution of soils in biodiversity protection

Soil biodiversity can be measured through a range of approaches, including species richness, diversity indices, or the presence of keystone species and functional diversity (Vogel et al. 2019). However, a key challenge remains to relate these measures of soil biodiversity to the actual functions of the soil, and to understand how to relate changes in soil biodiversity to soil functioning.

Soil biodiversity depends upon a large number of factors, including SOC, the water balance, temperature, texture, bulk density, and pH. However, it is increasingly clear that, within any given soil, biodiversity is very closely linked to SOC content, such as shown throughout Europe where it has been reported that "high SOC was a common attribute amongst croplands with a high biodiversity habitat provision" (Vazquez et al. 2021). This is perhaps not surprising given that the SOC is the energy source that drives soil communities. Thus, changes in biodiversity are often most closely related to the changes in SOC (both quality and concentration) caused by changes in land use or management.

2.5 Water cycling

2.5.1 Role of soil in water cycling

Soils are the largest store of fresh water in the terrestrial ecosystem (McColl et al. 2017). Globally, soil can store 121,800 km^3 of water (Webb et al. 1993); and yet on average, soils contain only about a tenth of its capacity (approximately 17,000 km^3), which is still larger than that held in the atmosphere (13,000 km^3) and living organisms (1 km^3) (Oki and Kanae 2006). This interface between the atmosphere, plant and groundwater is an essential part of the hydrological cycle, providing services of: storing and supplying water to plants, transmitting and filtering water for storage in groundwater, supporting runoff generation to rivers, exchanging water in the soil-plant-atmosphere system, moderating drought and flood potentials (Wu et al. 2015), and a buffer in climate change's impact on the hydrological cycle.

Soil aggregation is largely responsible for water regulation where water is held and transmitted in the soil due to its unique pore size distribution expressed by the soil water retention curve, with this soil aggregation occurring due to a range of processes including interplays between the soil biodiversity and SOC. No other porous material can hold water over the energy range that many soils are able to. The pore network of the soil simultaneously controls gaseous and solute flow (Ghezzehei et al. 2019; Young and Ritz 2000) and provides a habitat for soil microbes in the water-films and bio-films surrounding the organo-mineral components of soil. These water films in the pore network can restrict oxygen flow through the pore network and thus affect biological activity. Conversely, soil microorganisms such as nematodes, protozoa and bacteria rely on water films for their movement through the soil. Fungi however rely on a moist atmosphere in soil with good air connectivity to extend their hyphae. Thus, soil architecture controls the hydrological cycle as well as critical microbially mediated processes.

2.5.2 Effects of anthropogenic land use change on soil water cycling

Land use change and conventional agricultural practices have severely impacted these soil water cycling functions. Both tillage and the loss of SOC, together with other factors, have caused compaction and the associated loss of soil aggregation. In turn, this degradation has enhanced runoff, reduced infiltration, increased evaporation, lessened water storage, and reduced recharge. Land use not only affects the physical condition of the soil and its ability to transmit and store water, but also has an impact on the hydrological cycle of the area. For example, in a semiarid area in southwestern Australia, a 750 km rabbit proof fence established around 1901-1907 that separated natural vegetation from agricultural land provided a comparison between soils under native vegetation and agriculture. Observations from this site have demonstrated that agricultural land, compared to natural vegetation, has distinct characteristics such as albedo, surface roughness, and canopy resistance. These, in turn, affect the energy balance and decrease cloud formation and precipitation on agricultural land (Lyons 2002). The impact of land use on the availability and loss of water through precipitation and runoff will continue to be further impacted locally by climate change, and combined with the condition of the soil, will cause soil moisture droughts (Samaniego et al. 2018).

Conservation agriculture, including the use of minimum tillage, stubble retention, and cover crops, has been found to reduce the deleterious effect of land use related to water management. These beneficial practices result in increased soil aggregation and macropores, which in turn increased water infiltration into the soil, higher water storage and reduced soil erosion, and act as natural flood management infrastructure (Palm et al. 2014; Thomas et al. 2007). Nevertheless, the relationships between conservation tillage, SOC and soil water parameters are not always clear. Increased organic matter has been widely promoted to increase soil water retention or available water capacity. However, a detailed analysis of experimental data from Minasny and McBratney (2018) reveals that organic matter only affects large pores and hence has only a small effect on available water capacity. Additionally, the classic concept of more organic matter means more water retention is no longer held – ongoing research is also showing that organic matter can exhibit significant repellence, with this directly impacting upon water ingress into the soil (particularly on sandy soils) and subsequent water distribution (Hallett et al. 2001) with preferential flow of water leaving large volumes of soil dry. Furthermore, although comparisons between conventional tillage and no-tillage systems often show a higher infiltration rate in the no-till system, other studies show the reverse (Palm et al. 2014). These apparently conflicting results suggest that we cannot measure soil functions using few parameters, rather soil needs to be studied as a system to understand all the complexities and interactions.

2.5.3 Quantifying the contribution of soils in water cycling

For any given soil, the actual contribution to water cycling depends upon the climate, a range of soil physical properties (including texture, aggregation, porosity, and water retention), and various chemical properties (including SOC content). Quantifying water cycling is challenging as water in soil is highly dynamic. The most commonly quantified parameter is water holding capacity, which is related to biomass production. A fully quantified function should balance minimal runoff and erosion, persistence of moisture storage, and drainage.

3 Optimizing trade-offs in soil functions to ensure planetary survivability: A central role for soil carbon as an indicator of functioning

It is clear from the preceding discussion that whilst we rely on agricultural production systems for our survival and the functioning of our economies, the land-use change that has occurred, and continues to occur, to produce this food is having profound effects on the ability of soil to provide other critical functions related to human wellbeing and quality of life. Given the existential threats humanity now faces, it is critical that we increase our focus on the multiple globally-important functions that soil provides. For this, there is an urgent need to develop predictive, multiscale models that quantify soil functional complexity to guide policy and decision-making processes (Lehmann et al. 2020). These multiscale models are required because information is required at scales that are broad enough to facilitate policy interventions whilst simultaneously being local enough to reflect the functional complexity of the specific soils (Lehmann et al. 2020).

Multiple studies have examined approaches for quantifying and predicting soil functioning (Greiner et al. 2017; Jónsson and Davíðsdóttir 2016; Vogel et al. 2019; Zwetsloot et al. 2021). However, despite the extreme complexity of soil functions, it is clear that SOC plays a central role and is a master indicator for examining changes in soil functioning. Indeed, within any given soil, SOC is the primary indicator of climate regulation by soils, it is central for nutrient storage and cycling, and is closely linked to soil biodiversity. For example, consider a managed system where anthropogenic use of the soil has resulted in a substantial decrease in SOC stocks. In this system, differences in C stocks between the actual state (i.e. the current, degraded state of the managed system) and the potential state (i.e. an estimate of the state if the soil was restored) (Vogel et al. 2019) can be used to estimate the additional capability (value) (McBratney et al. 2019) of a soil to regulate the climate, protect biodiversity, and cycle nutrients. However, the mechanisms by which increased SOC fulfills these functions in quantitatively poorly understood. The most prominent role of managing soil C is the possibility to link the mitigation of climate changes with beneficial effects in agricultural production, thus closing yield gaps (Amelung et al. 2020). These authors demonstrate that the potential of soils to store additional C, and thus provide beneficial effects on the multitude of soil functions discussed above, strongly depends upon the specific ecoregion, with this differing between soil types and land use history. As land use, together with soil type, soil structure, and soil mineral composition, directly determine the capacity of soils to store and sequester C (Wiesmeier et al. 2019), future research has to address the mechanistic underpinnings of these relationships.

Thus, we contend that a focus should be given to better understanding the factors driving C persistence in soils (both biotic and abiotic), along with the dynamics of labile pools. Both are needed to predicting how SOC stocks change depending upon management, land-use, and other stressors such as climate change, and to understand the multiple soil functions related to biological activity. Economic considerations should be coupled to such an approach to determine the consequences of alteration of multiple soil functions for human societies. In this regard, it is clear that we need novel management approaches to increase soil functionality, and it is also imperative that we identify areas where the environmental benefits obtained by restoring degraded soils, and hence allowing them to maximize provision of other functions, exceeds their value when continuing to be used for food, fiber, and energy.

4 Knowledge gaps

In order to effectively develop multiscale models that quantify the functional complexity of soils and their contributions to broad ecosystem services sustaining the wellbeing of human societies, it is clear that there are multiple knowledge gaps that must be addressed.

4.1 Understanding carbon persistence in soils and the scaling of information

Given the central role of SOC across multiple soil functions, we need not only to develop a better understanding of the factors controlling the behavior and persistence of C in soils but also to assess the importance and dynamics of labile pools. Although the critical importance of SOC has long been recognized, soil scientists are now refuting the traditional assumptions that SOC is based on ‘humic substances’, with these previous assumptions having now diverted research efforts for multiple decades (Lehmann and Kleber 2015). Rather, there is now increasing evidence that C persistence is driven by molecular diversity, spatial heterogeneity, and temporal variability intimately related to microbial accessibility (Lehmann et al. 2020). However, much remains only poorly understood in this regard with a concerted research effort required to continue probing the factors determining SOC dynamics in soils, including in subsoils, which remain comparatively understudied. Such information is critical in developing ‘models with intent’ in order to predict how changes in land use, management, or other stressors (such as climate change) alter SOC concentrations and persistence (Lehmann et al. 2020), with this being central to predicting soil functionality.

In addition, we currently do not have an adequate, multiscale, theoretical framework that bridges the gap from the fine scales (nano-scale to micro-scale) where C accumulates, to the large scales which are relevant for C-management policy (kilometer-scale) (Lehmann et al. 2020). Similarly, observations of soil C at the field and regional scale cannot be linked back to the processes at the nano-scale. One possible solution to bridge these scales is through the application of statistical physics framework that could describe how the mineral and organic components intervene in aggregation using an equilibrium thermodynamic model of self-assembly. This framework had been successfully developed for protein spontaneous formation (Sartori and Leibler 2020), and thus the assembly of aggregates based on physical and chemical potential and binding energy could be described in a set of parameters through algebraic relations that enabled scaling laws to be applied. Thus, we can link how nanoscale interactions of minerals and organic matter affect water and gas flow, biodiversity interactions and biogechemical processes are relevant to regional and national scale assessment of soil functional change.

4.2 Soil biodiversity and functionality

Although soil biodiversity contributes substantially to multiple critical soil processes and hence to the provision of functions that support human well-being, much remains unknown about soil biodiversity. Of utmost importance, we require an understanding of how measures of soil biodiversity (such as species richness or diversity indices) relate to the functioning of the soil, and critically, to understand how human-induced changes in soil biodiversity impact upon soil functioning. In this regard, Young and Bengough (2018) stated: “in perhaps the most exhaustive analysis and review of research on soil biodiversity, (there were) no consistent links between soil species diversity and function”. For example, it remains unclear how the decreasing complexity of soil food webs observed in intensive agricultural systems (Geisen et al. 2019; Tsiafouli et al. 2015) impacts upon the provision of soil functions such as nutrient cycling, biomass production, or SOC stocks.

Indeed, it is imperative that we gain a better understanding of how modifying uses of soils by humans alters soil biodiversity, their interactions with environments, and most importantly, the effect of these impacts on their ability to provide long-term soil functioning. It is also important to understand how the soil matrix and rhizosphere microbial community interact via their effects on water availability and nutrient cycling from both inorganic and organic sources, with this potentially allowing optimization of plant productivity whilst also mitigating greenhouse gas emissions.

4.3 Novel approaches for increasing multifunctional capacity of soils

Poor management and climate change are degrading soils and having detrimental effects on soil C and productivity. A range of management approaches have been developed to ameliorate degraded soils, but detailed analysis of their effect on soil properties and how the effects vary across scales are missing. This information is critical for improving existing management approaches and developing new strategies. There is an urgent need to develop new strategies to alleviate degraded soils and optimize SOC dynamics leading to increased soil C sequestration and productivity, with this generating new ways to rejuvenate and regenerate soil functionalities and its resilience. Such approaches might include methods to optimize the soil matrix functionality throughout the entire profile, design novel rhizosphere systems, or find new methods to minimize greenhouse gas emissions whilst maintaining soil productivity.

4.4 Refine models for ecosystem services to incorporate multifunctionality of soils

Due to the complexity of the soil system, the multifunctionality of soil has generally been excluded from broader models that assess interactions between humans and the environment. Indeed, most models of ecosystem services include a maximum of one or two soil-based functions (Greiner et al. 2017). While these models may address individual problems, optimization of systems by focusing on only one or two soil-based functions will result in unknown and unintended consequences. This requires the expansion of models to be truly multifunctional, with this necessitating the identification of indicators that can be easily monitored for evaluating the soil's multifunctionality. Such an approach will ultimately expose the trade-offs that are being made when certain land-use and management options are prioritized over others. Furthermore, these indicators not only need to meet the requirements and rigor of the biophysical sciences, but also provide data and information that is valued by the economic and policy arenas, with this requiring a clear multidisciplinary effort. Such models will be implemented locally, whilst their outputs need be mapped across broader areas to identify which soil functions are threatened (i.e. multiscale). From this present review, we identify SOC as being a master indicator for multiple soil functions given that it is responsive to the impacts of land-use change and is a biophysical indictor that is valued and relevant to assessments made by the economic and social sciences (Dowell et al. 2020; Pascual et al. 2015; Sykes et al. 2020).

5 Conclusions

As befits the most complex biomaterial on the planet, there are no easy solutions to solving the ongoing soil security crisis of the planet. We need to find innovative practices that ensure the survival of future generations by sustainably using soils for the wide range of functions highlighted in this review. To do this, we need a highly collaborative effort across basic science, where new discoveries await to be revealed, and translational science, where we better connect laboratory and field. The answers do not lie in any one discipline, but rather, in a close cooperation across disciplines, connecting experimental research with the broader modelling community to ensure accurate predictions of the state of soils as we use them for food production and more general, but equally important, functions.

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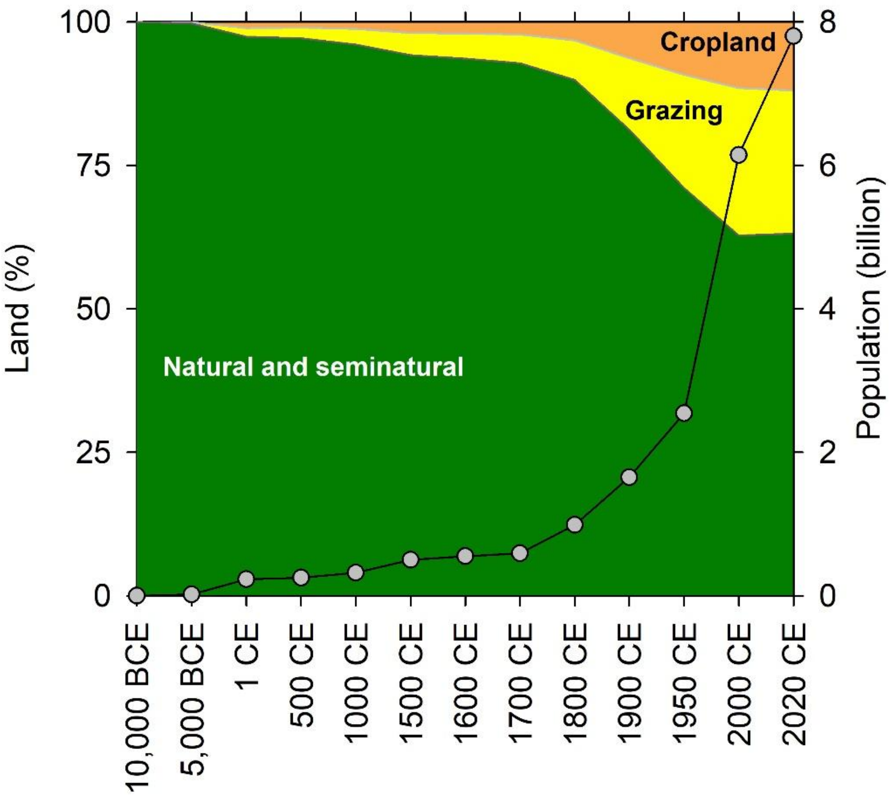

Figure 1. Land-use changes for cropland and grazing as a percentage of the global ice-free land (shaded areas) and the change in human population (grey points). Data were obtained using the HYDE 3.2 database (Klein Goldewijk et al. 2017) and updated from Kopittke et al. (2019).

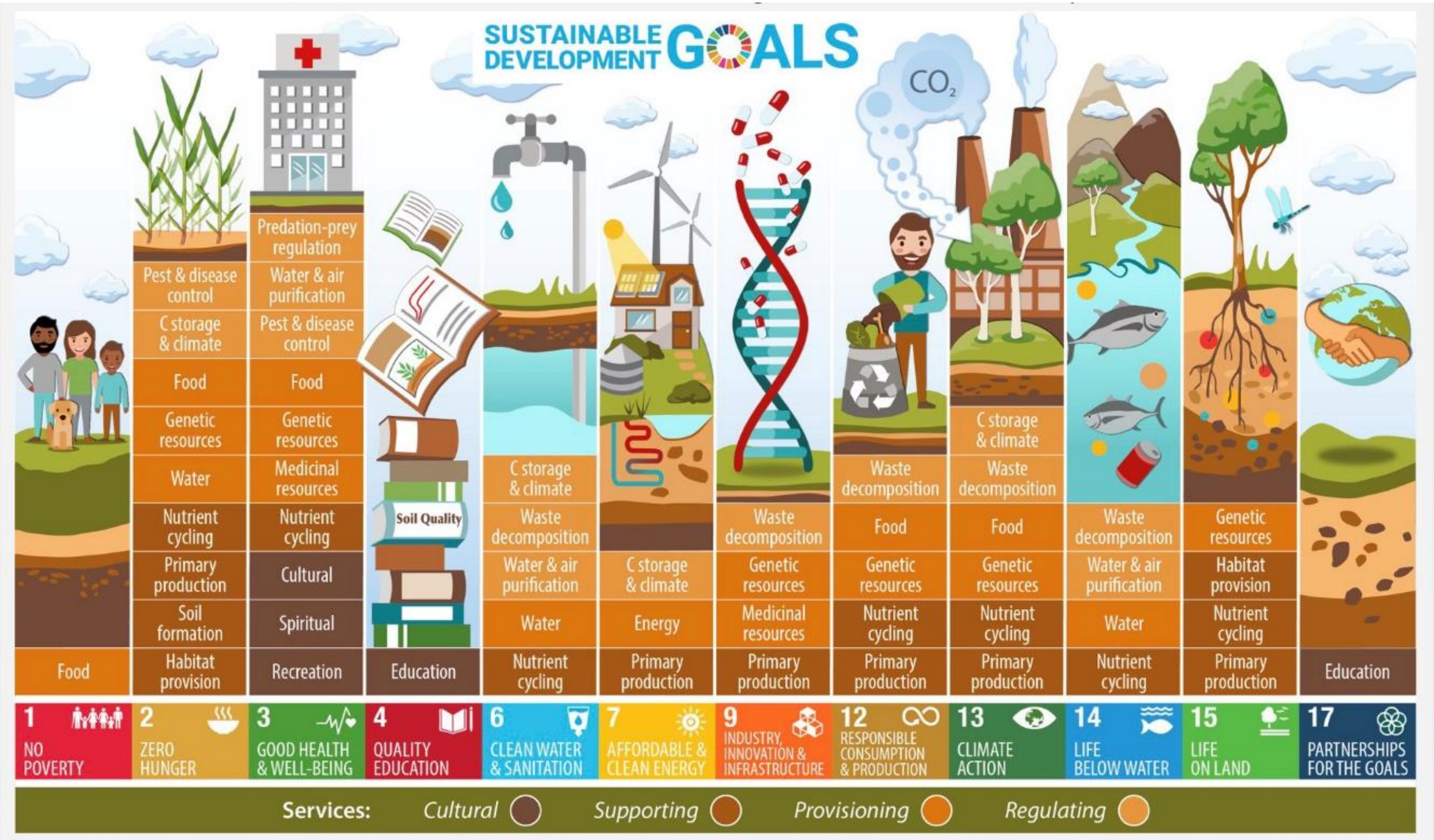

Figure 2. The role of soil functions in supporting at least 12 of the 17 sustainable development goals (SDGs) of the United Nations.

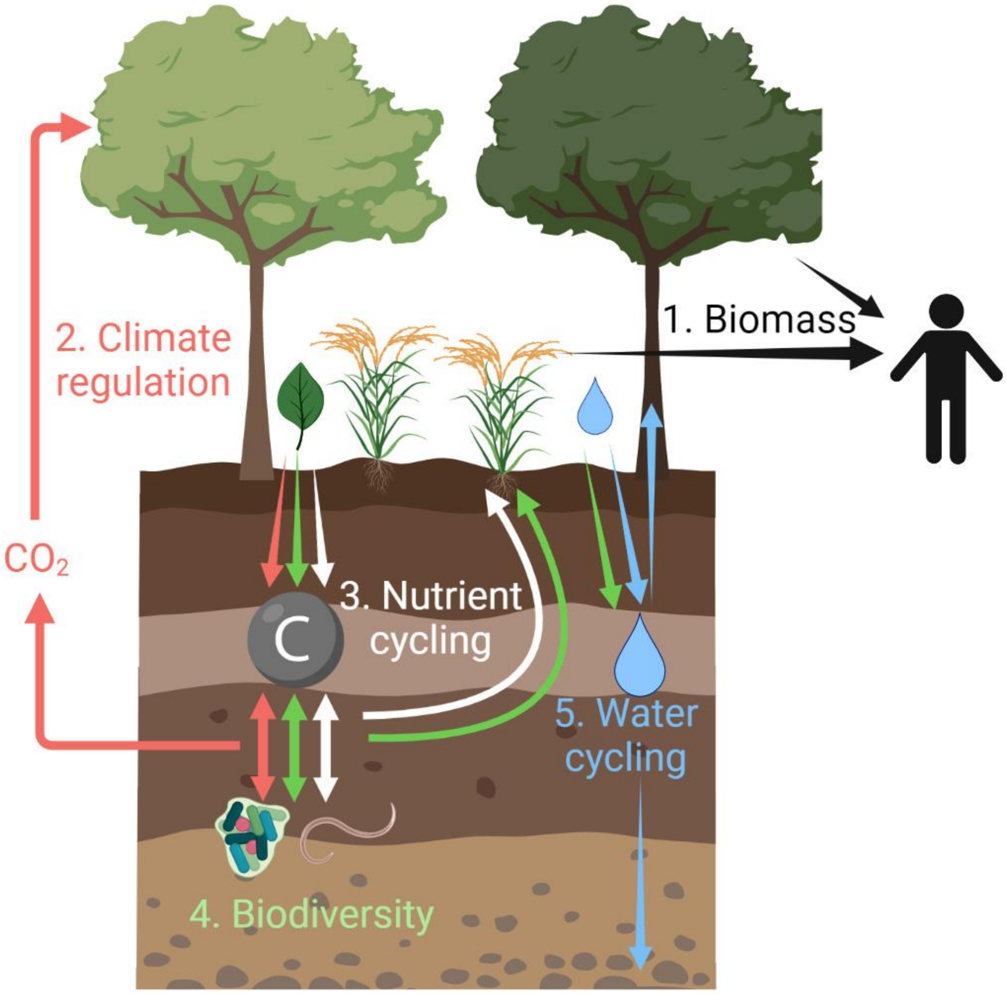

Figure 3. A simplified diagram illustrating the five interconnected key dimensions describing soil multifunctionality, being (1) provision of biomass (black), (2) climate regulation (red), (3) nutrient cycling (white), (4) biodiversity (green), and (5) water cycling (blue).