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The role of soil in defining planetary boundaries and the safe operating space for humanity

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ABSTRACT

We use soils to provide 98.8% of our food, but we must ensure that the pressure we place on soils to provide this food in the short-term does not inadvertently push the Earth into a less hospitable state in the long-term. Using the planetary boundaries framework, we show that soils are a master variable for regulating critical Earth-system processes. Indeed, of the seven Earth-systems that have been quantified, soils play a critical and substantial role in changing the Earth-systems in at least two, either directly or indirectly, as well as smaller contributions for a further three. For the biogeochemical flows Earth-system process, soils contribute 66% of the total anthropogenic change for nitrogen and 38% for phosphorus, whilst for the land-system change Earth-system process, soils indirectly contribute 80% of global anthropogenic change. Furthermore, perturbations of soils contribute directly to 21% of climate change, 25% to ocean acidification, and 25% to stratospheric ozone depletion. We argue that urgent interventions are required to greatly improve soil management, especially for those Earth-system processes where the planetary boundary has already been exceeded and where soils make an important contribution, with this being for biogeochemical flows (both nitrogen and phosphorus), for climate change, and for land-system change. Of particular importance, it is noted that the highly inefficient use of N fertilizers results in release of excess N into the broader environment, contributes to climate change, and results in release of ozone-depleting substances. Furthermore, the use of soils for agricultural production results not only in land-system change, but also in the loss (mineralization) of organic matter with a concomitant release of CO_2 contributing to both climate change and ocean acidification. Thus, there is a need to markedly improve the efficiency of fertilizer applications and to intensify usage of our most fertile soils in order to allow the restoration of degraded soils and limit further areal expansion of agriculture. Understanding, and acting upon, the role of soils is critical in ensuring that planetary boundaries are not transgressed, with no other single variable playing such a strategic role across all of the planetary boundaries.

1. Introduction

The concept of planetary boundaries "defines a safe operating space for humanity based on the intrinsic biophysical processes that regulate the stability of the Earth-system" (Steffen et al. 2015). This framework defines boundaries for anthropogenic perturbation of critical Earth-system processes and thereby assists in reducing the risk that these perturbations could drive the Earth to a less hospitable state (Rockstrom et al. 2009; Steffen et al. 2015). This framework is of particular importance given the global nature of our current society coupled with our unprecedented capacity to cause change, with this having implications for the entire planet. This is largely in contrast to the historical situation where localized environmental degradation often (but not always) caused harm only to those societies within that particular region. Furthermore, the rapidly increasing human population has resulted in a marked increase in the scale of environmental degradation.

Within the planetary boundaries framework, nine individual boundaries are considered, with these being: climate change, biosphere

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integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows (both N and P), land-system change, freshwater use, atmospheric aerosol loading, and the introduction of novel entities. Of these nine boundaries, only seven have been quantified by Steffen et al. (2015), with atmospheric aerosol loading and novel entities not yet able to be quantified. Furthermore, two of these boundaries are considered to be 'core', being climate change and biosphere integrity, with these having potential to drive the Earth into a new state should they be substantially and persistently transgressed (Steffen et al. 2015). All nine of these planetary boundaries defined by Steffen et al. (2015) are dependent upon a complex multitude of factors that drive the various underlying processes. However, it is clear that soil-related factors play a pivotal role.

Despite the importance of soil systems within the planetary boundaries defined by Steffen et al. (2015), there remains much unknown regarding soil functioning, with this limiting our ability to manage soil in such a manner as to reduce the likelihood of transgressing the soil-related planetary boundaries. Leonardo Da Vinci famously stated, "We know more about the movement of celestial bodies than about the soil underfoot". This is perhaps not necessarily surprising, given that soils are one of the most complex and diverse ecosystems in the world, hosting a quarter of the planet's total biodiversity (Bach and Wall 2017).

Although not the core focus of the present study, it is important to note that soils are essential to the survival of humanity, providing 98.8% of human calories as well as wood and fibre (FAO, 2020). In addition, soils provide a wide range of other ecosystem services such as, filtration of nutrients and contaminants, and storage of carbon and regulation of greenhouse gases (Dominati et al. 2014). The total value of these ecosystem services provided by soils has been estimated to be US$11.4 trillion (McBratney et al. 2017). Accordingly, these diverse services provided by soils are central to ensuring global food security, with this forming part of the United Nations sustainable development goals (SDGs) (Bouma et al. 2019). As a result of this, the services provided by soils are under increasing threat, with soils under pressure to provide 70% more food globally between 2005 and 2050 as a result of a rapidly growing human population and changing diets (ELD 2015; Glæsner et al. 2014; Kopittke et al. 2019).

The aim of the present study is to use the planetary boundaries framework to determine the contribution of soil-related processes to anthropogenic perturbations of critical Earth-system processes. This study complements others that have focussed on examining the complex problem of how to increase food production from soils (in order to meet the SDGs, for example) without causing soil degradation and without impacting on soil functioning (Bouma et al. 2019; Glæsner et al. 2014; Kopittke et al. 2019). Indeed, as we identify later, it is often this use of soils to produce increasing amounts of food for humanity that is causing the planetary boundaries to be exceeded, thereby threatening the very hospitability of the entire Earth itself. Our study also value-adds to existing information on planetary boundaries, such as the study of Campbell et al. (2017) who examined the contribution of the entire agricultural system to the anthropogenic perturbation of critical Earth-system processes using the planetary boundaries framework. Here, however, we focus on a specific ecosystem – soil.

Of the seven boundaries that have been quantified by Steffen et al. (2015), we discuss the five control variables to which soil makes a contribution, either directly or indirectly, with soil having a substantial impact for at least two of these control variables. In addition, we discuss a sixth control variable for which soil makes a contribution, but the magnitude of which is currently difficult to quantify. After quantifying the contribution of soils, we discuss the safe operating space for each boundary and consider whether these soil-related processes contribute to our transgression of any boundaries. Accordingly, we also discuss how we can make changes to the way in which we manage soil systems to reduce the likelihood of transgressing the relevant planetary boundaries. Thus, the focus of the present study is on mitigation rather than adaptation. Also, we recognize that there are a range of approaches that are not soil-related that can be used to reduce the likelihood of transgressing the planetary boundaries, such as reducing consumption, changing diets, or reducing wastage (West et al. 2014), but such approaches are beyond the scope of the present study. Soil is critical for the sustenance of humanity, therefore it is not possible for us to cease using soil for food production. However, it is hoped that the present study encourages further discussion as to how we can manage soils more efficiently so that we do not trespass the boundaries, with this being essential for ensuring that the Earth is not pushed into a less hospitable state.

2. Methods

We used the planetary boundaries framework as defined by Steffen et al. (2015). In this framework, nine individual boundaries have been considered, being climate change, biosphere integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows (both N and P), land-system change, freshwater use, atmospheric aerosol loading, and the introduction of novel entities. However, two of these boundaries have not been quantified by Steffen et al. (2015), being atmospheric aerosol loading and novel entities – these two boundaries are not considered in the present study.

For each of the seven planetary boundaries quantified by Steffen et al. (2015), we aimed to determine the role of soil in regulating critical Earth-system processes. To do this, we first considered the control variables that Steffen et al. (2015) used to assess the Earth-system processes. Where control variables had been defined by Steffen et al. (2015) at both the global and regional levels, we focussed primarily on the global values. Thereafter, we used literature estimates and mass balances to estimate the contribution of soil processes to global impacts. For six of the planetary boundaries that were quantified by Steffen et al. (2015), the control variables used and the calculations performed are listed in the relevant parts of the *Results and discussion* section. Although Steffen et al. (2015) also examined the freshwater use Earth-system process, we did not quantify the role of soil for this planetary boundary.

3. Results and discussion

3.1. Biogeochemical flows – Nitrogen

3.1.1. Quantifying the role of soil for nitrogen flows

Understanding and regulating the biogeochemical flows of N are important given that excessive N levels cause eutrophication of water bodies, contribute to climate change through the release of N_2O as a greenhouse gas, and contaminate drinking waters by NO_3^-. Within the planetary boundaries framework, the control variable for the biogeochemical flows of N is defined as being the "industrial and intentional biological fixation of N" (Steffen et al. 2015) with this being the sum of the reduced N from both the industrial fixation of N (the Haber-Bosch process) plus intentional (anthropogenic) biological N fixation (de Vries et al. 2013). Thus, this excludes any of the unintended N fixation due to emission of N oxides from transport and industry (i.e. from combustion). When determining the role of soils for industrial and intentional biological N fixation, we calculated the total proportion of this N which is applied to soils where this N is highly mobile and contributes to eutrophication of the environment.

For the year 2020, it is estimated that the Haber-Bosch process produced 109 Tg N for fertilizers and 41 Tg N for other purposes (mostly as a feedstock for industrial processes) (FAO, 2019). In addition to anthropogenic fertilizer production using the Haber-Bosch process, the use of N-fixing crops in agriculture is estimated to contribute 60 Tg N per year through soil cycling (Fowler et al. 2013). Thus, total anthropogenic production of reactive (reduced) N to the Earth-system for intended human fixation purposes is estimated to be 210 Tg N per year, of which 169 Tg N per year (80%) is used in agricultural production. Of this 169 Tg N per year used for agricultural production, this is either applied directly to soil (as is the case for almost the entire 109 Tg N used for fertilizers) or is partially returned to soils (as is the case for the 60 Tg N per year for N-fixing crops, with the N in some of the plant tissues of the N-fixing crops directly exported in the harvestable product whilst the N in the remaining non-harvestable plant tissues is returned to the soil). As a conservative estimate, if we assume that all legumes grown in agricultural systems have the harvestable portion exported (which is conservative because legumes are also grown in situations where the entire plant biomass is returned to the soil, such as in cover crops), then this would represent the removal of ca. 50% of the N fixed by legumes in agriculture. This is based upon the assumption that the N harvest index, averaged across a wide range of conditions and legume crops, is ca. 50% (Peoples and Craswell 1992). This suggests that a minimum of 50% of the 60 Tg N per year for N-fixing crops is returned to soils (30 Tg N per year). Thus, the total anthropogenic N applied to soils is likely at least 139 Tg N per year, representing a minimum of 66% of the 210 Tg N per year of the anthropogenic production of N added to the Earth-system for intended human fixation purposes (Table 1 and Fig. 1).

3.1.2. *The safe operating space for N and opportunities to improve efficiency of N use in soils*

For the control variable "industrial and intentional biological fixation of N", Steffen et al. (2015) define a planetary boundary of 62 Tg N per year, with a zone of uncertainty of 62–82 Tg N per year, and with the current value of the control variable being 150 Tg N per year (in the present study we determined a value of 210 Tg N per year). Above, we calculate the total anthropogenic N applied to soils to be at least 139 Tg N per year, being a minimum of 66% of the 210 Tg N per year of the anthropogenic production of N added to the Earth-system for intended human fixation purposes. Thus, the soil-related contribution of N (139 Tg N per year) is in itself more than double the planetary boundary (62 Tg N per year). It is clear that urgent action must be taken to profoundly reduce the quantity of N applied to soils through the industrial and intentional biological fixation of N.

Whilst it is not possible to eliminate the use of N fertilizers in agricultural systems given that they feed half of the global population (Erisman et al. 2008), there is an utmost need to improve the efficiency of their usage. Indeed, global N use efficiency has decreased from 68% in 1961 to 47% in 2010 (Lassaletta et al. 2014). Thus, more than half of the N added to soils is lost into the broader environment.

Given that the N use efficiency from soils is currently ca. 50% or lower, there is considerable opportunity to increase the efficiency of N additions to soils. The main pathway to improve N use efficiency, and thereby reduce the loss of N from soil, is by more closely matching the supply of N to the demand of the plant (IPCC 2019). This can be achieved either through the use of enhanced efficiency fertilizers, including slow release fertilizers, or through repeated (smaller) applications throughout the growing period. Other approaches that can also improve N use efficiency are to more accurately account for spatial variation in soil N availability (precision agriculture) to more accurately supply fertilizers and to improve fertilizer placement, or through plant breeding approaches for genotypes with higher N use efficiency. Furthermore, although the present discussion has focussed on the global system, special focus needs to be given to specific regions where applications of N fertilizers are comparatively large and where N use efficiency is markedly lower than the global average, including parts of China and India for example (Mekonnen and Hoekstra 2015; Mogollón et al. 2018). That N use efficiency is currently so low (ca. 50%) also suggests that N fertilizers are too cheap relative to other inputs and that there lacks an incentive for farmers to maximize the N use efficiency. It is also important to note that improving the N use efficiency has also been identified as being critical to prevent soil degradation through acidification, which in turn is important for increasing food production (Dashuan and Shuli 2015; Kopittke et al. 2019).

Table 1
Contributions of soils to six of the seven planetary boundaries that were quantified by Steffen et al. (2015).

	Soil-related contribution (%)
1. Biogeochemical flows (N)	66
1. Biogeochemical flows (P)	38
2. Climate change	21
3. Ocean acidification	25
4. Stratospheric ozone depletion	25
5. Land-system change	80 (indirect)
6. Biosphere integrity	?

Although increasing the N use efficiency from the current value of ca. 50% would make very important contributions to lowering N fixation to levels that are closer to the planetary boundary, this in itself would not be sufficient to move below the planetary boundary. Rather, we must also examine other opportunities to reduce rates of N fixation that are not related to soils, such as by closing the loop and recovering N from the wastewater process to allow its reuse in agricultural production systems (Beckinghausen et al. 2020).

3.2. *Biogeochemical flows – Phosphorus*

3.2.1. *Quantifying the role of soil for phosphorus flows*

Release of P into the broader environment not only results in potential eutrophication of freshwater bodies but could also potentially cause an ocean anoxic event that could result in a large-scale, mass extinction of marine life. Thus, the global control variable is defined by Steffen et al. (2015) as the P flow from freshwater systems into the ocean, whilst the regional variable is the P flow from fertilizers to erodible soils. Following the framework of Steffen et al. (2015), we focus on the flow of P into freshwater systems (which eventually flow into the ocean), and hence we calculate the contribution of P fertilizers applied to soils in agriculture to total global P flows to freshwater systems.

Even more so than for N, the global use of P is dominated almost entirely by its use for agricultural production through the addition of P fertilizers to soils. Indeed, in 2020, it is estimated that global supply of P is 22.0 Tg P of which 20.7 Tg P (94%) is for fertilizers (FAO, 2019), and this is applied directly to soils almost in its entirety (Carpenter and Bennett 2011). Accordingly, using the framework of Steffen et al. (2015), the total anthropogenic P applied to soils is estimated to be 20.7 Tg P per year, accounting for 94% of the total added to the Earth-system. Of this, contributions from agricultural soils is 38% of the total anthropogenic flow of P into waterbodies, with the domestic sector accounting for 54% and industry for 8% (Mekonnen and Hoekstra 2018). Thus, whilst soils account for 94% of the total added to the Earth-system, their actual direct contribution to anthropogenic flow of P into waterbodies is calculated to be at least 38% (Table 1 and Fig. 1).

3.2.2. *The safe operating space for P and soil-based opportunities to reduce flows of P to waterbodies*

For the global control variable of "P flow from freshwater systems", Steffen et al. (2015) define a planetary boundary of 11 Tg P per year, with a zone of uncertainty of 11–100 Tg P per year, and with the current value of the control variable being 22 Tg P per year. Thus, the current value of the control variable is double the value for the planetary boundary, and hence action must be taken to reduce the movement of P into waterbodies. Given that we calculate that 38% of the total anthropogenic flow of P into waterbodies is soil-related, there is an important role for soil to play in ensuring that the Earth-system is not destabilized. However, between 2002 and 2010, anthropogenic P loads to freshwater systems from agricultural soils increased by 27% (Mekonnen and Hoekstra 2018), highlighting the need for urgent intervention.

Given that P binds strongly with the solid-phase in most soils, it is the erosion of soils that is generally the principle source of P to surface freshwaters. In this regard, management of P flows typically differs markedly from N. Thus, there are two critical factors for reducing P flows to waterbodies from soil, being (i) to optimize P fertilizer use,

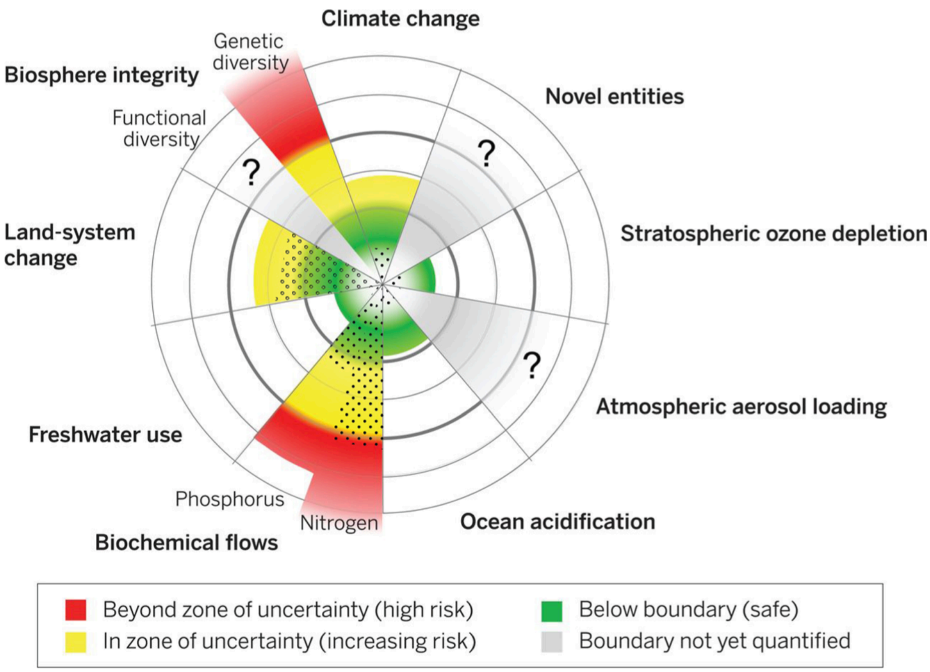

Fig. 1. The contribution of soils to the planetary boundaries defined by Steffen et al. (2015), with green being the safe zone (below the boundary), yellow being within the zone of uncertainty (increasing risk), and red being above the zone of uncertainty (high risk). Soils contribute to these control variables either directly (solid circles) or indirectly (hollow circles). Image is modified from Steffen et al. (2015). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

especially in areas where there remains over-fertilization with P compounds such as South Asia and Brazil (Lu and Tian 2017), and (ii) reduce erosion in agricultural systems. In this regard, rates of erosion from croplands are 10–20 times higher (for no tillage) or > 100 times higher (conventional tillage) than natural values (IPCC 2019). Of utmost importance in this regard is the retirement of marginal and degraded soils from productive use in order to restore the landscapes. Marginal soils typically make small contributions to production but contribute greatly to degradation. Reducing erosion is also critical for decreasing soil degradation in order to maximize food production, with an estimated 20–30 Gt of soil lost per year and with the nutrients lost through the erosion of fertile soil being equivalent to the loss of US$33–60 billion for N and US$77–140 billion for P (FAO and ITPS, 2015).

It is also important to note, however, that it is clear that interventions that are not related to soil also need to be considered in terms of the planetary boundary given that agricultural soils account for 38% of the total. Of particular importance is the need for increased removal of P in the wastewater treatment process (Mekonnen and Hoekstra 2018).

3.3. *Climate change*

3.3.1. *Quantifying the role of soil in climate change*

Climate change is considered by Steffen et al. (2015) to be one of the two ‘core boundaries’. This is because if the boundary is “substantially and persistently” transgressed, it has the potential to drive the Earth-system into a new state (Steffen et al. 2015). For the climate change Earth-system process, Steffen et al. (2015) uses two control variables, being the atmospheric carbon dioxide (CO_2) concentration and the energy imbalance at top-of-atmosphere (i.e. the change in radiative forcing) relative to preindustrial levels. We focussed on the control variable that is the energy imbalance at top-of-atmosphere (i.e. the change in radiative forcing) relative to preindustrial levels, with Steffen et al. (2015) considering this to be more stringent. Here, we consider CO_2, nitrous oxide (N_2O), and methane (CH_4), with soils being intrinsically linked to anthropogenic emissions of these three gases

Carbon dioxide is the most important greenhouse gas, having made the largest contribution to the energy imbalance at top-of-atmosphere [1.8 W m^{-2} from a total of a 2.8 W m^{-2} increase due to greenhouse gases, being 64% of the total (Myhre et al. 2013)]. Soil simultaneously acts as both a source and a sink of CO_2 and thus plays a critical role in climate change (IPCC 2019). Soils release anthropogenic greenhouse gasses through three broad pathways, with all being related to their use for agricultural production. The first is that soils contribute to the release of CO_2 through land-use change. Soils are an important reservoir of organic C, storing ca. 2344 Pg of organic C (OC) within the surface 3 m (ca. 1500 Pg C in the surface 1 m) (Scharlemann et al. 2014), with this value exceeding that in the atmosphere (875 Pg C in 2019) and vegetation (600 Pg C) combined. It is well known, however, that long-term cropping can reduce soil OC concentrations by 30–60% (Kopittke et al. 2017; Murty et al. 2002). Accordingly, the release of CO_2 from soils due to land-use change and the loss of soil OC resulted in the release of ca. 133 Pg of C, primarily in the last 200 y (Sanderman et al. 2017). In contrast, the estimated total global cumulative release of CO_2 from fossil fuel consumption, cement production, flaring, and land-use change between 1750 and 2010 was 540 Pg of C (1980 Pg CO_2) (IPCC, 2014). Thus, release of CO_2 from soil OM during land-use change accounted for ca. 25% of total cumulative release of CO_2 during that period. Thus, given that the total increase in radiative forcing due to greenhouse gas emissions is +2.8 W m^{-2}, of which CO_2 accounts for + 1.8 W m^{-2} (64% of the total), we calculate soils account for 16% of the total increase in radiative forcing due to anthropogenic increases in greenhouse gases.

The second major pathway whereby soils contribute to greenhouse gas emissions is through the release of nitrous oxide (N_2O). When calculated as the increase in radiative forcing, of the total of +2.8 W m^{-2} increase in radiative forcing due to greenhouse gas emissions, +0.17 W m^{-2} is due to N_2O (i.e. 6.1% of the total is due to N_2O) (Myhre et al. 2013). The release of N_2O from soils results primarily from the addition of inorganic N fertilizers and the application of animal manure to soil (IPCC, 2014). Indeed, soils account for ca. 60% of total N_2O emissions (Tian et al. 2019), and thus account for a total of 3.7% of the total increase radiative forcing due to greenhouse gases.

The third important pathway whereby soils contribute to anthropogenic greenhouse gas emissions is through methane (CH_4) emissions. Methane is an important greenhouse gas – when calculated as the increase in radiative forcing, of the total of + 2.8 W m^{-2} increase in radiative forcing, +0.48 W m^{-2} is due to CH_4 (i.e. 17% of the total is due to CH_4) (Myhre et al. 2013). Soils contribute to CH_4 emissions primarily through emissions from waterlogged soils, such as rice paddies (Jiang et al., 2019). It is estimated that the total anthropogenic emissions of CH_4 are 331 Tg per year, with soils accounting for 28 Tg CH_4 per year (Kirschke et al. 2013). Thus, the contribution of soils to the total anthropogenic CH_4 emissions is 8.5%, and thus account for a total of 1.4% of the total increase in radiative forcing due to greenhouse gases.

Overall, we thereby estimate the contribution of soils to greenhouse gas emissions as being ca. 21% (Table 1 and Fig. 1), consisting of a 16% contribution to the total increase in radiative forcing due to greenhouse gases emissions due to the loss of OM from historical and ongoing land-use change, plus 3.7% due to N_2O emissions from soils during agricultural production, plus 1.4% due to CH_4 emissions from soil systems.

3.3.2. The safe operating space for climate change and management of soils for better climate outcomes

For climate change, Steffen et al. (2015) define the planetary boundary using the energy imbalance at top-of-atmosphere as being + 1.0 W m^{-2}, with a zone of uncertainty of + 1.0 to 1.5 W m^{-2}, and with a current net value of + 2.3 W m^{-2}. Although the overall net increase in the effective radiative forcing is + 2.3 W m^{-2} (being a balance of factors that both increase and decrease radiative forcing), the total increase in radiative forcing from greenhouse gas emissions is + 2.8 W m^{-2} (Myhre et al. 2013). Furthermore, it must be noted that the energy imbalance at top-of-atmosphere is currently increasing rapidly, increasing by ca. + 0.27 W m^{-2} per decade for CO_2 alone (Myhre et al. 2013). Thus, as for the biogeochemical flows of N and P, it is clear that we need to rapidly decrease greenhouse gas emissions in order to ensure that the Earth-system is not destabilized. With soils contributing 21% of total greenhouse gas emissions, there is clearly an important role for soils in this regard. However, changes in soil management alone will clearly not be sufficient and must be coupled with other approaches that are not related directly to soils.

To obtain better climate outcomes through altered management of our soils requires two broad approaches. The first broad approach considered here is to minimize, and even reverse, the loss of OM associated with usage of soils for agricultural production. In this regard, the most fertile soils should be identified and agricultural production on these soils intensified (Kopittke et al. 2019). Through this, marginal lands can be restored by removing them from productive agriculture (thus again increasing concentrations of soil OC) – it is these marginal lands where environmental degradation is the greatest and production is the lowest. To further minimize the loss of OM from soils, it is also necessary to manage and restore wetlands and peatlands, with these systems playing critical roles (Prananto et al. 2020). Secondly, management practices should be implemented to reduce disturbance of the soil during agricultural production whilst also increasing the return of organic materials to soils, with this increasing soil OM concentrations. Not only is decreasing the rate of OM mineralization important for decreasing CO_2 emissions, but the loss of OM also decreases inherent soil fertility and thereby making production systems increasingly reliant on fertilizers and decreasing our the ability to produce food (Kopittke et al. 2019).

The second broad approach whereby we can obtain better climate outcomes through altered management of our soils is through the better management of N in soils to reduce N_2O emissions. Of particular importance are synthetic N fertilizers, as it is known the rate of N_2O emissions from soils increases exponentially with increasing N fertilizer rates (Shcherbak et al. 2014). Given that the N use efficiency reduced from 68% in 1961 to 47% in 2010 (Lassaletta et al. 2014), there remains considerable scope to improve N use efficiency, which not only reduces the adverse effects of excess N on the environment (for example, eutrophication, see earlier), but would also reduce the contribution of soils to greenhouse gas emissions through release of N_2O. A discussion regarding suitable approaches for improving the N use efficiency is given earlier. Indeed, the importance of improved N management was highlighted by Griscom et al. (2017) who estimated that improved N management had a maximum additional mitigation potential of 0.19 Pg CO_2e-C/y (706 Tg CO_2e/y), exceeding the value of 0.11 Pg CO_2e-C/y (413 Tg CO_2e/y) for additional soil C sequestration likely through conservation agriculture. Regardless, there remains considerable interest in increasing storage of C within soils to account for that already released to the atmosphere as CO_2, including through the 'soil carbon 4 per mille' initiative which aims to increase global soil organic C stocks by 4 per 1000 (0.4%) per year as compensation for the emission of greenhouse gases (ADEME 2015; Minasny et al. 2017).

Finally, we must also note the overall contribution of soils to greenhouse gases may increase markedly in the future. Of particular importance are the large stores of OC in high latitude soils, including in permafrost. Under an increasingly warming climate, the microbial degradation of this OC will accelerate, resulting in the release of CO_2 and CH_4, and thereby accelerating climate change (Schuur et al. 2015).

3.4. Ocean acidification

3.4.1. Quantifying the role of soil in ocean acidification

For the ocean acidification Earth-system process, the control variable is the carbonate ion concentration, which is related to the average global surface ocean saturation state with respect to aragonite. Ocean acidification is important as it is a threat to coral reefs and other calcifying organisms, and it weakens the marine carbon sink and thereby amplifies the feedback to global warming (Steffen et al. 2015). As noted by Steffen et al. (2015), the ocean acidification boundary is "intimately linked with one of the control variables, CO_2, for the climate change planetary boundary". This is because as atmospheric CO_2 concentrations increase this causes a direct increase in the carbonic acid concentration in seawater, with this lowering the saturation state of aragonite. Thus, changes in atmospheric CO_2 concentrations (as discussed for climate change) are directly and intimately linked to changes in ocean acidification.

Ocean acidification is caused by the increasing emissions of CO_2 to the atmosphere, with oceans absorbing ca. 25% of all CO_2 emissions which forms carbonic acid within the seawater. Given that the control variable for ocean acidification is directly dependent upon the control variable for climate change, much of the prior discussion also applies here. Indeed, as discussed in detail previously for climate change, soils are an important direct contributor of anthropogenic CO_2 emissions – the release of CO_2 from soils due to land-use change and the loss of soil OC resulted in the release of ca. 133 Pg of C (Sanderman et al. 2017) of the total emissions of 540 Pg of C (IPCC, 2014). Thus, as calculated earlier, the release of CO_2 from soil OM during land-use change accounts for ca. 25% of total cumulative release of global CO_2. Accordingly, given that ocean acidification is caused directly by increases in atmospheric CO_2 concentrations, and given that soils are responsible for 25% of the total increase in atmospheric CO_2 concentrations, we estimate the contribution of soils to ocean acidification as being 25% (Table 1 and Fig. 1).

3.4.2. The safe operating space for ocean acidification and management of soils for better outcomes

The control variable for ocean acidification, being the average global surface ocean saturation state with respect to aragonite (which is directly related to the carbonate ion concentration and the atmospheric CO_2 concentration), Steffen et al. (2015) define the planetary boundary as being 80% of the pre-industrial aragonite saturation state, with a zone of uncertainty of 80 to 70%, and with a current value of 84%. Thus, the control variable for ocean acidification currently remains below the boundary and in the 'safe' zone. However, given that atmospheric CO_2 concentrations continue to increase rapidly (see earlier), there is a need to act to ensure that this boundary is not transgressed. With soils accounting for 25% of the total cumulative release of global CO_2, there is a clear role for soils in this regard.

As outlined earlier, it is possible to manage soils more efficiently in order to minimize, and even reverse, loss of OM associated with the use of soils for agricultural production. This includes the removal of marginal lands from production in order to allow the re-accumulation of OM within these soils, as well as the implementation of practices to reduce disturbance of the soil whilst increasing the return of organic compounds, with these measures increasing accumulation of OM in soils (Kopittke et al. 2017).

3.5. Stratospheric ozone depletion

3.5.1. Quantifying the role of soil in stratospheric ozone depletion

Stratospheric ozone is critical for life, with stratospheric ozone absorbing ultraviolet radiation from the sun. The control variable for stratospheric ozone depletion is defined by Steffen et al. (2015) as being the ozone concentration, expressed in Dobson units (DU). Whilst anthropogenic production of halocarbons were largely phased-out following the Montreal Protocol in 1987, N_2O is another ozone-depleting substance that is examined here.

With anthropogenic production of halocarbons largely phased-out, the increasing emissions of anthropogenic N_2O has now become the most important of the ozone-depleting substances (Ravishankara et al. 2009). Given that soils are responsible for at least 50% of the total global anthropogenic flux of nitrous oxides through the addition of synthetic N fertilizers and animal manure to soils (Shcherbak et al. 2014), soils play a critical role in the ongoing emissions of ozone-depleting substances. In the assessment of Ravishankara et al. (2009), the ozone-depleting potential weighted emission of N_2O accounted for ca. 42% of the total. Assuming that soils account for ca. 60% of the total global anthropogenic flux of N_2O (Tian et al. 2019), then the contribution of soils to the current and ongoing emissions of ozone-depleting substances is 25% (Table 1 and Fig. 1).

3.5.2. The safe operating space for stratospheric ozone depletion and management of soils for better outcomes

For stratospheric ozone depletion, the boundary is defined by Steffen et al. (2015) as being a 5% reduction (to 275 DU) from the pre-industrial level (300 DU) when assessed by latitude. This boundary is currently only transgressed over Antarctica in the austral spring, reaching 200 DU, with ozone concentrations expected to increase over the coming decades due to the phase-out of ozone-depleting substances (Chipperfield et al. 2017). Thus, although the contribution of soils to the current and ongoing emissions of ozone-depleting substances is 25%, this is not currently expected to cause the stratospheric ozone depletion boundary to be transgressed. Nevertheless, care must be taken, especially given that N_2O is an important greenhouse gas and given that the biogeochemical flows of N already greatly exceed the planetary boundary. Indeed, given that (i) N use efficiency was 47% in 2010 (Lassaletta et al. 2014). and (ii) the rate of N_2O emissions from soils increases exponentially with increasing N fertilizer rates (Shcherbak et al. 2014), there remains considerable opportunity to reduce N_2O emissions through more efficient N management in agricultural soils. Of paramount importance is the need to better synchronize supply with crop demand (IPCC 2019). Increased efficiency in N management in agricultural soils would thus not only decrease emissions of ozone-depleting substances, but decrease emissions of greenhouse gases and improve the biogeochemical flows of N in the broader environment.

3.6. Land-system change

3.6.1. Quantifying the role of soil in land-system change

Changes in land-systems have a wide range of inter-connected effects, with changes in land-systems being directly connected to the two core planetary boundaries (climate change and biosphere integrity). When considering land-system change, the control variable is the area of forested land as a proportion of original forest cover. This land-system change boundary of Steffen et al. (2015) focusses on the biogeophysical processes in land systems that directly regulate climate, and hence the focus is on forest cover.

The main driver of land-system change is agriculture, with croplands accounting for ca. 1600 million ha (12% of the total ice-free land) in 2017 whilst permanent meadow and pasture account for a further ca. 3300 million ha (25% of ice-free land) (FAO, 2020). Given that the control variable of Steffen et al. (2015) is defined as the amount of forest cover remaining, it is also necessary to determine the contribution of agriculture to deforestation. This is difficult to determine historically, but recent estimates of deforestation suggest that agriculture accounts for 80% of deforestation worldwide (Hosonuma et al. 2012), being a similar proportion since at least the 1980s (Geist and Lambin 2001).

Given that agriculture accounts for 80% of deforestation, we contend that soils are the indirect driver of this deforestation. This is because agriculture is substantially reliant on the properties of the underlying soil to produce food (i.e. the supply of nutrients and water), with soils producing 98.8% of food worldwide (FAO, 2020).

3.6.2. The safe operating space for land-system change and management of soils for better outcomes

For land-system change, the planetary boundary (forest cover) has been set at 75% with an uncertainty of 75–54%, with the current value of the control variable being 62% (Steffen et al. 2015). As a result, the current status of the control variable is that it is within the zone of uncertainty and hence is an increasing risk. Certainly, with soils (and the ecosystem services directly provided by soils) being the driver for 80% of deforestation, it is clear that urgent action is required to prevent this boundary from being transgressed.

It is clear that in order to reduce rates of land-system change whilst simultaneously producing more food, we require intensification of agricultural production on the most fertile of the soils already used for production rather than expanding the area used for production (Kopittke et al. 2019). In particular, through intensification of production on the most fertile soils, not only does this reduce the need for further land-system change, but it also enables the removal of marginal soils from existing production so that they can be restored. Whilst some increases in food production in the future are expected to come from yield growth rather than area expansion, this is not the case for all regions. For example, although wheat yields are projected to increase by 11% by the year 2026, the area used to produce wheat is expected to increase by only 1.8% (OECD/FAO, 2017). In a similar manner, 93% of the expected increase in rice production is anticipated to be from yield growth rather than area expansion. However, in sub-Saharan Africa and in Latin America, area expansion for agriculture is projected to remain significant (OECD/FAO, 2017), with this having important implications for the land-system change boundary. In this regard, it is imperative that a proactive approach be taken to prevent the planetary boundary from being transgressed.

3.7. Biosphere integrity (genetic diversity)

Based upon its fundamental significance, biosphere integrity is the second boundary defined by Steffen et al. (2015) as being a core boundary. For example, the loss of ecosystems and their diversity increases risks associated with climate-induced changes in those ecosystems. The biosphere integrity process has two control variables, being genetic diversity and functional diversity, although functional diversity remains unquantified. For genetic diversity, the control variable is defined by Steffen et al. (2015) as being the extinction rate, with the boundary being $<$ 10 extinctions per million species-years. Compared to the background rate of 1 extinction per million species-years, the current rate is estimated to be $>$ 100 extinctions per million species-years.

The loss of biosphere integrity (genetic diversity) is largely associated with the clearing of land for agricultural production. This is because agricultural land accounts for 4,900 million ha (37% of global ice-free land), with agriculture being the largest user of land. Given that agriculture is the largest driver of land-system change, it would follow that it is also largely responsible for loss of genetic diversity. However, at this stage, it is not possible to estimate the contribution of soil, either directly or indirectly, to this loss of genetic diversity. However, it is important to note that soils account for approximately one quarter of the planet's total biodiversity (Bach and Wall 2017). Furthermore, it is known that intensive agricultural production profoundly reduces the complexity of soil food webs and also reduces the mass of soil fauna (Geisen et al. 2019; Tsiafouli et al. 2015). However, given that the control variable defined by Steffen et al. (2015) is the extinction rate, and with a paucity of information regarding soil extinction ecology (Veresoglou et al. 2015), it is not yet possible to define the contribution of soil to this planetary boundary. However, it is clear that soils are a critically important source of biodiversity but that our current management of soils is causing this biodiversity to be lost.

4. Conclusions

Soils are a master variable for regulating the critical Earth-system processes within the planetary boundaries framework, with no other single variable playing such a strategic role across a broad range of the Earth-system processes. Thus, it is imperative that we alter our direct management of soils in order to increase the efficiency of fertilizer usage as well as by intensifying our usage of our most fertile soils in order to allow the restoration of degraded soils and limit further areal expansion of agriculture. More broadly, amongst the interventions that can change our management of soils, we require the usage of social interventions (for example, by changing human diets), agronomic interventions (for example, increasing nutrient use efficiency), legislative interventions (for example, increasing intensification in order to reduce deforestation of marginal soils), as well as educational interventions. Finally, it is essential that humanity acts rapidly to improve our management of soils in order to ensure that the planetary boundaries are not transgressed and that the Earth is not pushed into a less hospitable state – all at a time when pressures on soils are increasing profoundly given that it is predicted that food production must increase by 70% between 2005 and 2050.

CRediT authorship contribution statement

Peter M. Kopittke: Conceptualization, Methodology, Investigation, Writing - original draft, Writing - review & editing. **Neal W. Menzies:** Methodology, Writing - original draft, Writing - review & editing. **Ram C. Dalal:** Methodology, Writing - original draft, Writing - review & editing. **Brigid A. McKenna:** Methodology, Writing - original draft, Writing - review & editing. **Søren Husted:** Methodology, Writing - original draft, Writing - review & editing. **Peng Wang:** Methodology, Writing - original draft, Writing - review & editing. **Enzo Lombi:** Methodology, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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