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# Planetary limits to soil degradation

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Soils are essential to life on Earth but are rapidly degrading worldwide due to unsustainable human activities. We argue that soil degradation constitutes a key Earth system process that should be added to the planetary boundaries framework.

In 2009, the planetary boundaries framework[1] identified nine processes key to Earth system stability, with the aim of finding a safe operating space for humanity within these boundaries. Ever since, scientists, policymakers, and entrepreneurs have used this framework to help achieve global sustainability[2]. Yet four planetary boundaries have already been crossed and there is a threat of reaching a state of severe environmental change[2]. Although strongly interlinked with other Earth system processes, such as land-system change, the crucial role of soil in water, energy, and biogeochemical cycles[3,4] is not explicitly recognized by the current framework. Soil, the ~1-m-thick layer of biogeochemically altered rock and sediment at Earth's surface[5], provides essential ecosystem services[3], such as producing 98.8% of our food[6] and hosting ~25% of Earth's biodiversity[7]. Based on the current evidence, we argue that soil degradation should be considered the 10th Earth system process in the planetary boundaries framework.

## Resilience versus degradation

Healthy soils have a degree of resilience that allows them to maintain structure and function in the face of repeated disturbance[8,9], including temperature perturbation[10], compaction[11] and copper pollution[12]. They provide essential ecosystem services[3] such as food production and can help us achieve several Sustainable Development Goals, including zero hunger, clean water and sanitation, life on land, flood regulation, and conservation of biodiversity[13]. However, human-induced degradation, such as soil erosion, contamination, and loss of soil organic carbon (Fig. 1), is compromising soil resilience[3,14]. Population growth, unsustainable agricultural practices, deforestation, industrial development, urbanization, and increasingly climate change pose the greatest threats to healthy soils[3,14,15]. Once disturbed beyond a critical level, soils are at risk of entering a downward spiral towards an alternative, degraded state[9,14]. This degraded state is characterized by a loss of soil functions and services including the ability to provide food for humanity and sustain human life on Earth[14,16]. As soil restoration is a slow process, soil is often considered a non-renewable resource[6,9,14,15].

The downward spiral of soil degradation is fueled by soil threats that are strongly interrelated and linked through powerful feedback loops. On a local scale, loss of soil structure due to compaction by heavy machinery or intensive grazing results in loss of soil biota and soil functioning and further degradation[17]. On a global scale, there is a strong positive feedback loop between soil erosion and climate change. Soil erosion causes a loss of soil organic carbon as carbon dioxide to the atmosphere, contributing to global warming[14]. Warmer conditions then drive increases in rainfall intensity, wind speed, and wildfire, all of which can increase soil erosion[14,18].

A degraded soil state is not uncommon in human history. The fall of past civilizations has been linked to societies' poor protection of soil health[19]. Among these, the Sumerian civilization in Mesopotamia was undermined by salinization and upland erosion[19], while both Ancient Greece

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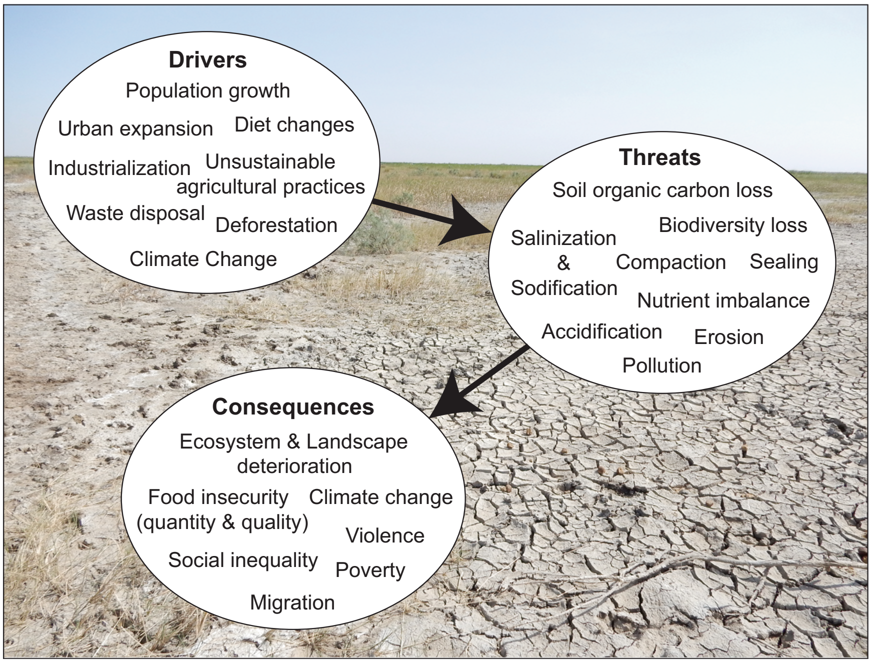


**Fig. 1 Soil degradation.** The process of soil degradation depicted by the main drivers, quantifiable threats and the consequences of soil degradation on planetary and societal health.

and the Roman Empire suffered from widespread, severe soil erosion[19]. Where healthy soils initially enable the growth and prosperity of civilizations, the increased demand for food production and unsustainable agricultural practices result in severe soil degradation. Followed by a decrease in food security and political stability, soil degradation compromises the resilience of civilizations and initiates their collapse[19]. In the past, however, the human population was smaller, more scattered, and less connected than at present[6]. This means that past impacts of soil degradation only undermined local ecosystems and societies. Today, with a human population of 7.9 billion people that is expected to grow to 9.8 billion by 2050 and a strongly globalized world, soil degradation is no longer a local issue[6]. Land degradation is already negatively impacting the wellbeing of at least 3.2 billion people worldwide[20] by decreasing food security and resilience of the landscape to extreme weather events, resulting in an increase in inequality and political instability[15,20]. In the European Union alone, costs related to soil degradation exceed 50 billion euro's a year[15]. On a global scale, soil degradation has also been linked to mass migrations, violence, and armed conflict[19,20]. Soil degradation is estimated to affect 90% of the soils globally by 2050[3], meaning almost all global ecosystems and populations will be directly affected.

## The 10th planetary boundary

Soil is integral to the Earth system processes already portrayed in the planetary boundaries framework[21] (Fig. 2): contributing to 80% of the anthropogenically induced changes in land-systems, 66% in the nitrogen cycle, and 38% in the phosphorus cycle[21]. Although not the main driver, soil degradation also contributes substantially to climate change (21%), ocean acidification (25%), and stratospheric ozone depletion (25%)[21]. In addition, soil degradation is one of the main causes of biodiversity loss worldwide as it severely deteriorates the natural habitats of species[7,14,20]. As a result of the strong interrelation between soil degradation and the Earth system processes present in the framework, transgressing the soil planetary boundary would force other Earth system processes to transgress their boundaries.

Soil degradation shares all key traits with the nine Earth system processes already present in the planetary boundaries framework. It is caused by human activity[3,14], has the potential to cause unacceptable environmental change[14,19], shows tipping point behavior when forced beyond a critical level[9], is relevant on both local and global scales[3,14,19], and is strongly interrelated with the other Earth system processes[21]. Hence, in order to improve the planetary boundaries framework and clearly signal the need to protect the soil, we call for soil degradation to be considered the 10th Earth system process in the planetary boundaries framework.

It is challenging to capture the many forms of soil degradation in just one or two indicators[22]. Earth system processes such as biosphere integrity quantified by measures of functional and genetic diversity[2], land-system change quantified by area of forested land as percent of original forest cover[2] and freshwater use, face the same challenges. Research into improving their indicators is still ongoing. For other processes such as climate change and stratospheric ozone depletion, greater consensus on the preferred indicator(s) has been reached[2]. A strong candidate for a global indicator of the soil planetary boundary could be the percentage change in soil organic carbon calculated from estimated historical soil organic carbon levels predating anthropogenic land-use and present-day soil organic carbon levels[20]. The current lack of consensus on a suitable indicator variable should not prevent soil degradation from being added to the framework. The Earth system processes novel entities and atmospheric aerosol loading also lack an indicator variable and as such has not yet been quantified[1,2] (Fig. 2). Including soil degradation as a 10th Earth system process (Fig. 2), could promote research into a reliable indicator and ensure its quantification within the next revisions of the framework.

The aim of the planetary boundaries framework is to determine a safe operating space for humanity[1,2]. This can only be achieved if all relevant Earth system processes are included and all interrelations are accounted for. At the moment this is not the case as soil degradation is not included in the framework[1,2] despite the fact that soil is one of our most vital and vulnerable natural resources and one of the main drivers of all four Earth system

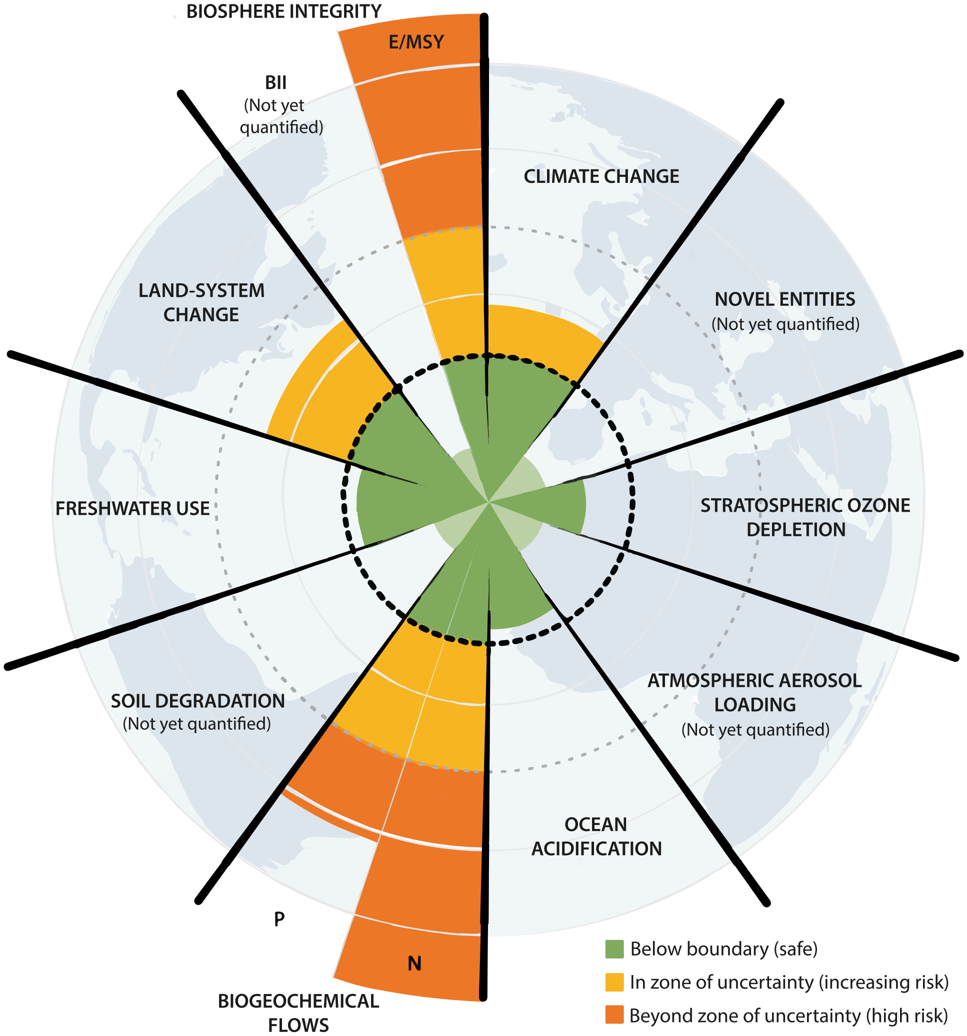


**Fig. 2 Proposed new planetary boundaries framework.** Updated version of the planetary boundaries framework portraying the current nine Earth system processes along with soil degradation as the 10th Earth system process. The small circle (bold dotted line) represents the planetary boundaries. The large circle (regular dotted line) portrays the thresholds. Adapted from the original image of the planetary boundaries framework constructed by J. Lokrantz/Azote based on Steffen et al.[2]. Licensed under CC-BY.

processes that have already crossed their boundaries[3,7,19] (Fig. 2). Based on the proven effectiveness of the planetary boundaries framework in providing common ground for researchers and policy-makers, adding soil degradation as a standalone Earth system process in the framework would help guide humanity towards more sustainable soil stewardship. This would prevent soil degradation from threatening human livelihood by undermining food security and societal stability and forcing the other Earth system processes outside of their safe zones. By giving soil degradation its rightful place and addressing it directly and with the required urgency, we can better achieve the sustainability goals and safeguard life on Earth.

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## Author contributions

C.T.K. and T.D. conceived of the presented idea. C.T.K. wrote the manuscript with support from A.B. and R.A.H. All authors contributed to the final manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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