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Title: Soil processes are constituents of planetary well-being

Year: 2024

Version: Published version

Please cite the original version:

Kataja-aho, S., & Haimi, J. (2024). Soil processes are constituents of planetary well-being. In M. Elo, J. Hytönen, S. Karkulehto, T. Kortetmäki, J. S. Kotiaho, M. Puurtinen, & M. Salo (Eds.), Interdisciplinary Perspectives on Planetary Well-Being (pp. 86-95). Routledge. https://doi.org/10.4324/9781003334002-9

6

SOIL PROCESSES ARE CONSTITUENTS OF PLANETARY WELL-BEING

Saana Kataja-aho and Jari Haimi

Introduction

Soils provide an excellent example of how one part of an ecosystem is both physically and functionally prerequisite for the well-being of all organisms and concomitantly for various interactions between them. Soils are related directly or indirectly to nearly all critical ecosystem processes on Earth. These processes include energy flow, element and water cycles, and interactions between living organisms (Figure 6.1). Hence, soils are closely interlinked with planetary well-being, which refers to the state in which the integrity of the Earth system and of ecosystem processes is unimpaired (Kortetmäki *et al.*, 2021). In addition, soil-centred ecosystem processes demonstrate how fragile and interlinked life-supporting local and global phenomena may be. For example, carbon released in the decomposition of dead organic matter affects the global climate. Understanding the role and functions of soils significantly helps to understand the critical value of planetary well-being for the well-being of all.

What are soils?

Soils form only a thin mantle between the Earth's atmosphere and lithosphere, yet they are integral parts of all terrestrial ecosystems. Synonyms for soil include *dirt*, *dust*, *earth*, *land*, *ground*, *substrate*, *integument of the planet* and *biomantle* (Johnsson and Johnsson, 2010; Oxford English Dictionary, 2021). The term 'soil' is commonly used in its traditional meaning, which Food and Agriculture Organization of the United Nations (FAO) (2021) defines as "the natural medium for the growth of plants". However, the multidimensionality and high variability in space and time make it difficult to define soil unequivocally. Johnsson and Johnsson (2010) summarized the work of soil scientists and ecologists from the last century in the

DOI: 10.4324/9781003334002-9

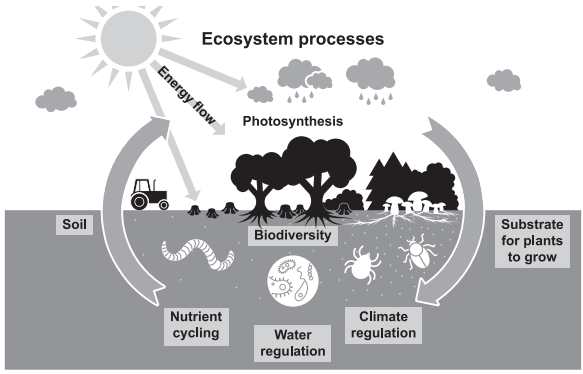

FIGURE 6.1 Significant ecosystem processes related to soil that are a prerequisite for planetary well-being.

following way: "Soil is substrate at or near the surface of Earth and similar bodies altered by biological, chemical, and/or physical agents and processes". Further, the Soil Science Society of America recently agreed on a multifunctional definition for soil: "The layer(s) of generally loose mineral and/or organic material that are affected by physical, chemical, and/or biological processes at or near the planetary surface, and usually hold liquids, gases and biota and support plants" (van Es, 2017; Soil Science Society of America, 2021).

The variability and complexity of the definitions indicate that soils are diverse parts of terrestrial ecosystems. They host multiple functions, but simultaneously appear as a kind of hidden resource. Land covers approximately 29% of Earth's surface and most of it bears some kind of soil (Ritchie and Roser, 2013). Soils have been formed throughout the history of the planet, and although soil formation occurs continuously, it is a slow and diverse process. The quality, quantity, and structure of soil depend on the bedrock quality, topography, climate, and history of the area, including both natural phenomena and human activity (Jenny, 1941). In addition, soil formation is affected by a range of organisms—from microbes and fungi to plants and animals living in the area—and vice versa, meaning soil partly determines which organisms can thrive at a site. Moreover, soils have typically evolved characteristic profiles through interactive climatic, physical, chemical, biological, and landscape processes. As a result, soils consist of mineral materials, dead organic matter of different stages of decay, water and gases in pore spaces, and plant roots, all in varying qualities and quantities (Coleman, Callaham and Crossley, 2018). Together, soils are a precious, non-renewable resource for numerous forms of both human and nonhuman life. The importance of soils has, however, largely been undervalued.

Soil biodiversity

Countless organisms inhabit soils, most of them small (even microscopic) in size. It has been estimated that more than 40% of the present organisms are associated

with soil during their life cycle (Wardle, 2002; FAO *et al.*, 2020). The patchy, heterogenous, and three-dimensional spatial structure of soils offers habitats for most organism groups. The belowground environment provides high variation not only in spatial architecture but also in microclimatic, physical, and chemical properties, and the level of specialization in each organism group can be very high. Countless suitable environmental and ecological conditions (niches) are thus available in soils for sufficiently small organisms. All this has reduced competition for resources between organisms (Bardgett, 2005). Most importantly, the diversity of soil organisms produces a high number of different ecosystem functions (Anderson, 2000).

In addition to their diversity, the abundance and biomass of soil organisms are also high. One gram of soil contains millions of bacterial cells and kilometres of fungal filaments. Correspondingly, millions of protistans and nematodes, hundreds of thousands of mites, tens of thousands of springtails and enchytraeids, and hundreds of earthworms, centipedes, millipedes, spiders, and other arthropods are found in a single square metre of forest and meadow soil (Coleman, Callaham and Crossley, 2018). Most of these organisms are functionally classified as decomposers that feed on dead organic matter and microbes living in that matter. Some of the decomposers are specialized in certain microhabitats and food sources, while others are generalists. All, however, have an important role in soil fertility and element fluxes, which are vital ecosystem processes.

Soils are not only the habitat for microbes and animals that are decomposers, but a myriad of other organisms inhabit soils during a certain part of their life cycles (*ibid.*). Some insects are belowground herbivores during their larval stage and feed on plants' roots or mycorrhiza, a vital symbiotic association of the fungus with the roots of plants. When these insects emerge from the soils, they transfer significant amounts of nutrients to aboveground parts of the ecosystems (Callaham *et al.*, 2000). In addition, many invertebrates and vertebrates nest belowground and even more spend unfavourable periods of the year (such as winter or the dry season) in soil, often in an inactive stage. In cold and cool climates, most pollinators (important for reproduction of myriad green plants including human food plants; see Chapter 5) and aboveground herbivores (a major part of terrestrial biodiversity) overwinter in soil. Without an opportunity to seek shelter belowground they would not be able to survive. In sum, the entire soil fauna is tied to the maintenance of soil functioning and concomitantly to many important ecosystem processes (Coleman, Callaham and Crossley, 2018), and hence, to planetary well-being.

Soil functions

Primary production and energy flow

Soils have multiple functions that stem from their diverse and three-dimensional structure (Figure 6.1). Generally, life on Earth depends on energy derived from solar radiation. Plants, algae, and cyanobacteria absorb energy into organic molecules in

the process of photosynthesis (also called primary production), and nearly all forms of life, including primary producers themselves, utilize those molecules to fulfil biological requirements such as life-supporting reactions, growth, and reproduction. Most terrestrial primary producers take the water and nutrients needed in the synthesis of biomolecules from soils. In addition, soils offer an essential substrate, or the growth platform, for the majority of plants. Soils, therefore, provide vital support for photosynthesis, the ultimate process of life on Earth, and are essential for all heterotrophic organisms. It is seldom understood that half or even more of the net primary production of plants is allocated belowground (Fogel, 1985; Coleman, Callaham and Crossley, 2018). The fine root production, including the root tissues and root secretion into soil, is requisite for many interactions between soil, plants, and microbes. The thin layer around fine roots, the rhizosphere, strongly mediates microbial communities and biogeochemical element cycles that, in turn, affect the life aboveground (McCormack *et al.*, 2015; Coleman, Callaham and Crossley, 2018).

Decomposition of organic matter and nutrient cycling

Because there are limited amounts of nutrients on the planet, at some point dead organic matter should be decomposed and nutrients recycled. Without decomposition processes, the planet would be covered with organic waste and life would soon wither. Nutrient mineralization (the release of nutrients in the form plants can uptake them) is prerequisite for terrestrial primary production and consequently for other organisms at the higher levels of food webs. A keystone of the decomposition of organic matter and nutrient mineralization is the efficient decomposer food web living in soils. The food web consists of a diverse microbial community and soil fauna (Coleman, Callaham and Crossley, 2018; FAO *et al.*, 2020). Decomposer animals can be classified based on their body size, from the smallest protistans (1–2 μm) to the largest earthworms. The body size of soil fauna is directly related to their microhabitat and role in decomposition processes. Many of the smallest decomposer animals are actually aquatic, inhabiting soil water and living in close interaction with microbes. Large decomposers, in turn, feed on soil organic matter with microbes and, at the same time, strongly modify the soil structure (Coleman, Callaham and Crossley, 2018). Moreover, some decomposers feed on dead plant material (*e.g.*, leaf litter). Hence, the decomposer fauna can be grouped according to how they participate in soil processes and soil formation in different spatial scales.

Decomposers form many functional groups and food webs (*ibid.*). Micro-food webs are composed of microbes and their microfaunal predators, such as nematodes and protistans. Microbes are primary decomposers having enzymes to chemically break down even the most recalcitrant substances. Microbes also finally mineralize most nutrients for reuse by plants. Certain nematodes feed either on bacteria or fungi, and regulate the microbe populations, thus indirectly affecting decomposition and nutrient mineralization. Litter transformers are microarthropods, such as

mites and springtails, which chop up dead organic matter and increase the surfaces available for microbes. Ecosystem engineers (organisms that significantly modify or even create their habitat) process the soil habitat by feeding and burrowing activities, such as mixing organic and inorganic materials and affecting soil structure. Earthworms, ants, and termites are often referred to as soil engineers as they significantly modify their habitats. Micro-food webs, litter transformers, and ecosystem engineers operate in the complex soil environment in their own spatial, size and timescales (Wardle, 2002; Coleman, Callaham and Crossley, 2018). All these diverse functional groups contribute to major ecosystem processes such as nutrient cycling, carbon transformation and further to formation and modification of soil structure. In addition, although they live in their own microenvironments, soil organisms strongly interact with the populations of other organisms and eventually affect aboveground biodiversity.

Climate regulation

Nearly 80% of the carbon in Earth's terrestrial ecosystems is found in soils (Lal, 2008; Eglinton *et al.*, 2021). Correspondingly, the soil carbon pool is more than three times larger than that of the atmosphere (Oelkers and Cole, 2008). More than 60% of the soil carbon is organic carbon, dead organic matter at some stage of the decomposition process. The rest is soil inorganic carbon, or elemental carbon and carbonate materials (Lal, 2008). By being the major terrestrial pool of carbon, the soil carbon stock is critical for the global carbon cycle and for regulating Earth's climate (Figure 6.1). Even a small change in the soil carbon pool can cause a large impact on atmospheric CO_2 concentration (Crowther *et al.*, 2016; Bispo *et al.*, 2017). Soil processes also control the emissions and sequestrations of the other significant greenhouse gases, such as methane and nitrous oxide, and release aerosols to the atmosphere. In addition to being the reservoir of carbon, soils with vegetation fix more than a third of anthropogenic carbon emissions to the atmosphere. Further, soils contribute to Earth's radiation balance, either positively or negatively, through evaporation and the albedo of Earth's surface (Lal *et al.*, 2021). Hence, the composition of atmosphere and consequently Earth's climate are strongly related to the structure, composition, and processes of soils.

Water retention and cleaning processes

When rain reaches Earth's surface, the water picks up varying amounts of different impurities, such as particles and chemicals. In rural settings and natural environments, most rainwater infiltrates through the soil. Part of the water is captured along the way down in the soil profile, reserved in soil pore spaces and gradually used by organisms that need water for their metabolism. Water is one raw material in photosynthesis, and nutrients needed in other biosyntheses (such as protein synthesis) are transported into plant tissues in the process of transpiration. As water

passes through the soil profile, it is cleaned physically, chemically, and biologically. Soils with many grain sizes contain a matrix of pores of different sizes and can efficiently filter particles out of the infiltrating water (Figure 6.1). Soil organic matter is, however, the most important in removing impurities from water (Ontl and Schulte, 2012). Most soils are negatively charged and hence they capture positively charged ions from soil water. These ions, inorganic forms of nutrients, are available for uptake by green plants and microbes, and also prevented from leaching into groundwater and surface waters. Many other chemicals are removed from the water as they become adsorbed into soil particles, for example through a process of covalent bonding. Moreover, many bacteria and fungi are capable of transforming and decomposing chemicals dissolved in water with appropriate enzymes. Even harmful anthropogenic organic chemicals, such as pesticides and solvents, can be metabolized by certain microbes (Cravo-Laureau *et al.*, 2017; Pesce *et al.*, 2020). Soils detoxify chemicals and prevent their problematic effects on non-target organisms and processes. In this way, they reserve and purify fresh water, which is a vital process for all terrestrial organisms, including human beings.

Degradation and loss of soils

Human impact on the Earth system is continuously intensifying, and land use for agriculture, livestock farming, and commercial forestry speed up the loss of biodiversity and habitat degradation (Vitousek *et al.*, 1997; Goudie, 2019). Agricultural management practices and intensive forestry have also degraded soils physically, chemically, and biologically, for example, through erosion and loss of organic matter (Kaiser, 2004; Ontl and Schulte, 2012). These substantial changes in soil composition and structure may lead to serious inhibition of soil-driven ecosystem processes.

Soil food webs have been shown to be strongly changed and simplified under more intensive management systems, such as increased use of fertilizers and pesticides, intensified tillage, use of larger and heavier vehicles, and higher grazing pressure (Bardgett, 2005). These changes are associated with increased nutrient leaching and carbon losses from the system. It also seems these changes in the soil food web structure may even be irreversible (*ibid.*). However, the reduction of organic matter losses from cultivated soils by using less intensive management practices and the addition of organic amendments could result in positive development in the abundance and diversity of soil biota and the intensity of soil-mediated ecosystem processes (Ontl and Schulte, 2012). Correspondingly, more sustainable management practices in forestry can increase soil health in forests.

The constantly increasing global population and urbanization have drastically decreased the amount of soil that is organically and functionally part of ecosystems. Globally, huge areas of land have been sealed with artificial impenetrable surfaces for housing as well as for transport, industrial, and commercial infrastructure (Liu *et al.*, 2014). Soil sealing leads to serious interference or total inhibition

of most ecosystem processes that either take place in the soil or are mediated by soils. This is simply because of the lack of fluxes of water, matter, and elements between belowground and aboveground settings and the disappearance of soil–plant interactions. In urbanized areas, water can flow over the sealed soil surface and transport impurities and nutrients to water courses or surface-water drains. The strain on the water systems may result in eutrophication and pollution of streams and lakes and thereby drastically decrease the quality of these water basins as habitat for aquatic organisms such as fishes, mussels, and plankton. Furthermore, water contamination decreases the quality of human drinking water, while large-scale soil sealing permanently disturbs carbon and nutrient cycling in urban areas (Lu, Kotze and Setälä, 2020). Sealed soils also become unavailable as habitats for any organisms, with the exception of a few microbes.

Soil degradation also affects the mitigation of climate change. The fixation of carbon emissions by vegetated soils is endangered because of human-induced environmental change (Eglinton *et al.*, 2021; Lal *et al.*, 2021). Especially, the amount of soil organic carbon is a critical component which controls soil–atmosphere carbon flux and climate change. Air temperature and precipitation significantly affect soil processes and, consequently, soil organic carbon stocks, while climate change may destabilize these stocks. The feedbacks may be large and unpredictable especially in the soils in northern permafrost regions. In addition, soil organic carbon stocks are prone to human land use changes. As a rule, intensive land use (deforestation, industrial agriculture, increasing mining and construction) increases the release of carbon from the soil to the atmosphere. Thus, all actions that minimize anthropogenic soil disturbance can help to restrain climate change. Sequestration of carbon in soils efficiently mitigates changes in the climate and environment that are evolutionarily too rapid.

Concluding remarks

Soils play a crucial role in numerous ecosystem and global processes that enable the existence and well-being of terrestrial organisms, from microbes and fungi to plants and animals, including humans (Figure 6.1). Conversely, those vital processes do not occur with the proper strength and frequency if organisms living in the soil are disturbed in a way that they are unable to play their roles in their communities. Soil organisms and processes, therefore, are an excellent example of how susceptible and fragile the integrity of the Earth system is and how important certain parts of the ecosystem can be for planetary well-being (Kortetmäki *et al.*, 2021). Although human well-being has not specifically been addressed in this chapter, all soil-driven and soil-mediated processes are also essential for human well-being: Soils provide many of the ecosystem services that humankind (regardless of all technological development) still requires (see Chapter 5).

For example, local populations of pollinators in cool regions depend on overwintering in soil, and human practices that degrade or seal soil with impermeable

surfaces harm this overwintering process, which in turn reduces the pollination success of food crops and further decreases food production for both humans and nonhumans. Moreover, the cultivation of food and forage crops requires arable land where soil fertility is maintained by soil structure and processes. If soil in an area is disturbed either physically, chemically, or biologically, vegetation will respond and reciprocally affect soil properties, which undermines beneficial food production conditions, with direct and indirect harmful impacts on human and nonhuman well-being. Soil disturbances that are strong enough and large enough are reflected also at the landscape level.

If human activity steadily and increasingly degrades soils by, for example, decreasing the amount of soil organic matter and changing the soil structure, soils cannot deliver the ecosystem services they used to offer. Human activities that have a strong negative effect on soil health include, for example, deforestation, intensification of agriculture and livestock farming, and the enlargement of urbanized areas. Soil degradation impairs the typical characteristics and capacities of myriad organisms, not only soil decomposers but also those inhabiting soils during a certain part of their life cycles, to the level where ecosystem-level and global processes do not function properly. At that stage, the integrity of the Earth system could be irreversibly lost. When humanity cares for the health of soil, it is also taking care of the well-being of both human and nonhuman organisms and contributing to planetary well-being.

Acknowledgements

We are grateful to the editorial team for their valuable comments on our earlier versions of this chapter, and Matt Wuethrich for language checking. Thanks to Boost project of Janne Kotiaho for supporting the language check. We thank Photogrunskis for the great illustration they prepared for our chapter.

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