

The role of soils in delivering Nature's Contributions to People

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Summary

This special issue provides an assessment of the contribution of soils to Nature's Contributions to People (NCP). The papers in this issue show that soils can contribute positively to the delivery of all NCP. These contributions can be maximised through careful soil management to provide healthy soils, but poorly managed, degraded or polluted soils may contribute negatively to the delivery of NCP. Soils are also shown to contribute positively to the UN Sustainable Development Goals (SDG). Papers in the special issue emphasise the need for careful soil management. Priorities for soil management must include: 1) for healthy soils in natural ecosystems, *protect* them from conversion and degradation, 2) for managed soils, *manage* in a way to protect and enhance soil biodiversity, health, productivity and sustainability and to prevent degradation, and 3) for degraded soils, *restore* to full soil health. Our knowledge of what constitutes sustainable soil management is mature enough to implement best management practices, in order to maintain and improve soil health. The papers in this issue show the vast potential of soils to contribute to NCP. This is not only desirable, but essential to sustain a healthy planet and if we are to deliver sustainable development in the decades to come.

Soils and Nature's contributions to People

Ecosystem services are the many and varied benefits to humans provided by the natural environment and from healthy ecosystems. Previous studies have examined the role of soils in contributing to ecosystem services, showing that soils have a decisive and positive contribution to many (1–5). Recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Global Assessment (6) attempted to contextualise ecosystem services by defining 18 Nature's Contributions to People (NCP) as “all the contributions, both positive and negative, of living nature (i.e., diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to the quality of life of people” (7). NCP and ecosystem services are related, but not precisely parallel concepts (8). The IPBES authors stressed that NCP are a way to contextualise ecosystem services, rather than a replacement for the term. As noted by McElwee et al. (9), NCP was proposed to be a broader umbrella to engage a wider range of disciplines, particularly from the social sciences and humanities, and a diverse range of values around ecosystems (10). Unlike ecosystem services described in the earlier Millennium Ecosystem Assessment (MA, 11), supporting services were no longer considered as separate entities, but many NCP can be mapped onto the MA ecosystem services. Table 1 shows NCP as proposed by IPBES, with the corresponding ecosystem services, as described in the Millennium Ecosystem Assessment, to which they are related.

Table 1. IPBES Nature’s Contributions to people (NCP), with the corresponding Millennium Ecosystem Assessment (MA) ecosystem services and categories shown (13).

NCP category	NCP	MA category	MA ecosystem service
		Supporting service	Soil formation
		Supporting service	Nutrient cycling
		Supporting service	Primary production
Material NCP	Food and feed	Provisioning Service	Food
	Materials and assistance	Provisioning Service	Fibre
	Energy	Provisioning Service	Energy
	Medicinal, biochemical and genetic resources	Provisioning Service	Medicinal products, biotechnical approaches and genetic biodiversity
Non-material NCP	Learning and inspiration	Cultural Service	Aesthetic values
	Supporting identities	Cultural Service	Spiritual and religious values
	Physical and psychological experiences	Cultural Service	Recreation and ecotourism
Regulating NCP	Regulation of climate	Regulating service	Climate regulation
	Regulation of freshwater quantity, flow and timing	Provisioning Service	Water
	Regulation of freshwater and coastal water quality	Regulating service	Water purification and waste treatment
	Regulation of hazards and extreme events	Regulating service	Natural hazard regulation
	Habitat creation and maintenance	Regulating service	
	Regulation of air quality	Regulating service	Air quality regulation
	Regulation of organisms detrimental to humans	Regulating service	Pest regulation and disease regulation
	Pollination and dispersal of seeds and other propagules	Regulating service	Pollination
	Regulation of ocean acidification	Regulating service	Water regulation
Formation, protection and decontamination of soils and sediments	Regulating service	Erosion regulation	
Cross-cutting NCP	Maintenance of options		

The papers in this special issue deal with each of these NCP in turn, except the NCP “Learning and inspiration”, “Supporting identities” and “Physical and psychological experiences” which are dealt with together (12). The final paper in this issue synthesises the findings of previous papers in the issue, examines the cross-cutting NCP “Maintenance of Options”, and examines the extent to which soils contribute to the UN Sustainable Development Goals (SDG) (13). Together, these papers constitute a most comprehensive treatment of the role of soils in delivering NCP.

The role of soils in delivering Material NCP

Silver *et al.* (14) describe the critical role that soils play in the production of *food and feed* for a growing global population. Global patterns in soil characteristics, agricultural production, and the fate of embedded soil nutrients are reviewed. Global crop yields were found to be highest in soils rich in nitrogen and organic matter, yet the efficiency of nutrient utilization, measured as the proportion of calories converted to food for human consumption, was concentrated in regions with lower crop productivity and lower rates of chemical fertilizer inputs. At a global scale, soil resources have increasingly been concentrated in the production of feed for animals, resulting in large inefficiencies in nutrient utilization and losses from the food system. The intercontinental transport of soil-derived nutrients *via* international trade displaced millions of metric tonnes of nitrogen and phosphorus annually, much of which was ultimately concentrated in urban waste streams. Local, small scale agriculture accounted for approximately 40% of the global agricultural land area and provided over 50% of the world’s food and feed needs but yield gaps and economic constraints limit the

ability to intensify production on these lands. The authors conclude that to better utilize and protect soil resources in the global food system, policies and actions should encourage shifts to more nutrient-efficient diets, strategic intensification and technological improvement, restoration and maintenance of soil fertility and stability, and enhancing resilience in the face of global change.

In terms of the NCP *materials and assistance*, Morel *et al.* (15) focus on earth as a construction material in the context of the circular economy. The paper addressed the need for a vast quantity of new buildings to address the increase in population and living standards and the need also for tackling global warming and the decline in biodiversity. The authors review the use of earth as a low-carbon construction material through use of alternative technologies and practices. The paper discusses why and how earth naturally embeds high-tech properties for sustainable construction and examine the potential of earth to contribute to addressing the global challenge of modern architecture and explores the need to re-think building practices. Barriers to the development of earthen architecture were examined showing that only technical barriers are being addressed by the scientific community.

In terms of the role of soils for *energy* provision, Smith *et al.* (16) show that soils have both direct and indirect impacts on available energy, but energy provision, in turn, has direct and indirect impacts on soils. The authors report that burning peats provides only ~0.02% global energy supply yet contributes ~(0.7-0.8)% carbon losses from land use change and forestry (LUCF). Bioenergy crops provide ~0.3% energy supply and occupy ~(0.2-0.6)% harvested area. Increased bioenergy demand is likely to encourage switching from forests and pastures to rotational energy cropping, resulting in soil carbon loss. However, with protective policies, incorporation of residues from energy provision could sequester ~0.4% LUCF carbon losses. All organic wastes available in 2018 could provide ~10% global energy supply, but at a cost to soils of ~5% LUCF carbon losses; not using manures avoids soil degradation but reduces energy provision to ~9%. Wind farms, hydroelectric solar and geothermal schemes provide ~3.66% of energy supply and occupy less than ~0.3% harvested area, but if sited on peatlands could result in carbon losses that exceed reductions in fossil fuel emissions. The authors conclude that to ensure renewable energy provision does not damage our soils, comprehensive policies and management guidelines are needed that would (1) avoid peats, (2) avoid converting permanent land uses (such as perennial grassland or forestry) to energy cropping and (3) return residues remaining from energy conversion processes to the soil.

In addressing the role of soils in provision of *genetic, medicinal and biochemical resources*, Thiele-Bruhn (17), finds that intact, 'healthy' soils provide indispensable ecosystem services that especially depend on biotic activity. The author highlights that soil health is connected with human health, yet knowledge of the underlying soil functioning is still incomplete. The review depicts some selected services, i.e. (i) soil as genetic resource and hotspot of biodiversity thereby forming the basis for the provision of (ii) biochemical resources and (iii) medicinal services and goods. Soils harbour enormous biodiversity of organisms especially microorganisms. Some of the abilities of autochthonous microorganisms and their relevant enzymes, respectively, are utilized (a) to improve natural soil functions and in particular plant growth, e.g. through beneficial plant growth-promoting, symbiotic and mycorrhizal microorganisms, respectively, (b) to act as biopesticide, (c) to facilitate biodegradation of pollutants for soil bioremediation and (d) to render enzymes or chemicals for industrial use. Soils also exert direct effects on human health. Contact with soil enriches the human microbiome, protects from allergy and promotes emotional well-being. Medicinally relevant are soil substrates such as loams, clays and various minerals with curative effects as well as pharmaceutically active organic chemicals like antibiotics that are formed by soil microorganisms. In contrast, harmful minerals, soil dust inhalation and maladjusted soil ingestion may adversely affect humans.

The role of soils in delivering Non-material NCP

McElwee (12) reviews the literature on soil and Nature's Contributions to People around *learning and inspiration, physical and psychological experiences*, and *supporting identities*, revealing a range of relationships to imagining, understanding, and experiencing soil. Soils have played a large role in human creative endeavours, are the root of significant relationships to the environment, and can be conceptualized

through key metaphors, ideas and theory as a bridge linking culture and nature together. Often been labelled elsewhere as “cultural ecosystem services,” these NCP provide a range of benefits that are mostly non-material, non-consumptive, and intangible. The review finds that soils have contributed to art, literature and film; to mental and physical health benefits of a wide range of activities from recreation to tourism; and to cultural identities and practices ranging from religious beliefs and rituals to language and politics. Yet despite the wide-ranging contributions of soils to these NCP, the literature remains uneven, and much more remains to be understood, including how expanded acknowledgement of human engagement with soils, understanding the 'biosocial' nature of soil, and the application of “Anthropocene thinking” around the future of soil, can help improve knowledge and theory about the importance of soils to both people and nature.

The role of soils in delivering Regulating NCP

Lal *et al.* (18) review the role of soils in the *regulation of climate*, covering greenhouse gas emissions from soils, and the role of soils as sinks for atmospheric carbon dioxide, *via* soil organic and inorganic carbon. Biophysical effects of soil (such as albedo) on climate change are also described. Soils are identified as a major pool of carbon and as a source of greenhouse gas emissions, and the authors conclude that improved management of soils could enhance the contribution of soils in regulating climate.

Keesstra *et al.* (19), examine the role of soils on *regulation of freshwater quantity, flow and timing*. They note that the United Nations SDG 6 aims for clean water and sanitation for all by 2030, through eight subgoals dealing with four themes: i) water quantity and availability, ii) water quality, iii) finding sustainable solutions, and iv) policy and governance. The paper assesses how soils and associated land and water management can help achieve this goal, considering soils at two scales: local and landscapes. The merging of these two viewpoints shows the interlinked importance of the two scales. Soil health reflects the capacity of soil to provide ecosystem services at a specific location, taking into account local climate and soil conditions. Soil is also an important component of a healthy and sustainable landscape, which is connected by the water that flows through the soil. Soils are linked to water in two ways, through plant-available water in the soil (green water) and through the water in surface bodies or available as groundwater (blue water). In addition, water connects the scales by flows through both. Nature-based solutions at both soil health and landscape-scale can help achieve sustainable future development but need to be embedded in good governance, social acceptance, and economic viability.

The role of soils in the *regulation of freshwater and coastal water quality* is addressed by Cheng *et al.* (20). The regulation of water quality is one of the important ecosystem service functions of soil. The pollutants entering the soil can be mitigated by precipitation, adsorption and desorption, ion exchange, redox and metabolic decomposition. Natural ecosystems, such as forests and grasslands, intercept water carrying pollutants from atmospheric deposition and sewage leakage through vegetation and ground cover, and increase soil infiltration to reduce surface runoff and purify water quality. Soil / sediment is an important part of natural wetland ecosystem and one of the best substrates for constructed wetland (CW), and mangrove wetland play an important role in coastal zone protection and coastal water quality restoration. Soil / sediment with variable and controlled redox conditions in CW are highly effective in adsorption and passivation of pollutants such as nitrogen, phosphorus and heavy metals in water, and degradation of pesticides and emerging contaminants. Treated wastewater irrigation in farmland can avoid the direct discharge of wastewater into water body, reduce the cost of sewage treatment and compensate for the shortage of water resources. However, the excessive application of agricultural chemicals may overload the soil, which can lead to the occurrence of agricultural non-point source pollution. Under the dual pressure of climate change and food security in the future, developing environmentally friendly and economically feasible soil sustainable management measures is the key way to maintain the water purification function of soil, and requires the accurate quantification of soil function using techniques such as big data and model approaches.

Saco *et al.* (21) examine the role of soils in the *regulation of hazards and extreme events*. The frequency and intensity of natural hazards and extreme events has increased throughout the last century, resulting in adverse socioeconomic and ecological impacts worldwide. Key factors driving this increase include climate

change, the growing world population, anthropogenic activities, and ecosystem degradation. One ecologically-focused approach that has shown potential toward the mitigation of these hazard events is the concept NCP, which focuses on enhancing the material and non-material benefits of an ecosystem to reduce hazard vulnerability and enhance overall human well-being. Soils, in particular, have been identified as a key ecosystem component that may offer critical hazard regulating functionality. The review investigates the modulating role of soils in the regulation of natural hazards and extreme events, with a focus on floods, droughts, landslides, and sand/dust storms, within the context of NCP.

The role of soils in *habitat creation and maintenance* is addressed by de Deyn & Kooistra (22). Soils are a fundamental component of terrestrial ecosystems. Across the globe different soil types with different properties are found, resulting from the interacting soil forming factors: parent material, climate, topography, organisms and time. The paper presents the role of soils in habitat formation and maintenance in natural systems, and reflects on how humans have modified soils from local to global scale. Soils host a tremendous diversity of life forms, most of them microscopic in size. Many of functionalities of this diversity at the level of individual taxa or through their interactions are, as yet, unknown. However, we do know that the interactions and feedbacks between soil life, plants and soil chemistry and physics are essential for soil and habitat formation, maintenance and restoration. Moreover, the couplings between soils and major cycles of carbon, nutrients and water are essential for supporting the production of food, feed and fibre, drinking water and greenhouse gas balances. Soils take thousands of years to form yet are lost very quickly through a multitude of stressors. The current status of our soils globally is worrisome, yet with concerted action we can bend the curve and create win-wins of soil and habitat conservation, regeneration and sustainable development.

The role of soils in the *regulation of air quality* is reviewed by Giltrap *et al.* (23). They note that soil has a key role to play in meeting the UN Sustainable development goals and describe how soils can act as both a source and a sink of air pollutants (and precursors to air pollutants). In addition, soils support the growth of plants which play a major role in regulating air quality. The effect of soil on air quality can have both global (e.g. greenhouse gas fluxes, stratospheric ozone depletion) and local (e.g. odours, particulates, transport of pathogens) impacts. Agricultural soils can be a source of particulates and gases that negatively impact air quality. Although soils are not the only source of these pollutants, it is worthwhile managing them to reduce erosion and nutrient losses to maintain soil health so that we may continue to benefit from the services they provide.

The role of soils in the *regulation of organisms detrimental to humans* is addressed in the review of Sammadar *et al.* (24). They note that soil and soil biodiversity play critical roles in affecting nature's ability to regulate direct detrimental effects on humans, and on human-important plants and animals, through the control or regulation of particular organisms considered to be harmful. They evaluate the influence of soils' abiotic properties, in addition to effects on its extraordinary biodiversity, on pathogens in soil with a specific focus on human and crop plant pathogens. They review the ecological principles underpinning the regulation of soil pathogens, as well as relationships between pathogen suppression and soil health. Mechanisms and specific examples are presented of how soil and soil biota are involved in regulating pathogens of humans and plants. They evaluate how specific agricultural management practices can either promote or interfere with soil's ability to regulate pathogens. Finally, they conclude with discussion of how integrating soil, plant, animal, and human health through a "One Health" framework could point the way towards more effective, biologically-based, multifunctional management strategies that reduce impacts of pathogens on humans and plants.

The role of soils in *pollination and dispersal of seeds and other propagules* was addressed in the review of Carvalheiro *et al.* (25) which focussed specifically on the role of soils on pollination and seed dispersal. They note that ongoing environmental changes are affecting physical, chemical and biological soil components. Evidence of impacts of soil changes on pollinators and seed dispersers behaviour, fitness and density is scarce, but growing. They reviewed information on such impacts and on a number of mechanisms that may explain its propagation, taking into account the full range of resources required by the large and diverse number of species of these two important functional groups. They show that while there is substantial evidence on the

effects of soil nitrogen enrichment and changes in soil water content on the quality and quantity of floral and fruit resources, little is known on the effects of changes of other soil properties (e.g. soil pH, soil structure, other nutrients). Also, the few studies showing correlations between soil changes and pollinator and seed disperser foraging behaviour or fitness do not clearly identify the mechanisms that explain such correlation. Finally, most studies (including those with nitrogen and water) are local and limited to a small number of species, and it remains unclear how variable such effects are across time and geographical regions, and the strength of interactive effects between soil properties. Increasing research on this topic, taking into consideration how impacts propagate through species interaction networks, will provide essential information to predict impacts of ongoing environmental changes and help guide conservation plans that aim to minimize impacts on ecosystem functioning.

Renforth & Campbell (26) review the role of soils in the *regulation of ocean acidification*. They find that soils play an important role in mediating chemical weathering reactions and carbon transfer from the land to the ocean. The alkalinity that the land contributes to the ocean plays an important role in the oceanic carbon cycle. Proposals to increase the contribution of alkalinity to the oceans through 'enhanced weathering' as a means to help prevent climate change are gaining increasing attention. This would create a direct connection between the biogeochemical function of soils and alkalinity levels in the ocean. The feasibility of enhanced weathering depends on the combined influence of what minerals are added to soils, the formation of secondary minerals in soils or the drainage regime, and the partial pressure of respired CO₂ around the dissolving mineral. Increasing the alkalinity levels in the ocean through enhanced weathering could ameliorate the effects of ocean acidification in two ways. First, enhanced weathering would slightly elevate the pH of drainage waters, and the receiving coastal waters. The elevated pH would result in an increase in carbonate mineral saturation states, and a partial reversal in the effects of elevated CO₂. Second, the increase in alkalinity helps to replenish the ocean's buffering capacity by helping to maintain the 'Revelle Factor', making the oceans more resilient to further CO₂ emissions. However, there is limited evidence to constrain the downstream and oceanic impacts of enhanced weathering and its wider impact on ocean ecosystems.

To address the role of soils in the *formation, protection and decontamination of soils and sediments*, Sarkar *et al.* (27) examine the role of soils in the disposition, sequestration and decontamination of environmental contaminants. The article describes how soil serves as both a 'source' and 'sink' for contaminants. As a source, contaminants are derived from both 'geogenic' and 'anthropogenic' origins. Typically, while some of the inorganic contaminants including potentially toxic elements (PTEs) are derived from geogenic origin (e.g., As and Se) through weathering of parent materials, the majority of organic (e.g., pesticides and microplastics) as well as inorganic (e.g., Pb, Cd) contaminants are derived from anthropogenic origin. As a sink, soil plays a critical role in the transformation of these contaminants and their subsequent transfer to environmental compartments including groundwater (e.g., pesticides), surface water (phosphate and nitrate), ocean (e.g., microplastics) and atmosphere (e.g., nitrous oxide emission). A complex transformation process of contaminants in soil involving adsorption, precipitation, redox reactions and biodegradation control the mobility, bioavailability and environmental toxicity of these contaminants. The authors examine the geogenic and anthropogenic sources of contaminants reaching the soil and discuss the role of soil in the sequestration and decontamination of contaminants in relation to various physico-chemical and microbial transformation reactions of contaminants with various soil components. Finally, they propose future actions that would help to maintain the role of soils in protecting the environment from contaminants and delivering sustainable development goals.

Implications for soil management

Whilst highlighting the great potential of soils to contribute to sustainable development, the recognition that poorly managed, degraded or polluted soils may contribute negatively to both NCP and SDGs shows that this positive contribution cannot be taken for granted. Soils must be managed carefully to keep them healthy and capable of playing this vital role (28-32).

The importance of maintaining healthy soils needs to be viewed against a backdrop of widespread and increasing rates of soil degradation globally (33). There are around 11 million km² of degraded land globally (34), and around 120 thousand km² of land is lost to degradation every year, with over 3.2 billion people adversely impacted by global land degradation (35). Therefore, soil management is not only required to keep soils healthy; there is also an enormous task to restore millions of km² of degraded lands to health. In light of this, a few priorities emerge to allow soils to contribute optimally to delivering NCP and ultimately, the SDGs, as follows:

- For healthy soils in natural ecosystems, *protect* them from conversion and degradation
- For managed soils, *manage* in a way to protect and enhance soil biodiversity, health, productivity and sustainability and to prevent degradation
- For degraded soils, *restore* to full soil health

These priorities map well onto the categories *protect*, *manage* and *restore*, outlined for nature-based solutions (36). Options to restore degraded soils include revegetation, reduction of grazing pressure where soils are degraded by overgrazing, bioremediation with appropriate vegetation and restoring or maintaining soil organic matter levels by returning organic matter to the soil (34,37). Options to better manage soils in managed systems include maintaining ground cover, reducing disturbance e.g. by reducing the intensity of tillage, maintaining soil organic matter levels by returning organic matter to the soil, increasing soil biomass and diversity by providing carbon and nutrients, reducing disturbance, preventing erosion, minimising chemical inputs and preventing overgrazing of grasslands (38,39).

There is still a wealth of work to be done to better understand the processes linking soil functions to delivery of NCP, but we already have sufficient knowledge to implement best management practices to maintain and improve soil health. This analysis shows that this is not just desirable, but it is essential if we are to meet the SDG targets by 2030, and sustainable development more broadly in the decades to come.

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Figure and table captions

Table 1. IPBES Nature's Contributions to people (NCP), with the corresponding Millennium Ecosystem Assessment (MA) ecosystem services and categories shown.

Authors' Contributions

PS wrote the first draft of the article, with input from all authors. All authors revised drafts and approved the final version to be published.

Competing Interests

We have no competing interests.