PHILOSOPHICAL TRANSACTIONS B

royalsocietypublishing.org/journal/rstb

Introduction

Cite this article: Smith P, Keesstra SD, Silver WL, Adhya TK. 2021 The role of soils in delivering Nature's Contributions to People. *Phil. Trans. R. Soc. B* **376**: 20200169. https://doi.org/10.1098/rstb.2020.0169

Accepted: 14 June 2021

One contribution of 17 to a theme issue 'The role of soils in delivering Nature's Contributions to People'.

Subject Areas:
environmental science, ecosystems, ecology

Keywords:
soil, soil health, Nature's Contributions to People, NCP

Author for correspondence:
Pete Smith
e-mail: pete.smith@abdn.ac.uk

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

Pete Smith[1], Saskia D. Keesstra[2,3], Whendee L. Silver[4] and Tapan K. Adhya[5]

[1]Institute of Biological and Environmental Science, University of Aberdeen, Aberdeen, UK
[2]Team Soil, Water and Land Use, Wageningen Environmental Research, Wageningen, The Netherlands
[3]Civil, Surveying and Environmental Engineering and Centre for Water Security and Environmental Sustainability, The University of Newcastle, Callaghan, Australia
[4]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA
[5]School of Biotechnology, KIIT University, Bhubaneswar, Odisha, India

PS, 0000-0002-3784-1124; SDK, 0000-0003-4129-9080; WLS, 0000-0003-0372-8745

This theme 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 maximized 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. Papers in the theme issue emphasize the need for careful soil management. Priorities for soil management must include: (i) for healthy soils in natural ecosystems, *protect* them from conversion and degradation, (ii) for managed soils, *manage* in a way to protect and enhance soil biodiversity, health, productivity and sustainability and to prevent degradation, and (iii) 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.

This article is part of the theme issue 'The role of soils in delivering Nature's Contributions to People'.

1. 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 contextualize 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 contextualize 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 MA, to which they are related.

THE ROYAL SOCIETY PUBLISHING

Table 1. IPBES NCP, with the corresponding MA ecosystem services and categories shown [12].

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
	genetic, medicinal and biochemical 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 theme 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 [13]. The final paper in this issue synthesizes 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 (SDGs) [12]. Together, these papers constitute a most comprehensive treatment of the role of soils in delivering NCP.

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

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 are 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, is concentrated in regions with lower crop productivity and lower rates of chemical fertilizer inputs. At a global scale, soil resources are increasingly 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 displaces millions of metric tonnes of nitrogen and phosphorus annually, much of which is ultimately concentrated in urban waste streams. Local, small scale agriculture accounts for approximately 40% of the global agricultural land area and provides 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 use 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 addresses the need for a vast quantity of new buildings to accommodate 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 the use of alternative technologies and practices. The paper discusses why and how earth naturally embeds high-tech properties for sustainable construction, examines 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 are 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 approximately 0.02% of global energy supply yet contributes approximately 0.7–0.8% of carbon losses from land use change and forestry (LUCF). Bioenergy crops provide approximately 0.3% of energy supply and occupy approximately 0.2–0.6% of 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 approximately 0.4% LUCF carbon losses. All organic wastes available in 2018 could provide approximately 10% of global energy supply, but at a cost to soils of approximately 5% LUCF carbon losses; not using manures avoids soil degradation but reduces energy provision to approximately 9%. Wind farms, and hydroelectric, solar and geothermal schemes provide approximately 3.66% of energy supply and occupy less than approximately 0.3% of 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 (i) avoid peats, (ii) avoid converting permanent land uses (such as perennial grassland or forestry) to energy cropping and (iii) return residues remaining from energy conversion processes to the soil.

In addressing the role of soils in the provision of ***genetic, medicinal and biochemical resources***, Thiele-Bruhn [17] finds that intact, 'healthy' soils provide indispensable ecosystem services that especially depend on the 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 a 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 used (i) to improve natural soil functions and in particular plant growth, e.g. through beneficial plant growth-promoting, symbiotic and mycorrhizal microorganisms, respectively, (ii) to act as biopesticide, (iii) to facilitate biodegradation of pollutants for soil bioremediation and (iv) 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. By contrast, harmful minerals, soil dust inhalation and maladjusted soil ingestion may adversely affect humans.

3. The role of soils in delivering non-material Nature's Contributions to People

McElwee [13] reviews the literature on soil and NCP 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 having been labelled elsewhere as 'cultural ecosystem services', these NCP provide a range of benefits that are mostly non-material, non-consumptional 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 or 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.

4. The role of soils in delivering regulating Nature's contributions to people

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 in ***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 landscape. 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 infiltration to reduce surface runoff, which improves water quality. Soil/sediment is an important part of the natural wetland ecosystem and one of the best substrates for constructed wetland (CW), and mangrove wetland plays an important role in coastal zone protection and coastal water quality restoration. Soil/sediment with variable and controlled redox conditions in CW is 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 of farmland can avoid the direct discharge of wastewater into the 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 pressures of climate change and food security in the future, developing environmentally friendly and economically feasible sustainable management measures for soil 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 to the role of soils in the ***regulation of hazards and extreme events***. The frequency and intensity of natural hazards and extreme events have 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 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 SDGs 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 by Samaddar *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 soil's 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 a 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*** is addressed in the review by Carvalheiro *et al.* [25], which focuses specifically on the role of soils in pollination and seed dispersal. The authors note that ongoing environmental changes are affecting physical, chemical and biological soil components. Evidence of impacts of soil changes on pollinator and seed disperser behaviour, fitness and density is scarce, but growing. They review information on such impacts and on a number of mechanisms that may explain the contribution of soils, 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 about 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 about 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 CO_2 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 CO_2. 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 CO_2 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 of 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 of 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, controls 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 SDGs.

5. Implications for soil management

While 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 km^2 of degraded land globally [34], and around 120 thousand km^2 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 km^2 of degraded lands to health. In the 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, preventing erosion, minimizing 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 essential if we are to meet the SDG targets by 2030 and sustainable development more broadly in the decades to come.

Data accessibility. This article does not contain any additional data.

Authors' contributions. P.S. 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 declare we have no competing interests.

Funding. The input of P.S. contributes to Soils-R-GRREAT (NE/P019455/1) and the input of P.S. and S.D.K. contributes to the European Union's Horizon 2020 Research and Innovation Programme through project CIRCASA (grant agreement no. 774378).

Acknowledgements. T.K.A. acknowledges the support of 'Towards Integrated Nitrogen Management System (INMS)' funded by the Global Environment Facility (GEF), executed through the UK's Natural Environment Research Council (NERC).

References

1. Dominati E, Patterson M, Mackay A. 2010 A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecol. Econ.* **69**, 1858–1868. (doi:10.1016/j.ecolecon.2010.05.002)
2. Robinson DA, Lebron I, Vereecken H. 2009 On the definition of the natural capital of soils: a framework for description, evaluation, and monitoring. *Soil Sci. Soc. Am. J.* **73**, 1904–1911. (doi:10.2136/sssaj2008.0332)
3. Robinson DA *et al.* 2014 On the value of soil resources in the context of natural capital and ecosystem service delivery. *Soil Sci. Soc. Am. J.* **78**, 685–700. (doi:10.2136/sssaj2014.01.0017)
4. Smith P *et al.* 2015 Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *Soil* **1**, 665–685. (doi:10.5194/soil-1-665-2015)
5. Adhikari K, Hartemink AE. 2016 Linking soils to ecosystem services—a global review. *Geoderma* **262**, 101–111. (doi:10.1016/j.geoderma.2015.08.009)
6. IPBES. 2019 *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany: IPBES Secretariat.
7. Díaz S *et al.* 2018 Assessing nature's contributions to people. *Science* **359**, 270–272. (doi:10.1126/science.aap8826)
8. Kadykalo AN *et al.* 2019 Disentangling 'ecosystem services' and 'nature's contributions to people'. *Ecosyst. People* **15**, 269–287. (doi:10.1080/26395916.2019.1669713)
9. McElwee P *et al.* 2020 The impact of interventions in the global land and agri-food sectors on Nature's Contributions to People and the UN Sustainable Development Goals. *Glob. Change Biol.* **26**, 4691–4721. (doi:10.1111/gcb.15219)
10. Pascual U *et al.* 2017 Valuing nature's contributions to people: the IPBES approach. *Curr. Opin. Environ. Sustain.* **26-27**, 7–16. (doi:10.1016/j.cosust.2016.12.006)
11. Reid WV, Millennium Ecosystem Assessment, World Resources Institute (eds). 2005 *Ecosystems and human well-being: synthesis; a report of the Millennium Ecosystem Assessment*. Washington, DC: Island Press.
12. Smith P *et al.* 2021 Soil-derived Nature's Contributions to People and their contribution to the UN Sustainable Development Goals. *Phil. Trans. R. Soc. B* **376**, 20200185. (doi:10.1098/rstb.2020.0185)
13. McElwee P. 2021 The role of soils in learning and inspiration, physical and psychological experiences, and in supporting identities. *Phil. Trans. R. Soc. B* **376**, 20200184. (doi:10.1098/rstb.2020.0184)
14. Silver WL, Perez T, Mayer A, Jones AR. 2021 The role of soil in the contribution of food and feed. *Phil. Trans. R. Soc. B* **376**, 20200181. (doi:10.1098/rstb.2020.0181)
15. Morel J-C, Charef R, Hamard E, Fabbri A, Beckett C, Bui Q-B. 2021 Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome. *Phil. Trans. R. Soc. B* **376**, 20200182. (doi:10.1098/rstb.2020.0182)
16. Smith J, Farmer J, Smith P, Nayak D. 2021 The role of soils in provision of energy. *Phil. Trans. R. Soc. B* **376**, 20200180. (doi:10.1098/rstb.2020.0180)
17. Thiele-Bruhn S. 2021 The role of soils in provision of genetic, medicinal and biochemical resources. *Phil. Trans. R. Soc. B* **376**, 20200183. (doi:10.1098/rstb.2020.0183)
18. Lal R, Monger C, Nave L, Smith P. 2021 The role of soil in regulation of climate. *Phil. Trans. R. Soc. B* **376**, 20210084. (doi:10.1098/rstb.2021.0084)
19. Keesstra S, Sannigrahi S, López-Vicente M, Pulido M, Novara A, Visser S, Kalantari Z. 2021 The role of soils in regulation and provision of blue and green water. *Phil. Trans. R. Soc. B* **376**, 20200175. (doi:10.1098/rstb.2020.0175)
20. Cheng K, Xu X, Cui L, Li Y, Zheng J, Wu W, Sun J, Pan G. 2021 The role of soils in regulation of freshwater and coastal water quality. *Phil. Trans. R. Soc. B* **376**, 20200176. (doi:10.1098/rstb.2020.0176)
21. Saco PM, McDonough KR, Rodriguez JF, Rivera-Zayas J, Sandi SG. 2021 The role of soils in the regulation of hazards and extreme events. *Phil. Trans. R. Soc. B* **376**, 20200178. (doi:10.1098/rstb.2020.0178)
22. De Deyn GB, Kooistra L. 2021 The role of soils in habitat creation, maintenance and restoration. *Phil. Trans. R. Soc. B* **376**, 20200170. (doi:10.1098/rstb.2020.0170)
23. Giltrap D, Cavanagh J, Stevenson B, Ausseil A-G. 2021 The role of soils in the regulation of air quality. *Phil. Trans. R. Soc. B* **376**, 20200172. (doi:10.1098/rstb.2020.0172)
24. Samaddar S, Karp DS, Schmidt R, Devarajan N, McGarvey JA, Pires AFA, Scow K. 2021 Role of soil in the regulation of human plant pathogens: soils' contributions to people. *Phil. Trans. R. Soc. B* **376**, 20200179. (doi:10.1098/rstb.2020.0179)
25. Carvalheiro LG, Bartomeus I, Rollin O, Timóteo S, Tinoco CF. 2021 The role of soils on pollination and seed dispersal. *Phil. Trans. R. Soc. B* **376**, 20200171. (doi:10.1098/rstb.2020.0171)
26. Renforth P, Campbell JS. 2021 The role of soils in the regulation of ocean acidification. *Phil. Trans. R. Soc. B* **376**, 20200174. (doi:10.1098/rstb.2020.0174)
27. Sarkar B, Mukhopadhyay R, Ramanayaka S, Bolan N, Ok YS. 2021 The role of soils in the disposition, sequestration and decontamination of environmental contaminants. *Phil. Trans. R. Soc. B* **376**, 20200177. (doi:10.1098/rstb.2020.0177)
28. Bouma J. 2019 Soil security in sustainable development. *Soil Syst.* **3**, 5. (doi:10.3390/soilsystems3010005)
29. Bouma J, Montanarella L. 2016 Facing policy challenges with inter- and transdisciplinary soil research focused on the UN Sustainable Development Goals, *Soil* **2**, 135–145. (doi:10.5194/soil-2-135-2016)
30. Bouma J, Montanarella L, Evanylo G. 2019 The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. *Soil Use Manage.* **35**, 538–546. (doi:10.1111/sum.12518)
31. Visser S, Keesstra S, Maas G, de Cleen M, Molenaar C. 2019 Soil as a basis to create enabling conditions for transitions towards sustainable land management as a key to achieve the SDGs by 2030. *Sustainability* **11**, 6792. (doi:10.3390/su11236792)
32. Keesstra SD *et al.* 2016 The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil* **2**, 111–128. (doi:10.5194/soil-2-111-2016)
33. 2015 *Status of the world's soil resources: main report*. Rome, Italy: FAO, ITPS.
34. Lal R. 2015 Restoring soil quality to mitigate soil degradation. *Sustainability* **7**, 5875–5895. (doi:10.3390/su7055875)
35. Montanarella L, Scholes R, Brainich A (eds). 2018 *The IPBES assessment report on land degradation and restoration*. See https://zenodo.org/record/3237392.
36. Seddon N, Smith A, Smith P, Chaussson A, Girardin C, House J, Key I, Turner B, Srivastava S. 2021 Getting the message right on nature-based solutions to climate change. *Glob. Change Biol.* **27**, 1518–1546. (doi:10.1111/gcb.15513)
37. Lal R. 2020 Managing soil quality for humanity and the planet. *Front. Agric. Sci. Eng.* **7**, 251–253. (doi:10.15302/J-FASE-2020329)
38. Smith P, Powlson DS. 2003 Sustainability of soil management practices – a global perspective. In *Soil biological fertility - a key to sustainable land use in agriculture* (eds LK Abbott, DV Murphy), pp. 241–254. Dordrecht, The Netherlands: Kluwer Academic Publishers.
39. Novara A *et al.* 2019 Long-term organic farming on a citrus plantation results in soil organic carbon recovery. *Cuad. Invest. Geog.* [*Geog. Res. Lett.*] **45**, 271–286. (doi:10.18172/cig.3794)