Soil-derived Nature's Contributions to People and their contribution to the UN Sustainable Development Goals

Pete Smith[1], Saskia D. Keesstra[2,3], Whendee L. Silver[4], Tapan K. Adhya[5], Gerlinde B. De Deyn[6], Luísa G. Carvalheiro[7,8], Donna L. Giltrap[9], Phil Renforth[10], Kun Cheng[11], Binoy Sarkar[12], Patricia M. Saco[13], Kate Scow[14], Jo Smith[15], Jean-Claude Morel[16], Sören Thiele-Bruhn[17], Rattan Lal[18] & Pam McElwee[19]

[1]Institute of Biological & 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]KIIT University, Bhubaneswar, Odisha, India

[6] Wageningen University, Wageningen, The Netherlands

[7] Departamento de Ecologia, Universidade Federal de Goiás, 74001-970 Goiânia, Brasil

[8] Centre for Ecology, Evolution and Environmental Changes (cE3c), Faculdade de Ciências da Universidade de Lisboa, Campo Grande, 1749-016 Lisboa, Portugal

[9] Manaaki Whenua Landcare Research, Palmerston North, New Zealand

[10] Research Centre for Carbon Solutions, Heriot-Watt University, Edinburgh, UK

[11] College of Resources and Environmental Sciences, Nanjing Agricultural University, Nanjing, Jiangsu, China

[12] Lancaster Environment Centre, Lancaster University, Lancaster, UK

[13] Civil, Surveying and Environmental Engineering and Centre for Water Security and Environmental Sustainability, The University of Newcastle, Callaghan, Australia

[14] Department of Land, Air and Water Resources, University of California, Davis, CA, USA

[15] Institute of Biological & Environmental Science, University of Aberdeen, Aberdeen, UK

[16] Tribology and Systems Dynamics Laboratory (LTDS-UMR CNRS 5513), National School of Civil Engineering (ENTPE), University of Lyon, France

[17] Soil Science, University of Trier, Trier, Germany

[18] Carbon Management and Sequestration Center, The Ohio State University, Columbus, Ohio, USA

[19] Department of Human Ecology, Rutgers University, New Brunswick, NJ, USA

Keywords: soil, soil health, nature's contributions to people, sustainable development goals, SDG, NCP

Summary

This special issue provides an assessment of the contribution of soils to Nature's Contributions to People (NCP). Here we combine this assessment and previously published relationships between NCP and delivery on the UN Sustainable Development Goals (SDGs) to infer contributions of soils to the SDGs. We show that in addition to contributing positively to the delivery of all NCP, soils also have a role in underpinning all SDGs. Whilst highlighting the great potential of soils to contribute to sustainable development, it is recognised that poorly managed, degraded or polluted soils may contribute negatively to both NCP and SDGs. The positive contribution, however, cannot be taken for granted, and soils must be managed carefully to keep them healthy

and capable of playing this vital role. A priority 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 and sustainability and to prevent degradation, and 3) for degraded soils, restore to full soil health. We have enough knowledge now to move forward with the implementation of best management practices to maintain and improve soil health. This analysis shows that this is not just desirable, it is essential if we are to meet the SDG targets by 2030 and achieve sustainable development more broadly in the decades to come.

Introduction

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). Other papers in this special issue (6)(7)(8)(9)(10)(11)(12)(13)(14)(15)(16)(17)(18)(19)(20) have considered each ecosystem service in turn, classified according to the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Nature's Contributions to People (NCP, (21,22)), thus providing the most comprehensive treatment to date of the role of soils in delivering NCP. Other studies have examined the role of soils in contributing to the UN Sustainable Development Goals (SDGs, (23–26)), arguing that soils also play a vital role in delivering the SDGs. In a Forum paper, Keesstra et al. (27) explored the role of soils in delivering the SDGs through a series of short essays focussing on the SDGs related to food security, water scarcity, climate change, biodiversity loss and health threats. They used an approach which mapped the functions provided by soils (Table 1) to these five SDGs.

Table 1. The seven soil functions as defined by the European Commission (28)

1	Biomass production, including agriculture and forestry
2	Storing, filtering and transforming nutrients, substances and water
3	Biodiversity pool, such as habitats, species and genes
4	Physical and cultural environment for humans and human activities
5	Source of raw material
6	Acting as carbon pool
7	Archive of geological and archaeological heritage

Using a similar approach, Smith et al. (29) examined how soil carbon sequestration as a climate mitigation strategy provides co-benefits and trade-offs to the delivery of all SDGs. Like Keesstra et al. (27), Smith et al. (29) first considered the functions provided by the soils and mapped these to NCP, with the delivery of these NCP then mapped on to the delivery of the SDGs. We use a similar approach here, drawing on the extensive analysis presented in the other papers presented in this issue (6-20), to examine the role of soils in contributing, positively or negatively, to the UN SDGs.

The impact of Nature's Contributions to People on the UN Sustainable Development Goals

The IPBES Global Assessment (22) defined 18 Nature's Contributions to People (NC) 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" (21). NCP and ecosystem services are related, but not precisely parallel concepts (30). The IPBES authors stressed that NCP are a way to think of ecosystem services, rather than a replacement for the term. As noted by McElwee et al. (31), NCP was proposed to be a broader umbrella to engage a wider range of disciplines, particularly from the social sciences and humanities, and a larger range of values around ecosystems (32). Unlike ecosystem services described in the earlier Millennium Ecosystem Assessment (MA, 33), supporting services were no longer considered as separate entities, but many NCP can be mapped onto the MA ecosystem services. Table 2 shows NCP as proposed by IPBES, with the corresponding ecosystem services, as described in the Millennium Ecosystem Assessment, to which they are related.

Table 2. IPBES Nature's Contributions to people (NCP), with the corresponding Millennium Ecosystem Assessment (MA) ecosystem services and categories shown.

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 UN Sustainable Development Goals were developed under an initiative by the UN aiming to end poverty, protect the planet and improve the lives and prospects of everyone, everywhere by 2030. The 17 Goals were adopted by all UN Member States in 2015, as part of the 2030 Agenda for Sustainable Development which set out a 15-year plan to achieve the Goals (34). Table 3 summarises the SDGs.

Table 3. The UN Sustainable Development Goals (SDGs) (34)

SDG	Goal
1 NO POVERTY	End poverty in all its forms everywhere
2 ZERO HUNGER	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
3 GOOD HEALTH AND WELL-BEING	Ensure healthy lives and promote well-being for all at all ages
4 QUALITY EDUCATION	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5 GENDER EQUALITY	Achieve gender equality and empower all women and girls
6 CLEAN WATER AND SANITATION	Ensure availability and sustainable management of water and sanitation for all
7 AFFORDABLE AND CLEAN ENERGY	Ensure access to affordable, reliable, sustainable, and modern energy for all
8 DECENT WORK AND ECONOMIC GROWTH	Promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation
10 REDUCED INEQUALITIES	Reduce inequality within and among countries
11 SUSTAINABLE CITIES AND COMMUNITIES	Make cities and human settlements inclusive, safe, resilient, and sustainable
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Ensure sustainable consumption and production patterns
13 CLIMATE ACTION	Take urgent action to combat climate change and its impacts
14 LIFE BELOW WATER	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
15 LIFE ON LAND	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable, and inclusive institutions at all levels
17 PARTNERSHIPS FOR THE GOALS	Strengthen the means of implementation and revitalize the global partnership for sustainable development

There have been a number of studies that have mapped the relationship between NCP (or other categorisations of ecosystem services) onto the SDGs. Wood et al. (35), for example, assessed the contribution of ecosystem services to the SDGs and specific SDG targets using the "The Economics of Ecosystems and Biodiversity" definitions (36). Yang et al. (37) used an expert elicitation exercise to assess the contribution of ecosystem services to the SDGs and Anderson et al. (38) used a similar approach to assess the contribution of NCP to the SDGs. Johnson et al. (39) described a modelling toolkit to link ecosystem services described in the InVEST suite of models to delivery of the SDGs. For soils specifically, Keesstra et al. (27) and Smith et al. (29) used ecosystem services and NCP framings, respectively, to examine the role of soils, or soil carbon sequestration specifically in the case of Smith et al. (29), in contributing to the delivery on the SDGs.

Of the studies described above, the matrix of NCP and SDGs is based on Anderson et al. (38) since they specifically focussed on the NCP categorization on ecosystem services. Table 4 shows a matrix of NCP and SDGs, with an associated relationship indicated if over 50% of expert respondents in Anderson et al. (38) identified a relationship. We use the relationships identified by Anderson et al. (38), supplemented with other well-defined relationships, to map soil-derived NCP onto the SDGs.

Table 4. Relationship between NCP and SDGs. A relationship is shown (in blue) only to those interactions indicated by over 50% of expert respondents in Anderson et al. (38). Note: impacts where a relationship was not identified by Anderson et al. (38), but where the relationship is well-documented elsewhere are shown (in green). These are the impact of habitat creation and maintenance (40), and the impact of regulation of air quality (41) on SDG3, the impact of regulation of ocean acidification on SDG13 through enhanced mineral weathering (42) and the impact of regulation of organisms detrimental to humans on SDGs 2, 12 and 15 (14).

	NCP	SDG																
		1 NO POVERTY	2 ZERO HUNGER	3 GOOD HEALTH AND WELL-BEING	4 QUALITY EDUCATION	5 GENDER EQUALITY	6 CLEAN WATER AND SANITATION	7 AFFORDABLE AND CLEAN ENERGY	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	10 REDUCED INEQUALITIES	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS	17 PARTNERSHIPS FOR THE GOALS
Material NCP	Food and feed	blue	blue	blue					blue		blue		blue		blue			
	Materials and assistance	blue						blue	blue	blue			blue					
	Energy	blue						blue	blue	blue	blue		blue					
	Medicinal, biochemical and genetic resources			blue														
Non-material NCP	Learning and inspiration				blue	blue			blue	blue	blue		blue				blue	blue
	Supporting identities			blue	blue	blue			blue		blue						blue	blue
	Physical and psychological experiences			blue	blue	blue												
Regulating NCP	Regulation of climate						blue	blue						blue	blue			
	Regulation of freshwater quantity, flow and timing		blue				blue							blue				
	Regulation of freshwater and coastal water quality						blue								blue			
	Regulation of hazards and extreme events						blue			blue		blue		blue				
	Habitat creation and maintenance			green								blue		blue		blue		
	Regulation of air quality			green								blue						
	Regulation of organisms detrimental to humans		green	blue									green			green		
	Pollination and dispersal of seeds and other propagules		blue													blue		
	Regulation of ocean acidification													green	blue			

	Formation, protection and decontamination of soils and sediments																	
Cross-cutting NCP	Maintenance of options																	

Table 5. Summary of the potential positive, negative and context-specific contributions of soils to NCP arising from papers in this issue. Note, these impacts are illustrative rather than comprehensive.

NCP	**Positive impacts provided by soils**	**Negative impacts provided by soils**	**Mixed impacts provided by soils**
1) Food and feed (Material NCP; 20)	Nutrients to sustain life, physical environment to support plant growth, supports biota that contribute to plant growth	Insufficient nutrient concentrations to sustain life, toxic elements and compounds, physical environment inhibits plant growth, or supports pests and pathogens that inhibit plant success. Inequitable distribution of nutrients through trade.	Chemical stoichiometries and physical conditions that favour some plants over others
2) Materials and assistance (Material NCP;16)	Cheap construction materials; healthy indoor air quality in earthen architecture; low carbon construction materials; construction materials fulfilling the circular economy (no waste); reduced energy in use for well-designed earthen architecture	May lead to a shortage of soil for agriculture in some places. If extracted from a quarry --> related environmental impacts	Depending on the architecture some of the positive impacts may be withdrawn e.g. if stabilised with cement, may not any longer be a low carbon construction material;
3) Energy (Material NCP; 15)	Soils (peats) can be burnt to provide energy; soils contribute nutrients and water to grow energy crops	Burning of peats releases large stores of carbon so soils increase greenhouse gas emissions; energy crops may occupy areas that could otherwise be used for food production, so soils provide less food; energy crops encourage disturbance of permanent land use, which results in loss of soil carbon, so soils release carbon; use of organic wastes for energy reduces carbon inputs to soils, which results in reduced carbon storage in soils (soils increase greenhouse gas emissions); if wind turbines or hydro schemes are located on deep peats, changes to the hydrological regime can result in large emissions of soil carbon to the atmosphere (so soils increase greenhouse gas emissions)	
4) Medicinal, biochemical and genetic resources (Material NCP; 18)	Soils with their ecosystem services are indispensable for intact ecosystems, clean water, healthy food in general as well as the provision of	Soil dust, nutrient depletion and contamination may have direct or indirect adverse effects on human health.	The genetic and biochemical resources of soil are still largely unexplored.

	substances, enzymes and organisms for medicinal and technical purposes.		
5) Learning and inspiration (Non-material NCP; 17)	Soils provide opportunity for formal and informal study; inspiration leading to art and literature; and sources of biomimicry and design. Indigenous knowledge around soils is rich and widespread, contributing to better management around fertility and erosion in particular	None	None
6) Supporting identities (Non-material NCP; 17)	Soil has been metaphorically and linguistically linked to human identities in major world languages and religions; concepts of a 'land ethic' shape farmer and other identities, as well as gendered experiences of soil; cultural identities often expressed through use of soil in housing and food	Metaphorical concepts of 'native soil' and 'blood and soil' have been used to justify exclusion/violence against others.	Access to the benefits of soils for identities can be limited by environmental injustices or unfair blame for degradation
7) Physical and psychological experiences (Non-material NCP; 17)	Green spaces and gardening allow for physical and mental benefits of being in nature; recreation, tourism and sport all depend on, and can bring financial benefits to, good soil management	Recreation and tourism can be bad for soils; compaction and damage reported in some tourist sites	None
8) Regulation of climate (Regulating NCP; 19)	Restoration of soil functionality and enhancement of SOC concentration in the root zone has numerous environmental and economic co-benefits. In addition to creating climate resilient soil and agriculture, through adaptation and mitigation of climate change, restoration of soil health through sequestration of SOC is also pertinent to improving soil and environmental quality	Soils of agricultural and other managed ecosystems contain lower carbon stocks than natural vegetation because of the long-term land use and degradation (i.e., erosion) induced depletion of soil organic carbon stock. Soils are also major contributor to greenhouse gases like CH_4 and N_2O that has important role in climate change feedback and elemental cycling	Adoption of restorative management practices, which conserve soil and water and strengthen elemental cycling, can create a positive soil/ecosystem carbon budget and sequester atmospheric carbon. Understanding and predicting the impact of climate change on soil microbiomes is grand challenge for our planet.
9) Regulation of freshwater quantity, flow and timing (Regulating NCP; 10)	Healthy soils have high infiltration capacity that increases green water (for crop production and nature) and regulates blue water (less floods and droughts). Soils also function as a filter for pollutants	Unhealthy soils can form crusts and increase the risk on floods and droughts. Soil may be eroded and clog up waterways, reservoirs and infrastructure downstream	High infiltration rates may also cause a lack of water in the riverine system in (semi) arid system. Plants will make use of this water on the hillslopes in summer, but as a consequence, rivers run dry
10) Regulation of freshwater and coastal water quality (Regulating NCP; 11)	Natural soils and constructed wetlands provide water purification by absorbing pollutants.	Water pollution caused by non-point source pollution in farmland with overused chemicals	Positive and negative water quality impacts depend on soil environmental capacity
11) Regulation of hazards and extreme events (Regulating NCP; 13)	Healthy soils attenuate floods by storing and slowly releasing stormwater, and this ability to store water in the soil profile during wet periods is also important to mitigate droughts, which is used by plants during drought periods. Healthy soils can	Degraded soils or those with poor drainage or under intensive irrigation are prone to water logging conditions that increase risks for flood, severe erosion, and landslides. Soils that do not support healthy vegetative cover result in	While soils with commercial crops can have some beneficial effects on hazards, agricultural management practices must be carefully chosen to balance productivity with hazard protection.

	sustain vegetation with a root system that directly reduces erosion potential, landslide risk, and negative impacts associated with windstorms.	reduced infiltration, increased evaporation and reinforcement of drought conditions and soil loss via windstorms.	
12) Habitat creation and maintenance (Regulating NCP; 6)	Soils are a habitat for many species, including plants and species with aboveground life stages; soils store and provide nutrients, water and shelter; soils have buffering capacity for perturbations, enabling resilience of ecosystems	Soil loss proceeds faster than soil formation; specific interactions of soil biology, chemistry and physics required for adequate functioning which makes soil restoration difficult; opaqueness of soils precludes non-destructive *in situ* observations of soil life and its functioning	Plant-soil feedbacks promote certain habitat conditions over others; this can be beneficial when desired ecosystem development is promoted or detrimental when an undesired state is promoted (e.g. increased expansion of invasive species); propagules stored in soil can promote or counteract habitat creation depending on the identity and functioning of the species
13) Regulation of air quality (Regulating NCP; 8)	Sink for airborne pollutants Biofiltration of gaseous pollutants Landfill covers	Particulates and dust storms NH_3 and NO_x from fertiliser use	Positive and negative air quality impacts from plant growth
14) Regulation of organisms detrimental to humans (Regulating NCP; 14)	Suppression of pathogens by indigenous microbial communities. Inactivation of detrimental organisms by abiotic factors.	Reservoir for pathogens. Reduced capacity to regulate detrimental organisms when soil health is poor.	Practices that promote soil suppression of pathogens may reduce agricultural productivity
15) Pollination and dispersal of seeds and other propagules (Regulating NCP; 7)	Healthy, non-polluted soils provide nesting substrate for a vast number of pollinators and seed dispersers, as well as support for alternative (to crops) floral resources. Clay from soils is used to counteract toxicity associated to fruit secondary metabolites	Unhealthy, polluted soils (enriched with nitrogen or other nutrients, pesticides) will change floral resource availability and quality (nutrient and sugar content, odour, size and shape), leading to changes in foraging behaviour and reducing fitness. Tilled soils will reduce nesting opportunities	While nutrient enrichment can improve crop productivity, when in excess it can lead to loss of pollination services, leading to a null (or negative) net effect
16) Regulation of ocean acidification (Regulating NCP; 9)	Facilitates weathering which removes CO_2 from the atmosphere. Reduces the impact of ocean acidification. Improves ocean CO_2 buffering capacity.	Cation exchange and secondary minerals could reduce weathering contribution	Element release during weathering could impact wider ecosystems
17) Formation, protection and decontamination of soils and sediments (Regulating NCP; 12)	Physicochemical interactions of contaminants with mineral and organic soil components, and biochemical transformations facilitated by soil microorganisms confer contaminants ‘cleaning’ action of soil	Inorganic contaminants including heavy metal(loid)s are derived from geogenic origin through weathering of parent materials, while both organic inorganic contaminants are derived from anthropogenic origin in soil	Soil plays a critical role in the transformation of contaminants and their subsequent transfer to groundwater, surface water, ocean, and atmosphere, and controls the mobility, bioavailability and toxicity of contaminants
18) Maintenance of options (Cross-cutting NCP)	Healthy, well-managed soils allow multiple options to be considered now and in the future.	Unhealthy, poorly managed soils can lead to ecosystem degradation and desertification, with knock on effects for reduction in other NCP.	

Table 6. The contribution of soils to the SDGs, with contributions derived from relationships between NCP and the SDGs outlined in the section "The contribution of Nature's Contributions to People to the UN Sustainable Development Goals". Dependencies enabling positive SDG effects are shown in blue, those leading to negative SDG effects are shown in red.

NCP	Potential impacts on SDGs by soil-based NCP	Dependency on sign of the likely impact
1) Food and feed	1 NO POVERTY 2 ZERO HUNGER 3 GOOD HEALTH AND WELL-BEING 8 DECENT WORK AND ECONOMIC GROWTH 10 REDUCED INEQUALITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 14 LIFE BELOW WATER	If healthy and well managed, soils provide nutrients and a physical environment to sustain life and support plant growth. Poorly managed / polluted soils may lack nutrients, contain toxic compounds or pests and pathogens that inhibit plant growth.
2) Materials and assistance	1 NO POVERTY 7 AFFORDABLE AND CLEAN ENERGY 8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Soils provide cheap, low carbon construction materials with low levels of waste, and can reduce energy use in well-designed earthen architecture. Overuse of soils for construction could threaten soils to produce food and mining can have negative impacts.
3) Energy	1 NO POVERTY 7 AFFORDABLE AND CLEAN ENERGY 8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 10 REDUCED INEQUALITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Peat soils can be burnt to provide energy and soils contribute nutrients and water to grow energy crops. Burning of peats is bad for climate change and biodiversity. If sited on peats, wind turbines can damage biodiversity and cause loss of carbon.
4) Medicinal, biochemical and genetic resources	3 GOOD HEALTH AND WELL-BEING	Soils provide ecosystem services that are essential for intact ecosystems, clean water, healthy food, medicinal products and human well-being. Soil dust, nutrient depletion and contamination may have adverse effects on human health.
5) Learning and inspiration	4 QUALITY EDUCATION 5 GENDER EQUALITY 8 DECENT WORK AND ECONOMIC GROWTH 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE 10 REDUCED INEQUALITIES 12 RESPONSIBLE CONSUMPTION AND PRODUCTION 16 PEACE, JUSTICE AND STRONG INSTITUTIONS 17 PARTNERSHIPS FOR THE GOALS	Soils provide opportunity for study, inspiration leading to art and literature and sources of biomimicry and design. Indigenous knowledge around soils is rich and widespread, contributing to better management around fertility and erosion, in particular.
6) Supporting identities	3 GOOD HEALTH AND WELL-BEING 4 QUALITY EDUCATION 5 GENDER EQUALITY 8 DECENT WORK AND ECONOMIC GROWTH 10 REDUCED INEQUALITIES 16 PEACE, JUSTICE AND STRONG INSTITUTIONS 17 PARTNERSHIPS FOR THE GOALS	Soil has been linked to human identities; concepts of a 'land ethic' shape farmer and other identities, as well as gendered experiences and cultural identities through use of soil. Concepts of e.g. 'blood and soil' have been used to justify exclusion/violence against others
7) Physical and psychological experiences	3 GOOD HEALTH AND WELL-BEING 4 QUALITY EDUCATION 5 GENDER EQUALITY	Green spaces and gardening allow for physical and mental benefits of being in nature; recreation, tourism and sport all depend on, and can bring financial benefits to, good soil management. Recreation and tourism can be bad for soils through compaction and damage.
8) Regulation of climate	6 CLEAN WATER AND SANITATION 7 AFFORDABLE AND CLEAN ENERGY 13 CLIMATE ACTION 14 LIFE BELOW WATER	Restoration of soil health and increasing soil organic matter contribute to adaptation and mitigation of climate change. Poorly managed soils can lose carbon to the atmosphere and be a source of CH_4 and N_2O emissions.

9) Regulation of freshwater quantity, flow and timing	2 ZERO HUNGER; 6 CLEAN WATER AND SANITATION; 13 CLIMATE ACTION	Healthy soils have high infiltration capacity that increases green water and regulates blue water, and function as a filter for pollutants. Unhealthy soils increase the risk on floods and droughts. Eroded soil can clog up waterways, reservoirs and infrastructure.
10) Regulation of freshwater and coastal water quality	6 CLEAN WATER AND SANITATION; 14 LIFE BELOW WATER	Natural soils and constructed wetlands provide water purification by absorbing pollutants. Water pollution can result from non-point source pollution in farmland with overused chemicals.
11) Regulation of hazards and extreme events	6 CLEAN WATER AND SANITATION; 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 11 SUSTAINABLE CITIES AND COMMUNITIES; 13 CLIMATE ACTION	By storing water, healthy soils attenuate floods, mitigate droughts, and sustain vegetation root systems that reduce erosion and landslide risk and effects of windstorms. Degraded soils exacerbate the above risks.
12) Habitat creation and maintenance	3 GOOD HEALTH AND WELL-BEING; 11 SUSTAINABLE CITIES AND COMMUNITIES; 13 CLIMATE ACTION; 15 LIFE ON LAND	Soils are a habitat for many species and provide nutrients, water and shelter and enabling resilience of ecosystems through buffering. Soil loss proceeds faster than soil formation and soil restoration difficult.
13) Regulation of air quality	3 GOOD HEALTH AND WELL-BEING; 11 SUSTAINABLE CITIES AND COMMUNITIES	Soils are a sink for airborne pollutants, act as a biofilter for gaseous pollutants and are used as landfill covers, all helping to improve air quality. Soils contribute particulates and dust storms and NH_3 and NO_x from fertiliser use.
14) Regulation of organisms detrimental to humans	2 ZERO HUNGER; 3 GOOD HEALTH AND WELL-BEING; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION; 15 LIFE ON LAND	Suppression of pathogens by indigenous microbial communities. Inactivation of detrimental organisms by abiotic factors. Soils are also a reservoir for pathogens, and poor soil health leads to reduced capacity to regulate detrimental organisms.
15) Pollination and dispersal of seeds and other propagules	2 ZERO HUNGER; 15 LIFE ON LAND	Healthy, non-polluted soils provide nesting substrate for a vast number of pollinators and seed dispersers and support alternative floral resources. Unhealthy, polluted soils change floral resource availability and quality leading to changes in foraging behaviour
16) Regulation of ocean acidification	13 CLIMATE ACTION; 14 LIFE BELOW WATER	Soils facilitate weathering which removes CO_2 from the atmosphere, reduces the impact of ocean acidification and improves ocean CO_2 buffering capacity. Cation exchange and secondary minerals could reduce weathering contribution.
17) Formation, protection and decontamination of soils and sediments	2 ZERO HUNGER; 15 LIFE ON LAND	Physicochemical interactions of contaminants with soil and biochemical transformations facilitated by soil microorganisms confer the cleaning of contaminants by soils. Organic and inorganic contaminants are of anthropogenic and geogenic origin.
18) Maintenance of options	3 GOOD HEALTH AND WELL-BEING; 4 QUALITY EDUCATION; 7 AFFORDABLE AND CLEAN ENERGY; 8 DECENT WORK AND ECONOMIC GROWTH; 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE; 10 REDUCED INEQUALITIES; 16 PEACE, JUSTICE AND STRONG INSTITUTIONS; 17 PARTNERSHIPS FOR THE GOALS	Healthy, well-managed soils allow multiple options to be considered now and in the future. Unhealthy, poorly managed soils can lead to ecosystem degradation and desertification, with knock on effects for other NCP.

Soil-derived Nature's Contributions to People and their contribution to the UN Sustainable Development Goals

Each paper in this issue (6-20) has presented evidence for the contribution of soils to NCP. Table 5 summarizes the potential positive, negative and context-specific contributions of soils to NCP arising from these papers.

In table 6, we map the soil contributions to NCP onto the relevant SDGs using the relationships between NCP and the SDGs outlined in the section "The contribution of Nature's Contributions to People to the UN Sustainable Development Goals.

As seen from tables 5 and 6, soils have capacity to contribute positively to all NCP and SDGs, but if poorly managed, degraded or polluted, may contribute negatively. This highlights a) the great potential of soils to underpin the NCP and SDGs, and b) the importance of managing soils well and maintaining them in a healthy, unpolluted condition.

Conclusions

Figure 1 summarises the contributions of soils to delivering the SDGs by showing a) the functions provided by soils, b) the NCP provided by soils underpinned by these functions, and c) impacts on the SDGs through the NCP supported by soils.

As shown in the papers in this special issue, and summarised here (Table 5), soils contribute positively to the delivery of all NCP, and have a role in underpinning all SDGs (Table 6). 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 (23-27).

The importance of maintaining healthy soils needs to be viewed against a backdrop of widespread and increasing rates of soil degradation globally (43). There are around 11 million km^2 of degraded land globally (44), 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 (45). 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 light of this, a few priorities emerge to allow soils to contribute optimally to 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 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 (46). 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 (43,47). 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 reducing disturbance, preventing erosion, minimising chemical inputs and preventing overgrazing of grasslands (48).

There is still a wealth of work to be done to better understand the processes linking soil functions to delivery of NCP, and wider work to better understand how NCP contribute to the SDGs. But we have enough knowledge now to move forward with the implementation of 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.

[Figure 1 here – separate file attached]

Acknowledgments

The input of PS contributes to Soils-R-GRREAT (NE/P019455/1) and the input of PS and SK contributes to the European Union's Horizon 2020 Research and Innovation Programme through project CIRCASA (grant agreement no. 774378). PR acknowledges funding from UK Greenhouse Gas Removal Programme (NE/P01982X/2). GB De Deyn acknowledges FoodShot Global for its support. TKA 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). The input of DG was supported by the New Zealand Ministry of Business, Innovation and Employment (MBIE) strategic science investment fund (SSIF). PMS acknowledges support from the Australian Research Council (Project FT140100610). PM's work on ecosystem services is supported by a National Science Foundation grant #1853759, "Understanding the Use of Ecosystem Services Concepts in Environmental Policy". LGC is funded by National Council for Scientific and Technological Development (CNPq, Brazil – grants 421668/2018-0 and 305157/2018-3) and by Lisboa2020 FCT/EU (project 028360). BS acknowledges support from the Lancaster Environment Centre Project.

References

1. Dominati E, Patterson M, Mackay A. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecological Economics. 2010;11.
2. Robinson DA, Lebron I, Vereecken H. On the Definition of the Natural Capital of Soils: A Framework for Description, Evaluation, and Monitoring. Soil Science Society of America Journal. 2009;73(6):1904–11.
3. Robinson DA, Fraser I, Dominati EJ, Davíðsdóttir B, Jónsson JOG, Jones L, et al. On the Value of Soil Resources in the Context of Natural Capital and Ecosystem Service Delivery. Soil Science Society of America Journal. 2014;78(3):685–700.
4. Smith P, Cotrufo MF, Rumpel C, Paustian K, Kuikman PJ, Elliott JA, et al. Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. SOIL. 2015;1(2):665–85.
5. Adhikari K, Hartemink AE. Linking soils to ecosystem services — A global review. Geoderma. 2016;262:101–11.
6. De Deyn, G.; Kooistra, L. The role of soils in habitat creation, maintenance and restoration. Phil Trans R Soc. B. (this issue).
7. Carvalheiro, L.; Bartomeus, I.; Rollin, O.; Timóteo, S.; Tinoco, C.F. The role of soils on pollination and seed dispersal. Phil Trans R Soc. B. (this issue).
8. Giltrap, D.; Ausseil, A.-G.; Cavanagh, J.; Stevenson, B. The role of soils in the regulation of air quality. Phil Trans R Soc. B. (this issue).
9. Renforth, P.; Campbell, J. The role of soils in the regulation of ocean acidification. Phil Trans R Soc. B. (this issue).
10. Keesstra, S.; Sannigrahi, S.; Lopez V.M.; Pulido, M.; Novara, A.; Visser, S.; Kalantari, Z. The role of soils in regulation and provision of blue and green water. Phil Trans R Soc. B. (this issue).
11. Cheng, K.; Xu, X.; Cui, L.; Zheng, J.; Sun, J.; Li, Y.; Pan, G. The role of soils in regulation of freshwater and coastal water quality. Phil Trans R Soc. B. (this issue).
12. Sarkar, B.; Mukhopadhyay, R.; Ramanayaka, S.; Bolan, N.; Sik Ok, Y. The role of soils in the disposition, protection and decontamination of environmental contaminants. Phil Trans R Soc. B. (this issue).
13. Saco, P.; McDonough, K.; Rodriguez, J.; Rivera-Zayas, J.; Sandi, S. The role of soils in the regulation of hazards and extreme events. Phil Trans R Soc. B. (this issue).
14. Samaddar, S.; Karp, D.; Schmidt, R.; Devarajan, N.; McGarvey, J.; Pires, A.; Scow, K. Role of Soil in the Regulation of Plant Pathogens: Soils' Contributions to People. Phil Trans R Soc. B. (this issue).
15. Smith, J.; Farmer, J.; Smith, P.; Nayak, D. The role of soils in provision of energy. Phil Trans R Soc. B. (this issue).
16. Morel, J.-C.; Charef, R.; Hamard, E.; Fabbri, A.; Beckett, C.; Bui, Q. Earth as construction material in the circular economy context: practitioner perspectives on barriers to overcome. Phil Trans R Soc. B. (this issue).
17. McElwee, P. The role of soils in learning and inspiration, physical and psychological experiences, and in supporting identities. Phil Trans R Soc. B. (this issue).
18. Thiele-Bruhn, S. The role of soils in provision of genetic, medicinal and biochemical resources. Phil Trans R Soc. B. (this issue).
19. Lal R, et al. The role of soils in regulating climate. Phil Trans R Soc. B. (this issue).
20. Silver, W. et al. The role of soils in provision of food and feed. Phil Trans R Soc. B. (this issue).
21. Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, et al. Assessing nature's contributions to people. Science. 2018;359(6373):270–2.
22. IPBES. Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science- Policy Platform on Biodiversity and Ecosystem Services. Bonn, Germany: IPBES secretariat; 2019.
23. Bouma J. Soil Security in Sustainable Development. Soil Systems. 2019:3(1):5.
24. Bouma J, Montanarella L. Facing policy challenges with inter- and transdisciplinary soil research focused on the SDG's. SOIL Discussions. 2016:5;1–22.
25. Bouma J, Montanarella L, Evanylo G. The challenge for the soil science community to contribute to the implementation of the UN Sustainable Development Goals. Soil Use and Management. 2019;35(4):538–46.
26. Visser S, Keesstra S, Maas G, de Cleen M, Molenaar C. Soil as a Basis to Create Enabling Conditions for Transitions Towards Sustainable Land Management as a Key to Achieve the SDGs by 2030. Sustainability. 2019;11(23):6792.
27. Keesstra SD, Bouma J, Wallinga J, Tittonell P, Smith P, Cerdà A, et al. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. SOIL. 2016;2(2):111–28.
28. European Commission (EC): Communication from the Commission
to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions, Thematic Strategy for Soil Protection, COM 231 Final, Brussels, 2006.
29. Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, et al. Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals. Annual Review of Environment and Resources. 2019;44(1):255–86.
30. Kadykalo AN, López-Rodriguez MD, Ainscough J, Droste N, Ryu H, Ávila-Flores G, et al. Disentangling 'ecosystem services' and 'nature's contributions to people'. Ecosystems and People. 2019;15(1):269–87.

31. McElwee P, Calvin K, Campbell D, Cherubini F, Grassi G, Korotkov V, et al. 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. 2020;26(9):4691–721.
32. Pascual U, Balvanera P, Díaz S, Pataki G, Roth E, Stenseke M, et al. Valuing nature's contributions to people: the IPBES approach. Current Opinion in Environmental Sustainability. 2017;26–27:7–16.
33. Reid WV, Millennium Ecosystem Assessment, World Resources Institute, editors. Ecosystems and human well-being: synthesis; a report of the Millennium Ecosystem Assessment. Washington, DC: Island Press; 2005. 137 p.
34. United Nations Sustainable Development Goals. Available from: https://www.un.org/sustainabledevelopment/sustainable-development-goals/
35. Wood SLR, Jones SK, Johnson JA, Brauman KA, Chaplin-Kramer R, Fremier A, et al. Distilling the role of ecosystem services in the Sustainable Development Goals. Ecosystem Services. 2018;29:70–82.
36. The Economics of Ecosystems and Biodiversity. 2010. Available from: http://teebweb.org/publications/teeb-for/research-and-academia/
37. Yang S, Zhao W, Liu Y, Cherubini F, Fu B, Pereira P. Prioritizing sustainable development goals and linking them to ecosystem services: A global expert's knowledge evaluation. Geography and Sustainability. 2020;1(4):321–30.
38. Anderson CB, Seixas CS, Barbosa O, Fennessy MS, Díaz-José J, Herrera-F. B. Determining nature's contributions to achieve the sustainable development goals. Sustain Sci. 2019;14(2):543–7.
39. Johnson JA, Jones SK, Wood SLR, Chaplin-Kramer R, Hawthorne PL, Mulligan M, et al. Mapping Ecosystem Services to Human Well-being: a toolkit to support integrated landscape management for the SDGs. Ecological Applications. 2019;29(8):e01985.
40. Smith P, Ashmore MR, Black HIJ, Burgess PJ, Evans CD, Quine TA, et al. REVIEW: The role of ecosystems and their management in regulating climate, and soil, water and air quality. Journal of Applied Ecology. 2013;50(4):812–29.
41. Kinney PL. Climate Change, Air Quality, and Human Health. American Journal of Preventive Medicine. 2008;35(5):459–67.
42. Beerling DJ, Leake JR, Long SP, Scholes JD, Ton J, Nelson PN, et al. Farming with crops and rocks to address global climate, food and soil security. Nature Plants. 2018;4(3):138–47.
43. Status of the world's soil resources: main report. Rome: FAO: ITPS; 2015.
44. Lal R. Restoring Soil Quality to Mitigate Soil Degradation. 2015;21.
45. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, IPBES. The IPBES assessment report on land degradation and restoration. 2018. Available from: https://zenodo.org/record/3237392
46. 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. Global Change Biology (in press).
47. Lal R, Lal R. Managing soil quality for humanity and the planet. Front Agr Sci Eng. 2020;7(3):251–3.
48. Smith P, Powlson DS. Sustainability of soil management practices – a global perspective. In: Soil Biological Fertility - A Key To Sustainable Land Use In Agriculture. (ed. L.K. Abbott & D.V. Murphy), Kluwer Academic Publishers, Dordrecht, Netherlands: 241-254.

Figure and table captions

Figure 1. Functions provided by soils (inner ring), the NCP provided by soils underpinned by these functions (middle ring) and impacts on the SDGs through the NCP supported by soils (outer ring). Light blue numbered circles in the middle ring show the corresponding soil functions that contribute to the NCP. Grey numbered circles in the outer ring show the corresponding NCP that contribute to the SDGs.

Table 1. The seven soil functions as defined by the European Commission (28)

Table 2. IPBES Nature's Contributions to people (NCP), with the corresponding Millennium Ecosystem Assessment (MA) ecosystem services and categories shown.

Table 3. The UN Sustainable Development Goals (SDGs) (34)

Table 4. Relationship between NCP and SDGs. A relationship is shown (in blue) only to those interactions indicated by over 50% of expert respondents in Anderson et al. (38). Note: impacts where a relationship was not identified by Anderson et al. (38), but where the relationship is well-documented elsewhere are shown (in green). These are the impact of habitat creation and maintenance (40), and the impact of regulation of air quality (41) on SDG3, the impact of regulation of ocean acidification on SDG13 through enhanced mineral weathering (42) and the impact of regulation of organisms detrimental to humans on SDGs 2, 12 and 15 (14).

Table 5. Summary of the potential positive, negative and context-specific contributions of soils to NCP arising from papers in this issue. Note, these impacts are illustrative rather than comprehensive.

Table 6. The contribution of soils to the SDGs, with contributions derived from relationships between NCP and the SDGs outlined in the section "The contribution of Nature's Contributions to People to the UN Sustainable Development Goals". Dependencies enabling positive SDG effects are shown in blue, those leading to negative SDG effects are shown in red.

Authors' Contributions

PS wrote the first draft of the article, with input from all authors. All authors supplied information used in this paper, helped to revise drafts and approved the final version to be published.

Competing Interests

We have no competing interests.