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The role of soils in regulation and provision of blue and green water

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The United Nations Sustainable Development Goal 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. In this opinion paper, we assess how soils and associated land and water management can help achieve this goal, considering soils at two scales: local soil health and healthy landscapes. The merging of these two viewpoints shows the interlinked importance of the two scales. Soil health reflects the capacity of a 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, and they are connected by the water that flows through the soil and the transported sediments. Soils are linked to water in two ways: through plant-available water in the soil (green water) and through water in surface bodies or available as groundwater (blue water). In addition, water connects the soil scale and the landscape scale by flowing 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.

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

1. Introduction

The United Nations Sustainable Development Goal (SDG) 6 (https://sdgs.un.org/2030agenda) aims for clean water and sanitation for all by 2030 [1,2]. Considering the enormous impact of water scarcity on overall human civilization, the World Economic Forum (WEF) has declared the water crisis as one of the largest global threats [3]. There is currently a lack of basic water services and access to safely managed sanitation facilities worldwide. Water scarcity currently affects more than 40% of the global population, as a lack of drinkable water for immediate consumption, but even more so as a lack of irrigation water for agriculture [4,5]. Additionally, nearly two-thirds of the global

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population (about 4 billion people) is currently under threat of water scarcity for at least one month a year [6]. Extraction of water from deep aquifers and overuse of surface water are affecting aquifer recharge, making the use of water resources unsustainable [7,8]. This is a particular problem in drylands, where more than 70% of all water is used for irrigation [9], and irrigation with saline water causes soil salinization and lower yields [10] and, ultimately, unproductive land [11]. Water-related problems (droughts and floods) are compromising livelihoods in large areas around the world, and are being aggravated by climate change [12].

Solutions to these problems may lie in appropriate soil management. It has been demonstrated by, e.g. Keesstra *et al*. [13], Hatfield *et al*. [14], Smith *et al*. [12] and Bouma *et al*. [15] that healthy soil and careful management of soils at landscape scale can help regulate the water cycle. Available freshwater in the landscape can be divided into green water and blue water. Blue water refers to the water in rivers, lakes and ponds, and groundwater available to be pumped to the surface, while green water is the plant-available water in the soil [16]. An estimated 74% of all freshwater used by humans derives from the soil [17]. A healthy soil can absorb and contain more green water than a soil in poor condition [18]. This is because a healthy soil has a higher infiltration rate and greater water-holding capacity, owing to better structure and aggregate stability and greater macro-porosity, which lowers the rainfall-runoff coefficient and erosion risk [19]. Soils are not only important for storing and supplying water but they also filter out pollutants [20]. Soils are part of the landscape in which they are located, so managing the functions of soils in the landscape can improve the ecosystem services of that landscape. This is particularly true for water-related ecosystem services [21]. Landscape management, which is steered by socio-economic and physical conditions of a specific site, plays an important role in regulating the amount of water that is available at a specific moment in time, ensuring that there is not too much (flooding) or too little (drought). Understanding the soil–water nexus provides insights into this regulation process [22].

We assessed the potential role of soils in achieving SDG6 by considering soils on two scales: local scale and landscape scale. The small local scale covers all aspects of soil health, which is a relatively new way of assessing soils and their characteristics and functions. Soil health is defined as the ability of a soil to provide key regulatory, supporting and provisioning ecosystem services, depending on the location and inherent characteristics of the soil itself; for instance, in optimal conditions, a sandy desert soil will provide different ecosystem services from a Chernozem. This approach considers the soil as a dynamic system in which different aspects of the soil are in balance (or not). A well-balanced (healthy) soil will be able to deliver the maximum amount of ecosystem services [23], while a poorly managed unhealthy soil can be attributed to the deficit of overall ecosystem service supply. Locally balanced and healthy soil can also facilitate the local spillovers and synergies among the ecosystem functions and eventually improve the overall supportive functions of the ecosystem components; for example, a healthy soil can store larger volumes of water for a longer period of time after heavy rainfall, resulting in less waterlogging problems downstream.

The landscape-scale covers the entire landscape, where the soil provides an important fundament of the landscape. The structure and composition of the landscape, such as fragmentation, connectivity, diversity, etc., determines soil–water interactions substantially. Connectivity of surface runoff and associated sediment transport and storage because of more complex landscape structures (geology, geomorphology, land use, slope length, man-made elements, etc.) affect hydrological and geochemical processes such as rainfall-infiltration rate, soil erosion rate, water storage capacity, sediment fate and temporal storage, and carbon sequestration potential [24,25]. How a soil functions within the landscape thus depends on land and water management of the soil, plants and the landscape. Terraced landscapes reduce the runoff connectivity [26], but field size, use of tillage, the use of herbicides and field drainage measures also impact the runoff potential at the landscape-scale [27].

In the following sections, we discuss the relevance of soils and knowledge about soil functions in achieving SDG6 (Clean water and sanitation). First, soil functions are evaluated in terms of their interaction with green and blue water for soils in agricultural and natural areas. This is followed by a discussion of soil solutions and landscape solutions based on natural processes on the small and larger scale. Finally, requirements for the implementation of these nature-based solutions are considered.

2. Soils contribution to SDG6: clean water and sanitation

The main objective of SDG6 is to ensure the availability and sustainable management of water and sanitation for all. It is divided into eight subgoals that can be grouped into four sets, dealing with: (i) water quantity and availability (Subgoals 6.1 and 6.4), (ii) water quality (Subgoals 6.2 and 6.3), (iii) finding sustainable solutions (Subgoals 6.5 and 6.6) and (iv) policy and governance (Subgoals 6.A and 6.B) (figure 1).

(a) Water quantity, location and timing: the natural system provides ecosystem services (figure 2*a*, green bar; Subgoals 6.1, 6.4)

Subgoals 6.1 (access to safe and affordable drinking water for all) and 6.4 (substantially increase water-use efficiency and address freshwater scarcity) relate to the amount of water available to human populations at different points in time and different locations. Soil plays a relevant role for both these subgoals (figure 2). At the local scale of soil health, they are affected by the infiltration capacity of the soil, with associated groundwater recharge, and by land management and biodiversity and how these affect water scarcity. At the landscape scale, they are affected by land and water management and effects on soil erosion and flooding.

(i) Infiltration and runoff: two pathways for rainwater

A healthy soil has a high organic matter content, which has no specific threshold for all soils, but the optimum amount of organic matter depends on the climate and geological location, which will be able to sustain optimum biodiversity [28]. Microbial activity and sufficient organic matter improve the soil structure and increase aggregate stability, resulting in high infiltration capacity and larger soil water storage

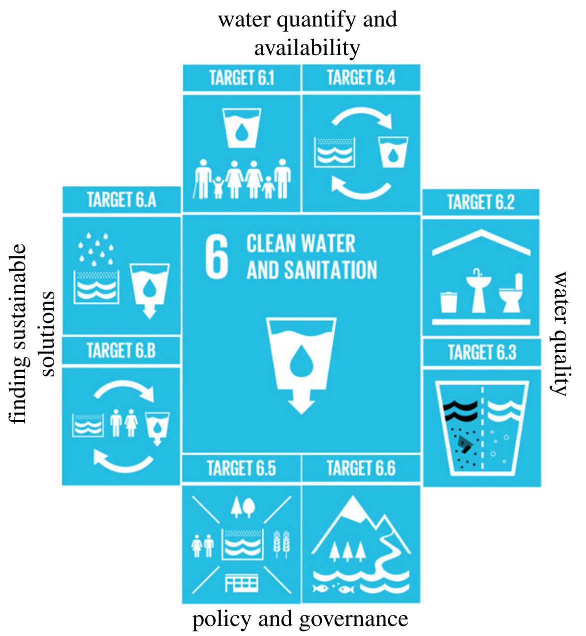

Figure 1. The eight subgoals of United Nations Sustainable Development Goal 6: clean water and sanitation. 6.1 Access to safe and affordable drinking water for all. 6.2 Access to sanitation and hygiene for all and end open defecation. 6.3 Improve water quality by reducing pollution, halving untreated wastewater and increasing recycling and safe reuse globally. 6.4 Substantially increase water-use efficiency and address freshwater scarcity. 6.5 Implement integrated water resources management. 6.6 Protect and restore water-related ecosystems. 6.A Expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes. 6.B Support and strengthen the participation of local communities in improving water and sanitation management (adapted from https://unstats.un.org/sdgs/report/2020/). (Online version in colour.)

capacity [29]. Hence, organic matter and soil biodiversity directly influence green water availability. Green water, also called plant available water content, is retained in the soil pores by soil colloids and is available for plant growth, while blue surface water and groundwater are replenished by streamflow and infiltration.

Higher water-holding capacity will enable a soil to provide more green water, which will be available for vegetation to use [30]. High infiltration capacity will allow much of the rain that reaches the soil surface to infiltrate into the soil and percolate down to recharge the groundwater. If the infiltration capacity is low, the percentage of rainfall that becomes runoff is high, although some water can pond on the surface and evaporate directly [31,32]. A healthy soil with abundant macropores owing to high soil biodiversity and good soil structure has a rougher soil surface, which results in longer ponding and provides more time for rainwater to infiltrate [33]. Management practices that allow the development of litter cover favour biocrust decomposition, enhancing soil quality and moisture [34,35]. Good soil structure and high aggregate stability will also prevent surface slaking on silty soils, which can prevent infiltration [36].

(ii) Downstream water and erosion problems related to poor water management

If the soil surface is smooth owing to lack of plant cover, resulting in surface slaking and poor micromorphology, or if the soil lies in a landscape with long slopes and high connectivity, most rainfall will become surface runoff. Runoff causes: (i) loss of soil and seeds through erosion and topsoil wash-off (e.g. [37]), (ii) landscape disruption through gully erosion (e.g. [38]), (iii) flooding [39,40], (iv) loss of soil nutrients and associated downstream eutrophication of downstream water bodies [41], (v) reduction in freshwater supply [42], and finally, (vi) water scarcity [43].

Large amounts of fast-running surface runoff have the capacity to dislodge soil particles and transport them downstream, where they are re-deposited. This erosion process creates problems on-site by removing the fertile topsoil. It also creates problems offsite as the transported soil and sediments can silt up waterways and reservoirs and block drains and culverts, causing flooding of roads and houses. In the transport zone, rills, gullies and rivers may be incised, breaking the connectivity of fields and creating channels for rapid water flow. The water that does not infiltrate into the soil cannot become local green water or blue water (groundwater recharge), which may result in future water scarcity. Therefore, too much water (flooding) at one time of the year may result in too little water at another time of the year.

(b) Water quality: Subgoals 6.2, 6.3

Subgoals 6.2 (access to sanitation and hygiene for all and end open defecation) and 6.3 (improve water quality by reducing pollution, halving untreated wastewater, and increasing recycling and safe reuse globally) are related to the quality of water, for human use and in the environment in its broadest sense (figure 1). In both instances, soil management can be part of the solution. The 'green shift' towards a bio-based economy consists primarily of more intensive land management to maximize both production of biomass and surface water quality [44]. In agriculture at the local and landscape-scales, pesticides and herbicides are used for crop protection and fertilizers are used to increase crop yields. However, these chemicals have negative effects on the environment and on soil health, by reducing overall landscape biodiversity and soil biodiversity. Lower microbial activity reduces the amount of carbon in the soil, which can have negative effects on soil structure, on infiltration and water storage capacity. Apart from the on-site problems, the higher runoff associated with lower infiltration is contaminated with agro-chemicals that are sprayed on the surface and vegetation. Even though some of these chemicals will be absorbed to the soil particles, much will be transported in solute form as overland flow that may affect the quality of water bodies downstream. If infiltration can be achieved, soils have the capacity to filter water, which is an important ecosystem service that can help to achieve Subgoal 6.3 [20]. The filtering function of soils is twofold: chemical filtering and soil physical filtering. Chemical filtering is based on (bio)chemical reactions in the soil, where exchange reactions occurring on charged surfaces can absorb dissolved chemicals in the soil water. Soil biota, which include bacteria, fungi and soil-dwelling animals, play an important role in the soil processes related to nutrient cycling and contaminant retention. The physical filtering function of a soil also depends on its physical characteristics, which determine the infiltration potential, water storage capacity and residence time of soil water [45]. In combination, chemical and physical filtration determine the potential of a soil to remove contaminants from infiltrating water, which helps to protect groundwater resources from diffuse contamination [46].

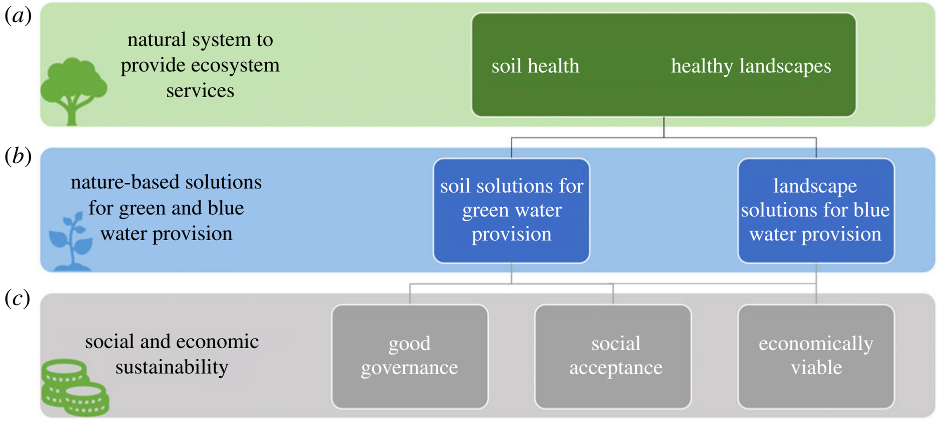

Figure 2. Step-wise approach to achieving social and economic sustainability in provision of green and blue water by nature-based systems, with soil as an important component. (Online version in colour.)

(c) Finding solutions (figure 2*b*, blue bar)

(i) Nature-based solutions on agricultural land: Subgoal 6.5

Subgoal 6.5 (implement integrated water resources management) requires the formulation of measures to achieve sustainable water use. As most freshwater is used for agricultural purposes, achieving sustainability in agriculture is of critical importance in fulfilling Subgoal 6.5. Agriculture is responsible for approximately 92% of all freshwater use by humans [17]. Worldwide, an estimated 6685 km^3 of water are used annually for crops, and of this amount, 800–1100 km^3 per year (12–16%) are supplied by irrigation from different sources, such as rivers, lakes, reservoirs and groundwater [47]. To reduce the consumption of water and reduce pollution of aquifers and surface water bodies, new solutions based on the natural systems are needed. Nature-based solutions are becoming more common in river and coastal management, and are also beginning to be used in agriculture [48,49]. Practices that make the soil surface rougher and the landscape less steep are as old as agriculture itself. Ploughing is still the most commonly used practice for roughening the soil surface and inducing more infiltration [50]. The higher roughness occurs only after recent tillage; however, over time after tillage surface soil crust develops, which is responsible for runoff increase [51]. However, ploughing has negative side-effects for soil biodiversity and reduces the amount of soil organic matter in the uppermost soil layer. This has led to the promotion of no-tillage practices, but when ploughing is omitted pesticides use generally increases to remove weeds that compete for soil water with the crop, increasing the risk to the environment and soil health. Considering future technological developments, automated handpicking by robots could significantly reduce the need to use pesticides [52]; and could be an excellent example of a nature-based solution combined with technological development. Today, alternative options are available such as the use of cover crops [53], straw cover [54] or a mulch of, e.g. chipped pruned branches [55] to avoid soil erosion, increase soil roughness and improve soil carbon content.

Step-like structures or soil or stone bunds that convert a long slope into a terraced landscape are another way to prevent or reduce runoff and allow water to infiltrate into the soil [56]. Such structures can also be used with good effect on irrigated land. Drip irrigation and fertigation are generally also recommended, as these are said to be more water-use efficient [57,58]. However, in many areas of the world, drip irrigation is now being installed at sites where there was previously no irrigation system at all [59]. This will increase the amount of water consumed by agriculture and result in groundwater depletion, owing to over-exploitation of water resources. In addition, when drip irrigation is installed on formerly terraced landscapes, the bunds or terrace structures are generally removed to rationalize farming operations, which leads to severe erosion events owing to the long slope lengths created. Thus, it is important to keep the sustainability of the landscape in mind during the planning of land-use and agricultural investments [60,61]. Nature-based solutions are needed to avoid land degradation and to help achieve sustainability in the use of natural resources and the livelihoods of farmers [24,25].

(ii) Nature-based solutions on natural land: Subgoal 6.6

Subgoal 6.6 (protect and restore water-related ecosystems) focuses on ways to protect natural ecosystems, with particular attention to water-related problems. The main threat to natural water bodies such as lakes, rivers, wetlands and seas is pollution originating from agricultural, industrial and urban activities. As soils are directly affected by agricultural pollution, the following analysis focuses on this aspect. The damage to ecosystems caused by agricultural pollution extends beyond natural environments to the people who rely on natural systems for their livelihoods [62]. Therefore, restoration of these water-related ecosystems is essential. Soils can play an important role in ecosystem restoration measures. For example, wetland restoration can have a dual function by reducing the risks of both downstream flooding and the influx of sediments from upstream to downstream areas [63]. Establishing specific plant species in a (constructed) wetland may help to reduce the influx of nutrient-rich water into downstream water bodies and create a richer, more biodiverse ecosystem [64,65]. Soil stabilization measures and vegetation restoration measures can also be used further upstream to reduce the connectivity of agricultural catchments and eroded hillslopes to the stream system [66,67].

(d) Social and economic sustainability: people as part of land and water (figure 2*c*, grey bar)

(i) International policy and governance: Subgoal 6.A

Sub-goal 6.A (expand international cooperation and capacity-building support to developing countries in water- and sanitation-related activities and programmes) focuses on the international policy and governance needed to reach sustainable water use. In such work, it is relevant to take the timeline of the SDGs into account. The aim is for the SDGs to be achieved by 2030, which is a very short time for biophysical processes. Moreover, progress to date has been slow since the SDGs were agreed upon by the United Nations in 2015 [68], and implementation is still a long way off in the majority of countries. Political leadership is needed to reach the goals—or to be well on the way to reaching them by 2030. The European Commission has recently launched the Green Deal [69], which provides a great opportunity to address land- and water-related SDGs, provided that shared ambitions are set, together with measurable targets and indicators to evaluate progress. These shared ambitions then need to be translated into national plans and strategies to implement the SDGs and to integrate them into existing policies. A specific focus on irrigation management will be necessary, e.g. to evaluate the impact of modern irrigation strategies on agricultural production, but also on land- and water-related SDGs. For each land use plan, it is important to evaluate trade-offs that could occur when the plan is implemented. New policy is needed to make this a standard procedure in the evaluation of new land-use planning. Promotion of regenerative or nature-inclusive agriculture is a potential option to achieve healthy soils and healthy landscapes that supply clean sustainably used water resources and help protect and restore natural areas. However, rewarding sustainable farmers may not be the best way to make a true transition to healthy soils and healthy landscapes [70]. Instead, polluting farmers and other stakeholders could be held responsible for the damage they cause to the environment and fined for unsustainable management. The growing consensus that favours adopting more inclusive and integrated approaches for managing and allocating land-water resources has recently been gaining more attention in the developing countries [71]. The example of land and soil conservation programs such as 'Grain for Green' in China [72], 'Drought Prone Area Programme' (DPAP) and 'Integrated Watershed Development Programme' in India [73], conservation agriculture (CA) programs in Sub-Saharan Africa (SSA) and South Asia (SA) [74], has proven successful in multiple ways and consequently had an impact on achieving land- and water-related SDGs. More inclusive and co-designing approaches would encourage stakeholders involved in planning and management decisions as such approaches have proven to be one of the key determining elements for successful implementation of policies in many African countries [75]. As part of nature-based solutions, the ecosystem-based approaches are another potential option to protect depleting water resources in the deprived regions to keep the societies and economies functional [76]. The concept of integrated water resources management has appeared in the policymaking process that allows the concerned authorities and stakeholders to link different components of the socio-ecological systems and to realize how decisions made for one component may affect the overall water resource consumption structure and its allied dependent sectors [77]. Priority is being given to technological innovations that promote sustainable use of water resources, empower capacity building that helps to create a more resilient irrigation system to increase water use efficiency, and encourage recycling of wastewater and reuse of technologies, etc. (https://unstats.un.org/sdgs/report/2017/goal-06/).

(ii) Acceptable local solutions: Subgoal 6.B

Subgoal 6.B (support and strengthen the participation of local communities in improving water and sanitation management) focuses on finding management options at the local scale to achieve sub-goals 6.1–6.6 of SDG6. The solutions suggested above in relation to different subgoals are mostly embedded in the biosphere, and the benefits highlighted are mainly to protect and restore the environment, with specific attention to water. However, to implement the SDGs, all goals need to be taken into account, including those relating to society and the economy [48,49]. For future development that is sustainable also from a socio-economic point of view [55], participatory solutions that are region-specific or even site-specific are needed. Strategies that take the soil and its functions and ecosystem provision into account are essential in land use planning on regional and local scales. The first step must be to raise awareness of the importance of this specific SDG [78] and the role soils can play in its fulfillment. In the interdisciplinary region- or site-specific land-use planning, ensuring soil health and landscape health is a critical task. The trade-offs of all future land use plans should be evaluated, to assess the on-site and off-site effects, in particular in water-scarce areas [79]. Truly sustainable plans must be embedded in the biosphere and should therefore have a long-term vision [80]. It is important to enable and encourage stakeholders to make the transition to sustainable land and water management [81,82]. This may require the phasing out of former unsustainable practices and promotion of new sustainable management so that it becomes the norm and not a niche [70,82]. Highlighting examples of good practices that have already been implemented and have proven to be successful can be a good strategy to promote adoption.

3. Conclusion

Soils can play a key role in achieving the United Nations SDG6, which aims for clean water and sanitation for all by 2030. SDG6 has eight subgoals, dealing with: (i) water quantity and availability, (ii) water quality, (iii) finding sustainable solutions and (iv) policy and governance. This paper assessed the potential for achieving these subgoals at the local scale of soil health and at the wider landscape scale. Based on this analysis, the following management options embedded in the functioning of the soil and the landscape were identified:

Manage soil health: improve soil characteristics and thus enhance soil functions that provide ecosystem services, which can help avoid water scarcity and result in more sustainable agriculture and use of natural resources.

Manage healthy landscapes: reduce the connectivity of surface water and sediment, and associated pollutants, to avoid soil erosion (including off-site effects), surface and subsurface water pollution, and flooding.

It is important to apply solutions that work together with the forces of nature (nature-based solutions) to improve the availability of plant-available green water in the soil and manage the amount and quality of blue water (surface water and groundwater) throughout the year(s) to avoid flooding and droughts. The nature-based soil management options can be supported by technological solutions to increase the impact. These management options must be fostered by embedding them in policy and governance on different scales (global, continental, national, regional, local), while: (i) taking into account trade-offs associated with new management strategies; (ii) phasing out old and unsustainable systems; and (iii) providing incentives for farmers to move away from chemical-based agriculture. All solutions will need to be sustainable from both the biophysical and socio-economic perspectives to be socially and economically acceptable to land users (mainly farmers).

Data accessibility. This article has no additional data.

Authors' contributions. S.K. designed and coordinated the study and drafted the manuscript; all other authors 'brainstormed' together and later critically revised the manuscript and were involved in answering the reviewer's comments. All authors gave final approval for publication and agree to be held accountable for the work performed therein.

Competing interests. We declare we have no competing interests.

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