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The role of soils in the regulation of hazards and extreme events

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Review

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The frequency and intensity of natural hazards and extreme events has increased throughout the last century, resulting in adverse socioeconomic and ecological impacts worldwide. Key factors driving this increase include climate change, the growing world population, anthropogenic activities and ecosystem degradation. One ecologically focused approach that has shown potential towards the mitigation of these hazard events is the concept of nature's contributions to people (or 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. Thus, this 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.

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

1. Introduction

Every year, natural hazards and extreme events are responsible for numerous fatalities and massive economic losses. Over 3.4 million people lost their lives to natural hazard-linked disasters (excluding epidemics) worldwide from 1970 to 2019 alone, while the number of people who were negatively impacted by natural hazard-linked disasters increased threefold from the 1970s to the 2010s [1]. Aside from immediate impacts on fatalities, natural hazards are also known to reap negative economic impacts [2], with global economic losses estimated at over $2554 billion USD for the period 2000–2019 [1]. Additionally, vulnerable socioeconomic populations are typically the most adversely impacted, evidenced by a higher death rate in countries with a low socio-demographic index value following high impact hazard events [3].

Unfortunately, the frequency and intensity of natural hazards and extreme events have increased throughout the last century, with reliable data showing a clear increase over the last four decades [1] (figure 1). The increase has been attributed to numerous factors, including climate change, the growing world population, anthropogenic activities and ecosystem degradation [2,4–6]. Climate change has driven an increase in the frequency and intensity of hazard events, related in part to the rising trend in temperature and the increase in frequency and intensity of precipitation events [6]. Human settlements increasingly occupy areas of the landscape that are naturally prone to hazards including floodplains, low-lying coastal areas and alluvial fans [2,6]. In addition, the associated changes to the physical, chemical and biological characteristics of the landscape, which stem largely from anthropogenic activities (including urbanization and deforestation), have resulted in widespread ecosystem degradation. This degradation leads to a diminished capability for nature and society to recover from a natural hazard [4], thus creating a positive feedback loop that drives an increase in a greater number of devastating

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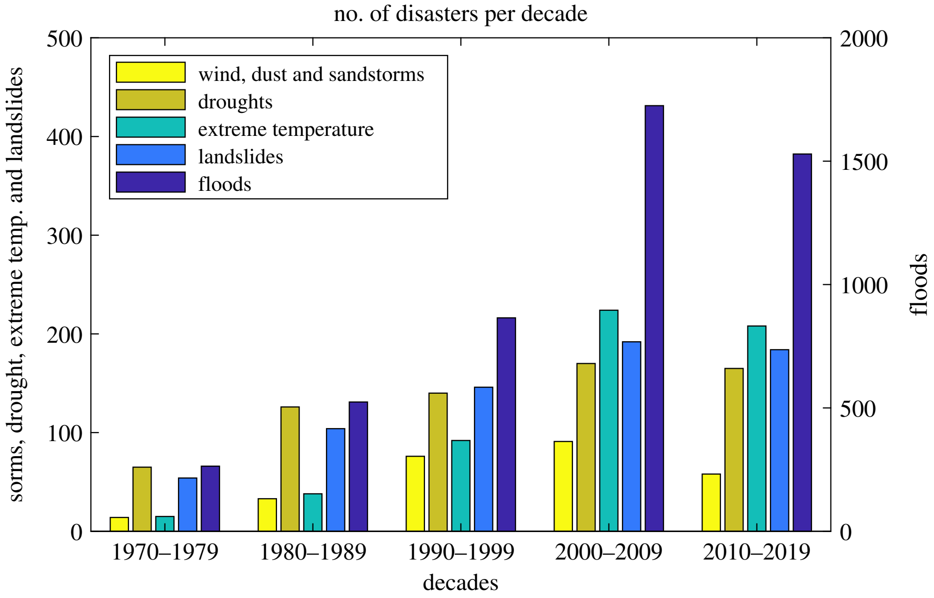

Figure 1. Number of disasters per decade. Note: data obtained from CRED [1]. (Online version in colour.)

disaster events. Associated ecosystem functions which are essential to human well-being, including the ability to grow food and the provision of freshwater, are also degraded.

One strategy that enables a more ecologically focused approach towards mitigation and/or management of natural hazards and extreme events is the concept of nature's contributions to people (or NCP). NCP refers to the 'contributions, both positive and negative, of living nature to the quality of life of people' [7, p. 270] and encompasses all of the processes and goods that nature provides to humans [8]. NCP is closely related to the concept of ecosystem services (ES), viewed as either a synonym to the term or a 'supra-concept' that encompasses all that ES offers and more [9].

Regulating contributions, within the context of NCP, describe the capability of an ecosystem to modify and sustain both the material and non-material benefits of a system [10], and include processes such as water purification, climate regulation and disaster risk reduction [2,4,10]. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [10] defined the regulation of hazards and extreme events as the 'amelioration, by ecosystems, of the impacts on humans or their infrastructure caused by e.g. floods, wind, storms, hurricanes, seawater intrusion, tidal waves, heat waves, tsunamis, high noise levels' and 'reduction, by ecosystems, of hazards like landslides, avalanches' [10, p. 6].

The ability of individual ecosystems to modulate the impact of hazard events and increase overall system resiliency is well documented [2,4]. Specific ecosystems are renowned for their capacity to provide protection against hazards and extreme events, such as mangrove swamps and coral reefs for the defence that they provide against coastal surges and tropical storms [2,4]. More general ecosystem characteristics, such as increased forest cover and the presence of wetlands, have also shown hazard mitigation benefits [4,8,11]. The regulating role of soils on natural hazards has long been recognized [12] through the soils' storage capacity of water, biomass and energy. Soils and their associated ecosystem have the ability to regulate water dynamics, for example, by trapping and slowly releasing stormwater to attenuate floods, and storing water in the soil profile during wet periods and redistributing the stored water during droughts.

We consider a broad definition of soil as the interface between the atmosphere, lithosphere and biosphere, which hosts flora and fauna, and is affected by geomorphological features in the landscape and other anthropic impacts [13]. Soils contribute to the regulation of hydrological, erosional and biogeochemical cycles, including the carbon cycle [14], and are known to store massive amounts of carbon (C) (second only to oceans) where management strategies can be used to increase current levels of soil organic C even further [15,16]. The interaction between soils and plants is particularly important for ecosystem functionality (including hydrological and biogeochemical functions) and to prevent degradation processes [17–19]. Healthy soils can sustain vegetation with a root system that directly reduces erosion potential, landslide risk and negative impacts associated with windstorms. Unfortunately, owing to improper management and/or poor ecosystem protection, these fundamental ecological functions of soils are often lost, including their regulating capacity of hazard events. Moreover, the integrity of soils and their associated ecological functions are increasingly under pressure from human development and climate change, in a time when the dependence of society on these critical functions is stronger than ever. Land degradation, owing to the impact of human activities, is currently negatively affecting around 3.2 billion people [20], and therefore the introduction of sustainable management practices has become critical to maintain human well-being, as will be discussed in later sections.

In this review, we report the state-of-the-art and current understanding of the modulating role of soils within the NCP category 'regulation of hazards and extreme events'. Following the classification of IPBES [10], we focus on categories of hazards and extreme events in which soils underpin the ecosystem's vulnerability, and in which sustainable soil management can improve the ecosystem's resilience (i.e. floods, droughts, landslides and sand/dust storms). Because soil degradation exacerbates this vulnerability to extreme events, we also discuss advances in sustainable soil management to control soil degradation.

2. Regulation of floods

Among all natural disasters, floods are the most frequent and devastating [21,22]. Floods are approximately 10 times more

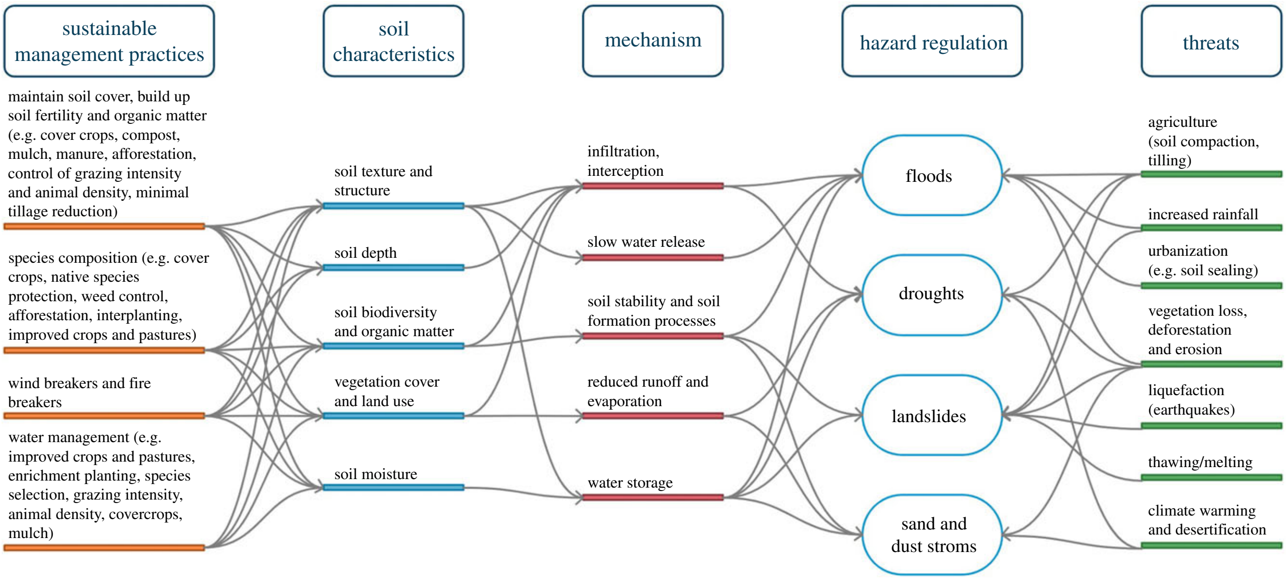

Figure 2. Sustainable management practices, soil characteristics and mechanisms contributing to hazard regulation, and threats to hazard regulation services from soils. (Online version in colour.)

frequent than any other natural disaster (figure 1). They account for about 40% of all losses owing to natural disasters since 1980, with a total cost estimated at more than 1000 billion USD [23]. More than 2 billion people were affected by floods between 1998 and 2017 (World Health Organization [22]). River and coastal flooding occur in low-lying areas and can be caused by intense rainfall, snowmelt, storm surges or tsunamis. These flood events are increasing in both frequency and magnitude and are expected to continue to increase owing to climate change [24]. Additionally, river flood-related economic losses are predicted to increase globally owing to increases in frequency and intensity of heavy precipitation events [25,26] and socioeconomic factors, such as the intensification of agriculture and the rise in human use of flood-prone areas [25,27]. These losses are expected to increase by a factor of 20 by the end of the twenty-first century [24].

River flooding typically results from intense or prolonged precipitation events that saturate the soil, reducing infiltration and increasing runoff. Runoff is collected in streams and rivers that overflow and can generate flooding far away from precipitation source areas. Soils and their associated ecosystems can provide important regulating contributions by reducing or delaying runoff, lowering flood volumes and reducing damage. Some of the physical mechanisms include canopy interception and slow precipitation release, increased infiltration into the soil and storage of water in subsurface layers and aquifers, and slow release of surface runoff from vegetated areas (figure 2) [25,28].

Physical soil properties, including soil structure, depth, permeability, organic matter content and texture, directly influence the capacity of soils to store and transfer water through lateral subsurface flow or infiltration to the aquifer, thus providing a natural buffering effect that can regulate the severity and frequency of floods. Soil structure, which is determined by the pattern of particle aggregates, determines the distribution of pores in soils. Its degradation through different processes (i.e. soil compaction or sealing) can trigger a substantial decrease in hydraulic conductivity, leading to higher runoff and losses in flood regulation capability [29]. Soil micro- and macro-organisms improve soil structure and exert an important control on organic C dynamics [30], while fungal sticky glycoproteins, fungal mycelia and bacterial exopolysaccharides enhance micro-soil aggregation properties and increase pore size [31]. Ants, earthworms and termites play a key role in increasing soil porosity by both their burrowing activity and the formation of granular aggregates [32]. The burrowing activity also leads to the generation of preferential water flow paths, enhancing hydraulic conductivity and infiltration. Though some soils have intrinsically low permeability (i.e. clays), and will produce runoff as the upper layers rapidly become saturated, well drained and highly permeable soils can store and transfer substantial amounts of water during heavy rainfall events, thus preventing or decreasing runoff. Soil organic matter content additionally promotes the stabilization of aggregates and increases the soil cation exchange capacity, improving water storage capacity and infiltration. Finally, soil texture is one of the main factors determining the pore size distribution of soils; it, therefore, has a major effect on infiltration and soil water retention, though it cannot be directly modified to improve soil water retention capacity.

The functional capacity of soils is largely affected by land use management practices, with soil compaction being perhaps the main problem that negatively impacts soil flood regulation capabilities at the watershed scale. In rural areas, agricultural practices that involve the use of heavy machinery cause soil compaction, particularly under wet conditions, while in cities, urbanization and industrial activities are largely responsible for the compaction of soil [29]. Soil compaction drives an increase in soil bulk density and reduces porosity in both the topsoil and/or the subsoil [29], thus reducing infiltration and increasing runoff either by ponding or lateral redistribution at small scales and influencing other factors, including surface connectivity, at larger scales. Because compacted soils are associated with the traffic of machinery or animals, they tend to display a well-connected and continuous spatial organization. This connectivity enhances the transport of water from the hillslopes and into the streams, increasing velocities, erosion and flood peaks

[33,34]. The effects of compaction on floods are larger in small catchments, where floods are generated by high-intensity short storms via the infiltration excess mechanism. In large catchments, the effects of compaction are less important owing to longer storms and the generation of floods via the saturation excess mechanism [29].

Additionally, soil sealing, a characteristic of urbanized systems, also substantially influences the flood regulation capacity of ecosystems. Soil sealing results from covering soils with layers of impermeable material (e.g. concrete, asphalts, etc.). The associated removal of the upper layer of topsoil and disturbance of the subsoil from building foundations and footings additionally degrades the functions of sealed soils [35]. As a result, both infiltration and water holding capacity are dramatically decreased, thus reducing the flood regulating capacity of urban soils [36]. Urban flooding can also increase owing to precipitation changes associated with the urban heat island effect [37], another by-product of urban soil sealing.

Management of soils for the regulation of flood events requires an understanding of soil and water dynamics at the catchment level. Soil management practices may assist soil recovery through improvements in the physical, chemical and biological characteristics of the soil, and have often been proposed as measures to reduce impacts of current and future development and climate. For example, alternative farming practices, including no-till, the introduction of perennials, crop rotations and integration of regenerative crop and livestock practices, have proven to protect the soil above and below ground [38]. In cities, issues such as compaction and soil sealing have been offset by implementing appropriate mitigation strategies through the use of green infrastructure and porous paving surfaces, networks of high-quality green spaces and the inclusion of sustainable drainage systems [36]. Furthermore, the implementation of native vegetation has been known to maintain and improve soil structure, because the extensive vegetative root networks will increase infiltration by leaving tubular macropores once they decay and through root-derived soil organic C, which improves soil aggregates [39]. Topsoil may recover quickly from compaction if management practices change; however, subsoil is likely to require a longer recovery time [40], though both responses are modulated by seasonal fluctuations. Depending on the sequence and impact of changing soil management practices, the response of soils can occur over multiple timescales: while compaction generates immediate changes of soil properties, regeneration may take years to centuries [41], particularly regarding subsoil characteristics. Other factors that affect recovery include soil type, topography and climate [40].

3. Regulation of droughts

Drought is a natural hazard that can lead to adverse ecological and socioeconomic impacts, including reductions in water supply, habitat degradation, crop failure, diminished power generation and more [42,43]. Approximately 10% of the total land area in the United States has undergone severe or extreme droughts at any given time during the last century [43]. The Sahel region of Africa has experienced drought conditions of unprecedented severity since the 1960s [43], while Australia's 'Millennium Drought' persisted for almost a decade and negatively impacted the southern and eastern regions of the continent [44]. The socioeconomic costs of large-scale intensive droughts has risen in recent decades, with the global cost estimated at $320 billion USD in the 1970s to $1326 billion USD in the 2010s [1].

As a temporary, physical state of the natural environment, drought is characterized by lower-than-normal water availability compared to average conditions [42,43,45]. Drought is typically sub-divided into three distinct categories: meteorological drought, hydrological drought and agricultural (sometimes referred to as 'soil moisture') drought [43,45]. Meteorological drought is characterized by lower-than-normal rainfall, while hydrological drought is defined by a deficit in surface and subsurface water availability [43,45,46]. Agricultural drought is described by below-normal soil moisture levels, and is directly linked to diminished crop yields and/or crop failure [43,45]. Additional categories of drought have also been developed to characterize drought phenomena within specific contexts, including ecological drought, socioeconomic drought and groundwater drought [43,47].

The inception and propagation of drought within a region is governed by the system water balance. Low system inputs (i.e. precipitation) coupled with high system outputs (i.e. evapotranspiration) and lack of available water storage or stored water (such as in soils or reservoirs) work in unison to create a drought [45]. The physical environmental characteristics of a region, such as soil texture, land use or land management and minerology, also play a role in drought propagation (figure 2) [42,45], particularly in regards to governing the system output and available water storage capacity. Anthropogenic activities may contribute to or enhance hydrological or agricultural drought through abstraction, deforestation and/or overexploitation of resources [43,45,46].

Soils play a role in the formation and persistence of agricultural drought, and, to some extent, hydrological and meteorological drought, through the land-atmosphere feedback loop. In the feedback loop, soil moisture anomalies are initiated by a precipitation deficit [48,49]. These drier-than-normal soils drive an increase in sensible heat flux, which leads to an increase in temperature [50]. Simultaneous declines in evapotranspiration, owing to the drying of the soil, coupled with the aforementioned temperature increase, results in a reduction in atmospheric moisture levels [43,49]. This decline in atmospheric moisture drives an increase in the vapour pressure deficit and, thus, the atmospheric evaporative demand, which depletes soil moisture even more and further propagates the drought, hence the 'feedback loop' [49,50]. Only atmospheric disturbances which carry sufficient moisture from outside the region will disrupt the feedback loop and end drought conditions [43].

The role of soils, and thus soil moisture, in the land-atmosphere feedback loop has been widely investigated. Spring and early summer soil moisture has been identified as a strong predictor of summer precipitation [48,51], with the role of soil moisture within the land-atmosphere feedback loop particularly enhanced in flood/drought years [52]. Furthermore, the existence of a strong land-atmosphere feedback loop has been reported to amplify summer temperatures, driving the occurrence of heat waves [53], with spring and early summer soil moisture also an integral factor for controlling the mean summer temperature [54]. Regions of strong land-atmosphere coupling where the soil moisture feedback is known to exist include the central United States, the Sahel, equatorial Africa and India [48,55].

The strategic management of soils with focus on controlling the dynamic biotic and abiotic processes of soils, such as drainage capacity or organic matter, has shown the potential to enhance the resilience of an ecosystem to local or regional drought impacts [42,56–58]. In agricultural systems, there are a variety of strategies which focus largely on soil management and can be used to mitigate local/regional drought effects. For example, the implementation of cover crops and mulching can minimize evaporation and reduce runoff by maintaining coverage of the soil surface [42]. The use of mulch to reduce soil evaporation has been reported to increase soil water storage by 10% [59], while no-till operations report a higher soil water content compared with conventional tillage [60]. The implementation of hedgerows, both singularly and in combination with no-till practices, have been shown to contribute to drought risk regulation [61]. Furthermore, early research in the field of crop ecology and on the topic of the soil–plant–atmosphere continuum demonstrate potential for the management of intermittent droughts through targeted rhizosphere intervention [42].

Within the framework of NCP and the ES concept, research surrounding the regulation of hazard events has focused primarily on flood management (see the section on floods). However, a few publications discuss drought mitigation [8,61,62], though none explicitly examine the role of soils within a drought-specific context. Approaches such as integrated water management, reduction of soil erosion and soil compaction, agricultural diversification and biodiversity conservation have demonstrated positive effects on natural hazard mitigation, including droughts [8]. Furthermore, alternative cropping systems, such as large-scale conservation tillage, may be beneficial for local and/or regional drought mitigation [62]. Outside of agricultural systems, improved forest management, reforestation and afforestation are landscape management measures that have shown potential to improve drought resiliency [8].

4. Regulation of landslides

Landslides have serious implications in terms of fatalities and economic losses [63,64]. The frequency of their occurrence is increasing (figure 1) owing to overexploitation of natural resources and deforestation that generates greater instability, as well as growing urbanization and uncontrolled land use in slide prone areas [65]. The global number of landslides are typically under-reported in disaster databases because they occur as a result of other disasters, including floods and earthquakes. However, the death toll associated with individual events is extremely high. Examples of landslide disasters include several mudflows owing to rain in Venezuela in 1999 (20 000 deaths), an earthquake landslide in El Salvador in 2001 (600 deaths), debris flows and landslides in Haiti and Dominican Republic in 2004 (2500 deaths), and the recent earthquake-generated landslides in Indonesia in 2018 (2000 deaths) [65,66].

Landslides consist of a localized mass movement of soil generated by the combination of gravitational force and the reduction of resistance to shear in soil layers [67]. They naturally occur and are an important landscape-forming process, maintaining slopes below their threshold angle [68] and facilitating sediment transport from the slopes to the fluvial system [69]. Extreme precipitation, earthquakes or thawing/melting processes are typical triggers of landslides [65,70]. The main factors that determine landslide occurrence are slope gradient, lithology (surface and shallow subsurface), land cover and use, climate (precipitation/freeze–thaw cycles), soil moisture and seismicity [65,71]. Soils, through their physical, chemical and hydraulic properties, provide important landslide regulating capacity.

As in the case of flood and drought regulation, soils with good drainage and vegetative coverage can greatly reduce the risk of landslides (figure 2). Many landslides occur in weathered soils with high slopes and high clay/oxyhydroxides content when heavy rain exceeds soil saturation capacity [72,73]. The weight of the saturated mass of soil combined with the weakness and low permeability of the weathered layers generates ideal conditions for the development of slip zones along which landslides occur [74]. Biofilm-forming bacteria and saprophytic fungi may contribute to degradation processes, leading to changes in soil properties possibly involved in the occurrence of landslides in clayey soils [75].

Landslides can also occur in non-clayey soils owing to the weakening of the strain in deep layers as a result of excessive irrigation. Soils can undergo localized strain softening and liquefaction at the base of the loess layer owing to increased pore pressure as groundwater levels increase as a result of intensive irrigation (e.g. rice irrigation) [76]. Landslides can even occur in sandy soils with very good drainage and low slopes during earthquakes owing to liquefaction of basal layers in areas of groundwater level increase due to intensive irrigation [66,77].

In general, vegetated healthy soils provide important ecosystem regulating functions for landslides. Vegetation cover promotes good drainage, but more importantly, it provides additional soil strength and cohesion through the root system [78]. In many instances, deposits from past landslides display much better soil structure than the original soil that was the source of the landslide [79,80]. These fertile areas are extensively used in terrace cultivation systems, but the root system of crops is not as effective as that of forest and meadows [81]. Moreover, studies show that in upland rice cultivation systems (used in Africa and Southeast Asia in landslide prone areas) landslide risk is still high owing to the timing of harvest and inability of soils to cope with high rainfall events due to tilling agricultural practices [81].

5. Regulation of sand and dust storms

Sand and dust storms are atmospheric events created when small particles are moved from the land surface owing to strong and turbulent winds. The economic impacts of sand and dust storms can incur over hundreds of million dollars per event and cause detrimental environmental and health implications [82]. General short-term impacts include crop damage, livestock mortality, interruption of transportation and communications, and infrastructural damages. Long-term implications include chronic health problems, soil erosion, soil fertility reduction and deposition of pollutants.

Sand and dust storms are a natural hazard formed in response to changes in abiotic parameters, including temperature and precipitation, which directly affect soil moisture [83]. Wind speed, soil structure, soil texture, soil moisture, snowfall and vegetation are key environmental factors which drive the occurrence of sand/dust storms (figure 2) [84,85]. Additionally, climate warming has been identified as another key factor in the formulation of sand/dust storms owing to drought conditions which deteriorate surface vegetation, damage soil structure and lead to desertification. Concurrent droughts and increasing temperatures affect the soil capacity to sustain vegetation, leaving the soil with little or no soil coverage.

Anthropogenic soil management practices can affect soil structure and promote poor soil health. Globally, agriculture and desertification are known to be the most common causes of dust storms [85,86]. Soil particle mobilization from agricultural and natural lands has been linked to reductions in topsoil and soil fertility. In deserts, smaller soil particles can remain suspended in the air for longer than a week. For example, the Bodélé depression annually transports about 40 million tons of dust across 5000 km, from the Sahara desert to the Caribbean and the Amazon basin [87]. The dust generated by the Bodélé depression is categorized as 'detrimental' for air quality in the Caribbean, but potentially 'beneficial' to the Amazon tropical rainforest owing to fertilization, especially phosphorous fertilization [86,88].

Over history, there have been several large-scale dust storms, including the 'dust bowl' in the Great Plains of the United States [89]. From an environmental and health perspective, it has been reported that desert dust contains a wide variety of chemical pollutants and microorganisms that have the potential to cause harm to plants, animals, humans and the overall ecosystem [90–92]. African dust events have been correlated with an increase in asthma incidents in the Caribbean [93], while, similarly, infectious agents in African dust have been linked to Caribbean widespread coral reef morbidity and mortality episodes [94]. However, the benefits of sand/dust storms such as the Bodélé depression includes the transport of nutrients and minerals which fertilizes land and stimulates oceanic plankton growth. These natural processes support and maintain the fertility cycle of critical natural ecosystems [95].

Management practices which aim to stabilize the soil by enhancing soil health have shown potential to control sand/dust storm events. An integrated multi-scale and multifunctional approach is most effective for the control of sand and dust storms [82,96], and is possible by assessing the three main stages of the sand/dust storm event: (i) the entrainment process of fine particles, (ii) particle transport, and (iii) particle deposition. Practices which promote long-term soil cover, retain plant residue and increase soil health have been proven to enhance soil structure, soil microbial communities and fertility [97,98], thus preventing degradation. Additionally, rangeland management practices that control animal density, promote grazing rotation and introduce improved pastures with tolerance to water stress, may avoid desertification by preventing and reversing land degradation [99]. In ecosystems such as deserts and forests, sand/dust storm mitigation strategies include the use of wind barriers and wildfire control.

6. Sustainable management strategies to avoid soil degradation and enhance the soil contribution to regulate other hazards and extreme events

Nearly one-third of the world's soils are degraded, mainly owing to intensive cultivation practices that include the use of industrial pesticides/fertilizers and mechanized agriculture [100]. Land use changes associated with cropland practices are significantly accelerating soil erosion, and are predicted to continue throughout the next century, with the greatest negative impacts primarily on the least developed economies [101]. The modification of soil physical, biological and chemical properties through land use change can result in degradation, leading not only to soil erosion [102–104], but also to soil contamination [14], reduced soil nutrients [105] and reduced infiltration [29,103]. Soil degradation also exacerbates the risks associated with the hazards mentioned in the previous sections owing to loss of soil organic matter and storage capacity, and increased erosion potential [18,39,106].

The integration of sustainable soil management practices plays a crucial role in enhancing or maintaining soil health, improving soil mechanisms and functions, food security and ecosystem resilience. Addressing the global challenges of climate change, food security and poverty alleviation requires that landscapes become adaptive and increase their mitigation potential [107]. Sustainable soil practices (figure 2) are a critical solution to increase soil health and improve soil physical, biological and chemical properties. Sustainable agricultural practices, like the use of organic fertilizers, crop rotation, reduced tillage, catch crops and straw mulch can result in higher soil nutrient content and reduced soil loss by improving soil structure and water holding capacity (figure 2). For example, a study in Maize plantations in Puerto Rico found that integration of organic fertilizers and crop rotation improved soil nutrient content, reducing nitrogen requirements by 40% compared to conventional farming [105]. In semi-arid vineyards, the use of cover crops (e.g. *Vicia faba*) with reduced tillage was estimated to reduce tillage erosion by 50% and water erosion by 80%, resulting in an overall soil erosion reduction of 70% [104]. In similar studies, no-tillage practices on a Persimmon farm resulted in an 80% reduction of bare soil areas, an 80% reduction of runoff and a 95% reduction of soil erosion, while citrus orchards managed using straw mulch reduced runoff losses by 30% and soil erosion by 80% [103].

Sustainable soil practices also have the potential to drive positive social, economic and environmental changes, and maintain the soils' role in building our current landscapes and habitats [108]. Sustainable farming improves food security (and therefore reduces the potential of famine hazards) by diversifying crop and livestock operations, which directly diversifies local diets [109]. For example, Bachmann *et al.* [110] reported two to three times higher diversification in vegetable and protein consumption in organic than in non-organic farmers in the Philippines. Simultaneously, this process increases and diversifies farmer's incomes, job opportunities and community economic development, leading to the development of a circular economy with a reduced environmental footprint [111]. In addition, healthy soils managed through sustainable practices contribute to a reduction in mental and physical health hazards by regulating air quality, ensuring protection against water contamination, producing enzymes and organisms for medicinal purposes and providing positive physical and psychological experiences [112–116].

7. Conclusion

Within the context of this special issue on soil-derived NCP and their contributions towards the Sustainable Development

Goals (SDGs) [117], this paper presents evidence of the contributions of soils to NCP 11: regulation of natural hazards and extreme events.

As summarized in figure 2, the soil physical, chemical and biological properties play a major role in regulating the effects of hazards, and management practices can negatively or positively affect specific properties [4,45]. The fields of soil science, hydrology, climatology and agronomy have examined the key role of soils in the development and propagation of floods, droughts, landslides and sand/dust storms through both identification of relevant soil processes and the management of soils. Floods are regulated by soils mainly through infiltration and water storage processes, and intensive land use practices producing soil sealing and compaction increase the risk of flood. Drought regulation benefits from increased soil moisture, and practices that limit vegetation cover reinforce dry conditions. Landslides are less likely to occur in soils with good drainage and a strong root system, but they can be triggered by intensive irrigation and deforestation practices. Sand/dust storms can be effectively regulated by a healthy topsoil with high organic content and vegetation acting as windbreak, and its regulation capacity is negatively affected by intensive soil use and deforestation.

Sustainable farming and soil use practices that protect the soil, prevent soil degradation, and, if needed, assist with restoration and enhancement of physical properties (figure 2) should be integrated into land management strategies for hazard regulation. Such practices include maintaining soil cover throughout the year by using cover crops, mulch, crop rotation, afforestation, reduced grazing and reduced tillage; improving soil fertility and soil organic matter via cover crops, compost, mulch, organic fertilizers, crop rotation and reduced tillage; improving species composition by fostering native species protection, weed control, afforestation and interplanting; providing wind and fire breaks by afforestation; and improving soil water drainage and storage by applying selective species planting, cover crops, mulch, reduced grazing and reduced tillage.

The strategic management of soils has the potential to mitigate the direct impacts of natural disasters and reduce the severity of associated ecological and socioeconomic impacts. However, we still lack sufficient knowledge of the full set of soil processes that contribute to the delivery of NCP towards achieving the SDG. It is unlikely that soil-focused interventions across the landscape will have the capability to singularly offset the impacts of disasters over large spatio-temporal scales, so a local approach may be more practical. Thus, future research that focuses on understanding the regulation of hazards and extreme events should target the role of soils within specific natural and social contexts, using previous research from adjacent fields to guide their investigation.

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