Status of the World's Soils

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Status of the World's Soils

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Keywords

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Abstract

Healthy soils contribute to a wide range of ecosystem services and virtually all of the UN Sustainable Development Goals, but most of the world's soil resources are in only fair, poor, or very poor condition, and conditions are getting worse in more cases than they are improving. A total of 33% of all soils are moderately to highly degraded as a result of erosion, loss of organic matter, poor nutrient balance, salinization and alkalinization, contamination, acidification, loss of biodiversity, sealing, compaction, and poor water status. Best management practices are available to limit or mitigate threats to soil health, and many of them mitigate multiple soil threats. In many regions of the world, policies or initiatives to protect or enhance the status of soils are in place, and they need to be strengthened and enforced. The Food and Agriculture Organisation will publish its second comprehensive assessment of the status of the world's soils in 2025, and this review provides an interim update on world soil status and offers an accessible overview of the topic.

Contents

1. INTRODUCTION

Healthy soils provide a range of key functions that support a broad range of ecosystem services, which in turn underpin the delivery of all 17 Sustainable Development Goals (SDGs) proposed by the United Nations (UN) (1). The UN Food and Agriculture Organisation (FAO) defines soil health as "the ability of the soil to sustain the productivity, diversity, and environmental services of terrestrial ecosystems" (2). Soil health is under threat from a variety of environmental and management pressures, including climate change, pollution, and mismanagement, which lead to soil degradation that, in turn, results in poorer soil health. Several types of degradation threaten soil health, including erosion, loss of organic matter, poor nutrient balance, salinization and alkalinization, contamination, acidification, loss of biodiversity, sealing, compaction, and poor water status (3).

In 2015, the FAO and the Intergovernmental Technical Panel on Soils (ITPS) produced the first global assessment of the status of the world's soil resources (4). Its findings were sobering. The majority of the world's soil resources are in only fair, poor, or very poor condition, and conditions are getting worse in more cases than they are improving. Alarmingly, 33% of soils are moderately to highly degraded because of erosion, compaction, pollution, acidification, salinization, and other types of degradation (4).

Three years later, in 2018, the Intergovernmental Panel on Biodiversity and Ecosystem Services published a report on land degradation and restoration (5). Although this report did not focus only on soils, it assessed the status of land degradation globally and regionally. Its first key message was: "Land degradation is a pervasive, systemic phenomenon: it occurs in all parts of the terrestrial world and can take many forms. Combating land degradation and restoring degraded land is an urgent priority to protect the biodiversity and ecosystem services vital to all life on Earth and to ensure human well-being" (5, p. xx). This statement echoes the findings of the 2015 FAO/ITPS report (4).

In 2019, the Intergovernmental Panel on Climate Change (IPCC) published a special report on climate change and land, one chapter of which focused on land degradation (6). It found that land degradation affects more than 25% of the Earth's ice-free land surface and adversely affects people's livelihoods, with most of the 1.3 to 3.2 billion affected people living in poverty in developing countries. Taken together, these three reports underscore the perilous state of the world's soils, the increasing threat of land and soil degradation, and the resulting costs for the environment and for human health and well-being.

In 2025, ten years after the release of their first report on the status of the world's soils, the FAO and ITPS will publish a new report. Its goal is to provide an update on the status of soils, how that status has changed, and what policies have been put in place since 2015 to halt and reverse soil degradation and improve soil health.

The aims of this review are to provide an interim update on the status of the world's soils and to present an accessible overview of the topic. We review the status of threats to the world's soils in Section 2 before examining sustainable soil management (SSM) to address soil threats in Section 3. In Section 4 we discuss policy frameworks and initiatives to improve the status of the world's soils, before presenting a discussion in Section 5.

2. STATUS OF THREATS TO THE WORLD'S SOILS

In the following subsections, we discuss each of the main threats to the world's soils as identified by the FAO and listed in Section 1.

2.1. Soil Erosion

Erosion is a natural geologic process that shapes the surface of the Earth through the actions of mass movement, wind, and water. Materials are detached from, transported to, and deposited on landscapes, resulting in loss and accumulation. The thin layer of soil that covers the Earth's surface is highly sensitive to erosion. Soil erosion is greatly accelerated through human activities. In agriculture, soil and crop management practices leave the soil vulnerable to wind and water erosion and introduce another form of erosion, tillage (7). All three erosion processes occur to some degree in all regions of the world. In drier regions wind erosion predominates, and in wetter regions water erosion predominates. Tillage erosion occurs in all landscapes where the soil is disturbed through farming practices. The combined, cumulative effects of these soil erosion processes can be severe and long-lasting. Worldwide, it is common for topsoil to be almost completely lost across significant portions of landscapes that are or have been intensively cultivated.

Although soil conservation efforts have been developed, promoted, and adopted around the world over the past several decades, soil erosion is still considered a major threat to soil health (4). The loss of organic-matter-rich topsoil and the exposure of subsoil impair soils' ability to produce crops for food and fiber. Recent studies in North America (8, 9) estimate that 5–10% of annual crop production is being lost due to historical losses of topsoil, and tillage erosion has been identified as the primary cause of these losses. As such, soil erosion is a major threat to regional and global food security, as well as to air and water resources.

The need to manage multiple erosion processes, which can have both positive and negative effects, presents a major challenge for future soil conservation efforts. An emerging issue in understanding and managing soil erosion is the effect of a changing climate. More intense and more frequent hot, dry, and windy environmental conditions as well as more intense and more frequent storms will result in increasingly widespread and severe wind and water erosion. For instance, soil erosion due to more intense rainfall in the European Union and the United Kingdom is expected to increase by 13% to 22.5% by 2050 (10).

2.2. Loss of Organic Matter

Soil organic matter (SOM) is the largest actively cycling reservoir of terrestrial carbon. Its decline negatively affects many soil properties and functions. It is caused by either a decrease of biomass inputs to soils or an increased rate of decay of SOM. Land use changes, vegetation disturbances, repetitive tillage, removal of crop residues (e.g., by burning), and peatland drainage are the major drivers of SOM loss. Compared with driving forces (climatic, geological, and soil forming factors), human interventions represent the most dominant causes of SOM reductions on managed lands.

The Harmonized World Soil Database, version 1.2, yields a total mass of 2,476 Pg of organic carbon globally when using the measured bulk density values (11). FAO (12) has published one of the largest compilations of hot spots and bright spots of soil organic carbon (SOC) in the world. In many parts of India, average SOC has decreased from 1% to 0.3% in the past 70 years, while in Europe, the Mediterranean region is particularly vulnerable to SOM loss and soil degradation (13), along with high erosion rates, increased human pressures (14), and high climate change vulnerability. **Figure 1** shows global soil organic carbon stocks as represented in the Global Soil Organic Carbon map (GSOCmap) database, version 1.6 (15).

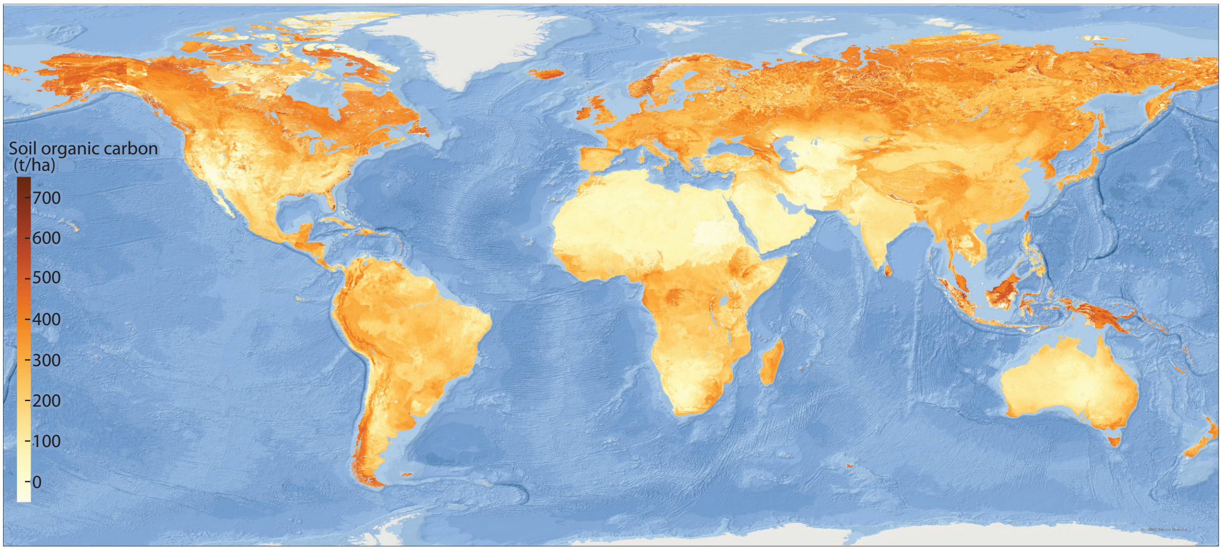

Figure 1

Soil organic carbon stocks to 1 m depth (in tonnes of carbon per hectare). Figure adapted from Reference 15 with permission (CC BY-NC-SA 4.0).

2.2.1. Mineral soils. Mineral soils have lost huge amounts (i.e., 133 Pg) of organic carbon since the advent of agriculture at a rate that has increased dramatically in the last 200 years. The hot spots of soil carbon loss are associated with major cropping regions and degraded grazing lands; each category is responsible for approximately half of the historic losses (16). These hot spots should be targets for SOC restoration efforts. Mineral soils under both forests and agricultural land have the greatest potential for carbon sequestration and for avoiding emissions, if well managed (17).

2.2.2. Peats. Despite covering only 3–4% of the planet's land surface (∼500 Mha across all continents), peatlands contain up to 33% of global soil carbon stocks, twice the amount of carbon as found in the world's forests (18). Around 12% of global peatlands have been drained and degraded, meaning that they are losing huge quantities of carbon. As a result, degraded peatlands contribute around 4% [∼2,000 Mt of carbon dioxide equivalent (CO_2e)] of annual global anthropogenic emissions (18). Every year, 500,000 ha of peatlands are destroyed by human activities. The main threats are drainage for agriculture, overgrazing by livestock, peat extraction for energy and horticulture, development of energy and other infrastructure (e.g., oil and gas exploitation), active burning, mining concessions in peatland areas, and urban expansion (18).

2.3. Poor Soil Nutrient Balance

Soil nutrient balance is the difference between nutrient inputs and outputs over a period of time. It is used for management decisions, based on whether soil fertility is being maintained, improved, or degraded (19). Reductions in soil fertility caused by soil nutrient mining, where agricultural practices result in a negative nutrient balance (i.e., where losses are greater than gains), lead to a negative nutrient balance resulting from a nutrient input lower than crop requirements/removal, soil erosion, and poor soil management practices (20). Poor fertility and negative nutrient balance are common in many underresourced farming systems and are a major challenge in developing countries (21), where they cause low productivity and poor crop quality that, in turn, contribute to greater food insecurity and poverty. Excess nutrient input occurs in intensive farming systems

(22, 23) and causes environmental pollution; alteration of soil chemical, physical, and biological properties; and high rates of greenhouse gas (GHG) emissions (24). The nutrients removed in harvested crops and feed are difficult to replace with fertilizers (25). For example, potassium fertilizers replenish only 35% of the potassium removed. Globally, a negative phosphorus balance is estimated at -1.9 kg ha^{-1} year^{-1}, with the highest deficit in Africa (-9.7 kg ha^{-1} year^{-1}) and the lowest deficit in Europe (-0.4 kg ha^{-1} year^{-1}), when phosphorus losses due to erosion are taken into account (26). Furthermore, approximately one-third of global arable soils are deficient in micronutrients, particularly zinc (27), mostly in Africa, the Middle East, and West Asia. Nutrient deficits are exacerbated by a global increase in fertilizer prices and a reduction of supply due to world crises. Reviews by Sartori et al. (28) and Alewell et al. (26), using RUSLE (Revised Universal Soil Loss Equation), considered soil erosion as the main cause of loss in fertile arable land, estimated at a total of 1,406 million ha in 2011. This loss of arable land contributed to an approximately 24% decrease in total arable land and an estimated 60% loss of phosphorus, resulting in an estimated loss of productivity of ~33.7 Mt of grain. Prudent nutrient management strategies for better crop yield and to avoid pollution from overuse are required.

2.4. Soil Salinization and Alkalinization

Soil salinity is a measure of the concentration of all the soluble salts in a soil solution and is usually expressed as electrical conductivity (ECe). Soil is considered saline when the ECe is greater than or equal to 4 dS m^{-1} at 25°C. Salinization is the second major cause of land degradation after soil erosion, with an estimated global loss of 2,000 ha of arable land daily (29). Soil salinity has many causes, but most are related to geogenic processes (dissolution and weathering of rocks) and inappropriate irrigation practices (30).

Sodification is the increase of adsorbed sodium in the soil exchange complex to the point that it damages soil physical properties. It is expressed either as a sodium adsorption ratio (SAR; the measure of sodium ions in a soil solution, relative to calcium and magnesium ions) or as an exchangeable sodium percentage (ESP). If a soil's SAR equals or exceeds 13 (mmol L^{-1})$^{0.5}$ or its ESP equals or exceeds 15%, the soil is termed sodic (31). When sodification occurs because of sodium carbonate, it is referred to as alkalinization. The pH of alkaline soils generally ranges between 8.5 and 10 and may be even as high as 11. Low ECe and high ESP values tend to break down soil aggregates and lower their permeability to water. When a soil is saline and sodic, the growth of most crops is affected and soil structure is degraded (30).

Salt-affected soil areas have been reported (2) to be 412 Mha for saline soils and 618.1 Mha for sodic soils. This report showed no difference in salinity in the top 0–30 cm of soil depth or in greater soil depth. More recently, FAO & ITPS (32) identified an increase in salt-affected areas to 433 Mha (0–30 cm soil depth), of which 105.8 and 97.2 Mha are in Eurasia and in the Near East and North Africa, respectively. Moreover, saline horizons are found below the topsoil (30–100 cm) in 833 Mha. Most of these areas are in Latin America (227.5 Mha), Eurasia (182.1 Mha), and the Near East and North Africa (176.1 Mha). The known area of salt-affected soils in the world will probably increase once the next report on the status of the world's soils is completed (in 2025) and more countries have provided information.

2.5. Soil Contamination

Soil contamination poses a serious environmental threat to humanity, but the global picture remains fragmented (33). Soil is a sink for pollutants, but because humans use soil, it represents a major source of exposure to humans and other organisms. Once present in soil, contaminants can be taken up by plants and leach into groundwater, posing a risk to groundwater quality.

Their presence in farmed soils has major implications for food security in terms of both quality and yield. Exposure to soil, water, and air pollutants has been linked to nearly 13 million deaths annually (34), more than 500,000 of which are premature (35).

Many different sources of soil pollutants exist and are linked to anthropogenic activities as well as geogenic or natural processes. Anthropogenic contamination is a result of industrialization, armed conflicts, mining, poor waste management, and intensification of agriculture, particularly the extensive use of pesticides and herbicides.

Geogenic contamination originates from the weathering of parent rock, though in many cases it is also attributable to human activities. For example, arsenic in groundwater is attributable to the installation of bore wells that introduced oxygen, leading to weathering of arsenic-bearing minerals in the bedrock and subsequent release of arsenic into water that was then used for irrigation, cooking, or drinking.

The UN Environmental Assembly (36) has called for accelerated action to address and manage soil pollution, and this resolution has been adopted by more than 170 countries. Once present in soil, contaminants are not easily removed, but the adoption of the resolution has prompted a global movement toward better assessment and management of soil pollution.

2.6. Soil Acidification

Soils with a pH lower than 5.5 are categorized as acidic soils. These soils occupy approximately 50% of global arable lands but are limited to two major biomes: the humid high-rainfall tropics and the humid northern temperate zone (37). A total of 60% of globally distributed acidic soils are located in the subtropics and tropics. Sub-Saharan African (56%), Southeast Asia (38%), Latin America and the Caribbean (31%), East Asia (20%), and some parts of North America are the hot-spot regions of soil acidity (38).

Pollution (from nitrogen and sulfur deposition, in particular) continues to increase the extent of soil acidification, leading to an estimated increase in aluminum toxicity of arable lands under a business-as-usual scenario, since aluminum is mobilized at low pH. Slessarev et al. (39) concluded that soil pH is ultimately controlled by changes in water balance, with an abrupt transition from alkaline to acidic soil pH, where mean annual precipitation begins to exceed potential evapotranspiration. In addition to pedogenic drivers, other major causes of soil acidity include the mineralization of organic matter, nutrient uptake by high-yielding crops, root exudates, land use change, and nitrogen enrichment (40). Tian & Niu (41) showed that nitrogen addition reduced soil pH by an average of 0.26 units globally. Forestation caused a significant decline in soil pH by 0.23 units globally, and this effect was stronger in places where soils were already acidic.

Understanding the impacts of soil and land management on soil pH is important for soil sustainability, as reflected in the role of soils as reservoirs and modifiers of atmospheric carbon. Wang et al. (42) reported that liming acidic soils results in an overall balance of GHGs but has the added benefit of improving soil health and productivity. Global soils are at a buffering transition from base cations to nonbase cations in susceptible zones (41). Climate change will further reduce soil pH. Restoring the balance though integrated acid soil management is a mitigation option.

2.7. Loss of Soil Biodiversity

Soils are an important reservoir of biodiversity at the global scale, hosting one-quarter of all living organisms on the planet. Soil biodiversity, including microbiome diversity, is decreasing at a worrying rate, driven mostly by human activities that cause pollution and alter climate.

The ranking of threats to soil biodiversity differs by region (43). Intensive farming, habitat destruction and fragmentation, harsh climatic conditions associated with the climate crisis, deforestation, and harvesting of soil organisms represent major threats for soil biodiversity loss in Africa (mainly reductions in agricultural productivity and increases in food insecurity in sub-Saharan Africa) and cost the region around US$68 billion per year (44). Fire, salinization, and sodification are additional threats in desert and dry shrubland regions.

In Asia, deforestation caused huge losses of soil biodiversity in the distant past, and conventional high-input agriculture, urbanization, and contamination have led to losses in the recent past; climate change represents a new threat. In Europe, soil sealing and salinization, compaction, and pollution affect soil biodiversity, leading to agricultural losses of approximately €1.25 billion per year (45).

In Latin America and the Caribbean, fire, deforestation, and land use change are the main causes of soil biodiversity loss, with the recent addition of agricultural intensification and urbanization. In North America, climate change is the major threat, although intensive agriculture and invasive species are the main stressors in the Southwest Pacific region.

In the European Union, several legislative frameworks, including the Biodiversity Strategy for 2030, Farm to Fork, and Zero-Pollution Action Plan (46), have been proposed to address concerns about the impact of contaminants on soil condition. Most importantly, in November 2021, the EU Soil Strategy for 2030 was launched to equalize the legal status of soil to that of water and air through a soil health law, enacted in 2023.

2.8. Soil Sealing

Soil sealing is defined as the permanent covering of the soil surface with impervious materials such as concrete or asphalt, tar seal, and buildings or other structures that cannot be easily removed (4). Once sealed, soil loses much of its functionality, namely its ability to support plant growth, store organic carbon, host biodiversity, and regulate the water cycle.

Soil sealing is caused mainly by urbanization processes, including conversion of agricultural, natural, or seminatural areas to artificial land use, including sparse settlements, urban fringes, industrial estates, and transport infrastructure. Not all built-up areas are (completely) sealed: Urban green areas not only continue to provide ecosystem services to a certain extent but also represent a tool for increasing the sustainability of urban environments.

In 2018, 55% of the world's population lived in urban areas, and 68% are projected to be urban by 2050 (47). These proportions vary by region, ranging from 43% in Africa (59% by 2050) to 82% in North America (89% by 2050). At the global scale, in 2000, built-up land occupied 0.5% of the terrestrial land surface, ranging from 0.12% of sub-Saharan Africa to 2.11% of Western Europe (48). Because urban growth is linked to urban population growth, the greatest expansion of built-up areas will most likely be in developing countries (49), particularly in Asia.

Urban expansion takes place predominantly on former croplands (50), which has a direct impact on food security and an indirect impact on biodiversity due to crop displacement on former natural and seminatural areas (50). D'Amour et al. (51) showed that urban expansion will result in a 1.8–2.4% loss of global croplands by 2030 versus 2000, with Africa and Asia accounting for 80% of this loss.

2.9. Soil Compaction

Soil compaction decreases or deforms soil porosity, leading to poorer drainage, more frequent anaerobic conditions, and stronger soils that limit root growth. Severe soil compaction affects approximately 25% of soils globally (52), especially under mechanized agriculture in Europe and the Americas. Since 1960, machinery weight on these farms has increased tenfold, exacerbating the transmission of mechanical stresses to subsoil depths, where mitigation is difficult. Lands converted to pasture in South America, mainly in the Amazon and Cerrado biomes, have been degraded by soil compaction, among other threats. Regions with more smallholder farms, such as Asia and Africa, as well as drier regions of North America and Europe suffer less from compaction (53), but the threat still exists. Natural, grassland, forest, and urban soils are also affected by the weight of machinery or by trampling.

Soil compaction interacts with many other threats to soils, including runoff-induced soil erosion, disrupted pore structure habitat for biodiversity, poorer soil water status, and poorer nutrient balance. Across different land uses, a meta-analysis found that soil compaction increased N_2O production (due to decreased soil porosity) at least twofold in 82% of studies, and the impacts were even greater in pasture or forest soils (54). Due to poorer root growth, nutrient cycling, and water availability, crop yields in compacted soil are typically 80% those of paired nontrafficked soil, with further losses and environmental damage resulting from greater fuel use by agricultural machinery (55). In Ukraine alone, soil compaction costs farmers €1.6 billion in lost income annually (56).

There is a paucity of data on soil compaction, confounded by poor indicators. Bulk density is the most widely used, but it does not describe aeration and water storage. Therefore, many researchers use water-filled pore space to predict impacts on gaseous emissions, although gas diffusivity has even greater predictive power (57). The mechanical state of soil, measured as precompression stress and penetration resistance, is also important for assessments of soil compaction (52).

2.10. Soil Water Status

Soil water affects, and is affected by, global climate and biogeochemical cycles. Soil water status is an important factor controlling primary productivity, soil redox status, and the physical transport of materials from soils to surrounding environments. As a result, soil water affects soil carbon and nutrient cycling, including fluxes to air and water resources that can contribute to nutrient pollution and GHG emissions. These processes can be very sensitive to soil water status because the relationships between these processes and soil water are generally nonlinear; for instance, maximum rates of microbial activity and plant growth occur around field capacity (58).[1] In the future, amplifying and stabilizing feedbacks between soil water and climate change may manifest through changes in evapotranspiration and through soil carbon and nitrogen cycling. For example, an increase in vapor pressure deficit could decrease soil water by increasing evapotranspiration; alternatively, rising atmospheric CO_2 concentrations could reduce transpiration by increasing the water use efficiency of C3 plants.[2]

However, there is great uncertainty about how these feedbacks might occur and what the net effect will be under future climate projections (59). At present, remote-sensing and modeling analyses indicate that climate change, at a global scale, has led to a decline in soil moisture despite increases in some locations. The reductions in soil moisture are greater in surface soils versus subsoils, a finding that is consistent with greater evaporation in surface soils and less evaporation in subsoils, where greater plant water use efficiency may mitigate drying from greater evaporation (60). Future drying is expected to increase with the level of warming that may occur. Historically, the assessment of soil water status focused on inputs from precipitation and the vadose zone,[3] but in the future, shallow groundwater could be an important source of soil water that buffers against drought (61).

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[1] Field capacity is the water remaining in a soil after it has been thoroughly saturated and allowed to drain freely, usually for 1–2 days.

[2] C3 plants use a metabolic pathway where the initial product of CO_2 assimilation is 3-phosphoglycerate.

[3] The vadose zone is Earth's terrestrial subsurface that extends from the surface to the regional groundwater table.

3. SUSTAINABLE SOIL MANAGEMENT TO ADDRESS SOIL THREATS

The *Revised World Soils Charter* (62) and a report on the status of the world's soil resources (4) outlined core principles of SSM that maintain or improve the supporting, provisioning, regulating, and cultural services provided by soil. Following this report, FAO (3) published voluntary guidelines for sustainable soil management, which encompass soil-specific practices that promote healthy soils for the long term in order to address the different soil threats they face. We outline these best practices in the following subsections.

3.1. Best Management Practices to Prevent Soil Erosion

Soil erosion by water or wind is the most important threat to soil health around the world (4). It can be prevented through best management practices (BMP), which in many cases are not difficult to implement (63). BMP to prevent soil erosion should be based on thorough knowledge of the ecosystem characteristics (i.e., soil, climate, and topography; 64).

The principles on which BMP to prevent soil erosion must be founded are:

1. Provision of soil cover with residues and/or live plants to protect the soil surface.
2. Stabilization and/or improvement of soil surface conditions to resist the effects of particle detachment and transporting agents (i.e., raindrop or particle impact) and enhance water infiltration.
3. Control or management of erosive agents (i.e., runoff flow and speed, wind speed).

Principles 1 and 2 account for an important proportion of practices to prevent soil erosion. Soil cover and improved surface conditions can be achieved through practices such as intensified cropping systems, conservation tillage, management of crop nutrition and water supply, and/or agroforestry. These practices contribute to soil cover throughout the year and enhance soil surface organic matter content, aggregate stability, and porosity and permeability. Under some environmental conditions, additional practices are needed to pursue principle 3, such as contour and/or strip cropping, mechanical practices and engineering techniques (i.e., terraces, ponds, channels, waterways), and/or windbreaks, which can help manage or control runoff flow and speed or wind speed (65, 66). Soil erosion prevention is necessary to accomplish food security; reduce soil, air, and water pollution; contribute to nutrient cycling and balance, carbon budget, and soil recarbonization; enhance soil biodiversity; and preserve the functionality of infrastructure and increase its life span (65).

3.2. Best Management Practices to Prevent Loss of Organic Matter

SOM is a dynamic pool determined by the balance between inputs and outputs (see Section 2.2). Strategies to prevent SOM loss in managed soils consist of (*a*) maintaining or increasing organic matter inputs and/or (*b*) minimizing organic matter losses by erosion or mineralization.

FAO & ITPS (67) published a technical manual including one of the largest compilations of SOM management practices in agricultural, forest, range, and urban soils (see the sidebar titled Management Practices That Enable the Preservation of or Increase in Soil Organic Matter Content and Stocks). The manual shows that the reported changes in total SOC stocks after the adoption of BMP are not easy to standardize and are detected only in the mid-term (>4 years). Furthermore, these practices are not necessarily climate neutral, and attention should be paid to trade-offs with other GHG emissions. Appropriate soil and land management practices for SOC protection and sequestration should consider land use and the local environmental, socioeconomic, cultural, and institutional contexts, as well as potential barriers to adoption (68).

MANAGEMENT PRACTICES THAT ENABLE THE PRESERVATION OF OR INCREASE IN SOIL ORGANIC MATTER CONTENT AND STOCKS

Cropland

- Soil organic cover
  - Cover cropping, organic mulch
- Crop diversification
  - Crop rotations; intercropping: multiple cropping, strip cropping
- Tillage
  - No till; conservation: reduced and superficial tillage; strip, precision, and zone tillage; noninversion tillage
- Nutrient management
  - Organic matter additions, chemical and mineral fertilization, biochar, addition of living organisms, chemical amendments
- Soil and water conservation techniques
  - Erosion control techniques, hedges and buffer strips, avoiding improper earth movements before planting tree crops
- Adequate irrigation practices
- Controlled traffic farming

Grassland

- Grassland conservation and restoration
  - Conservation of permanent grassland, grassland diversification, restoration of degraded grassland, conversion of cropland to grassland
- Grazing management
  - Improved pasture management, grazing exclusion and rotational grazing, pastoralism

Integrated systems and farming approaches

- Integrated systems
  - Integrated crop–livestock systems, agroforestry, syntropic agriculture, conservation agriculture, permaculture, zero-budget natural farming
- Farming approaches
  - Agroecological farming, climate-smart agriculture, regenerative agriculture, precision agriculture, organic agriculture

Managed forests and silviculture

- Harvest systems that limit soil disturbance and reduce the impact of logging
- Soil cover
  - Continuous cover forestry and extended rotations, residue retention
- Nutrient management
  - Inclusion of nitrogen-fixing species, forest fertilization
- Forest restoration
  - Forest afforestation, reforestation, and natural regeneration; rehabilitation of forest soils affected by wildfires; forest landscape restoration

(*Continued*)

(*Continued*)

Wetlands

- Wetland management
  - Avoiding conversion and conservation of wetlands, wetland restoration (water supplementation and promotion of plant growth)
- Peatland
  - Conservation of pristine peatlands and avoiding drainage of peatlands, restoration of peatlands, paludiculture (growing crops on peatlands with a high water table)
- Mangroves and organic forest soils
  - Restoration of mangrove forest, restoration of organic coastal and inland freshwater forests
- Rice paddies
  - Water-level management in rice paddies, straw residue management, selection of rice varieties adapted to salinity, integrated rice-based farming systems

Urban soils and infrastructures

- Urban infrastructures
  - Careful management of gardens, parks, and lawns; bioretention systems; green roofs
- Urban agriculture
- Urban forestry

Data from Reference 67.

3.2.1. Best management practices for mineral soils. In agricultural mineral soils, the balance between organic inputs and outputs can be improved by allowing for more photosynthesis and biomass returns (e.g., cover crops, grazing orchards), supplying organic amendments to compensate for the biomass exported by the harvest, and by minimizing losses via erosion or heterotrophic respiration,[4] as with reduced tillage. Given the variability and limited effects of tillage on SOC stocks, it appears more efficient to increase organic inputs to soils rather than decrease the outputs (70). BMP apply not only at the plot scale but also at the landscape scale; examples include hedges, agroforestry, and grass strips that help increase photosynthesis and protect soils from erosion.

3.2.2. Best management practices for peat. Global peatland areas are shown in **Figure 2**. Since 88% of the world's peats are not degraded (18), the most effective option is to conserve them. Globally, a small percentage of pristine peatlands are protected. For example, in North America and Europe, less than 20% of peatlands are in protected areas, whereas in Asia, the percentage is below 10%, and some world regions have no protection strategy (18). In Brazil, some tropical peats are preserved inside national parks in mountain areas (71). With regard to degraded peatlands, while it may not be possible to fully restore the most degraded, many of their functions can be restored by reversing drainage so as to raise the water level and, where possible, rewetting the peats completely (18). Rewetting is usually achieved by blocking drainage channels. Other interventions for peatland restoration include preventing erosion by physically stabilizing eroded peats through mounding or the addition of netting as well as revegetation (72).

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[4] Soil heterotrophic respiration represents CO_2 flux to the atmosphere from the decomposition of litter detritus and SOM by microorganisms.

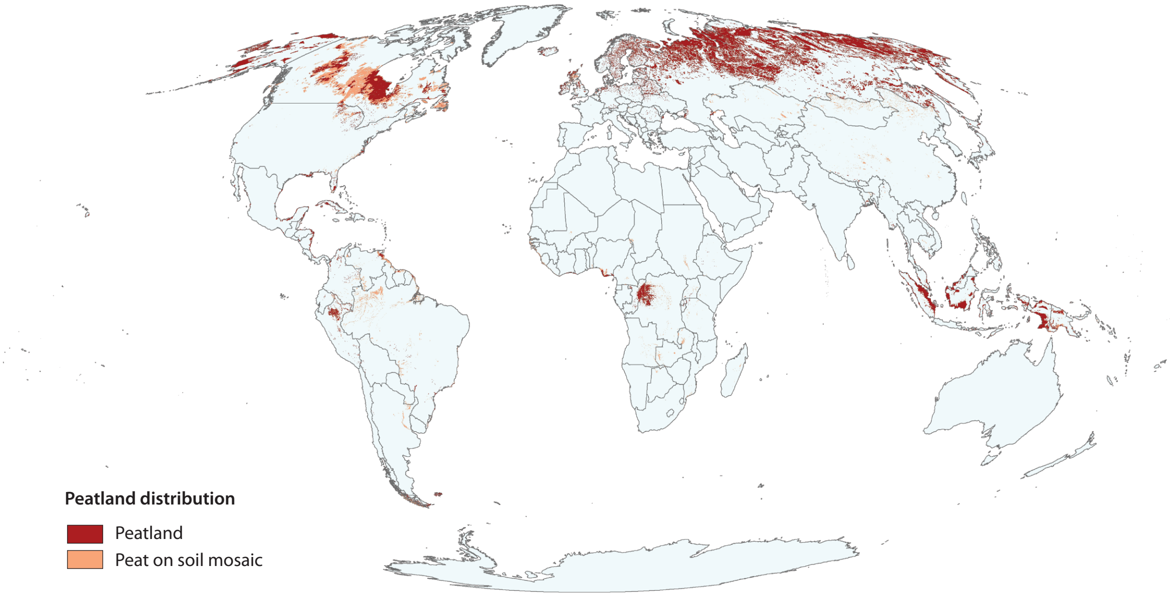

Figure 2

Global distribution of peatlands from the Global Peatland Assessment. Figure adapted from Reference 69 with permission.

3.3. Best Management Practices to Foster Soil Nutrient Balance

Nutrient balance aims to maintain soil fertility, and it is frequently used to evaluate and quantify the potential nutrient turnover in agriculture by assessing input, storage, and output processes through mass balance (73). High rates of soil nutrient cycling and low nutrient losses can reduce reliance on external fertilizer inputs (74) and decrease environmental pollution.

In both managed and natural ecosystems, rates of nutrient cycling are positively associated with primary productivity. Conservation agriculture practices, including reduced tillage, crop residue retention, and crop rotation, can foster soil nutrient cycling, but the results are context dependent and can be negative (75). Other practices are integrated soil fertility management, with the appropriate combination of organic and inorganic nutrient sources, and site-specific nutrient management, based on soil testing (76). The positive effects of these practices tend to be maximized when agronomic systems approaches are applied (75).

In the short term, the variation in practice performance can be explained by changes in stoichiometries of SOC, nutrients, soil water status, and soil temperature. In the long term, these practices can lead to ecologically sound soil nutrient cycling through alteration of nutrient balances.

BMP differ according to the nutrient of concern. In low-fertility soils that suffer from historical nutrient extraction through removal of plant products such as crops, managing for positive nutrient balances can restore fertility, particularly when integrated soil fertility management is adopted, because surpluses of inorganic nutrients alone cannot be retained without an available organic fraction capable of acting as a mineral sink. In high-fertility soils with repeated nutrient additions that exceed plant demand, positive nutrient balances and stoichiometric mismatches can lead to environmental pollution (77). In these soils, site-specific nutrient management can be used to manage temporary nutrient deficits and avoid excess nutrients without reducing productivity.

3.4. Best Management Practices to Prevent, Minimize, and Mitigate Soil Salinization and Alkalinization

The main approaches for the sustainable use of salt-affected soils can be grouped into three adaptation/mitigation strategies: (*a*) use of halophytic (salt-tolerant) crops or microbiota, either natural or genetically modified; (*b*) adequate management of irrigation to avoid further salt accumulation; and (*c*) application of techniques such as mulching in order to reduce evapotranspiration and thus salt accumulation in the topsoil (78). The traditional way to fight salinization in irrigated agricultural soils is to drain salts by adding a leaching fraction on top of the water needed by the crop. Given global water scarcity and the fact that some water efficient irrigation systems lead to only local redistribution of salts in the soil profile, not complete salt removal (79), more efficient methods may be available.

Organic amendments, which are rather limited in arid areas, can also improve the physical and chemical status of saline and sodic (sodium-affected) soils. Bioremediation with specific salt-tolerant microorganisms and phytoremediation has proved effective in some environments (78, 79).

Irrigation with saline water in winter can be applied in cold environments and has been effective in certain coastal regions of China. This saline water freezes and then thaws on the topsoil, causing a strong salt-leaching effect (80).

Classical management of soils affected by sodification and alkalinization involves the application of gypsum (or phosphogypsum) to reduce the exchangeable sodium percentage along with organic amendments to improve the soils' poor physical properties and increase infiltration and leaching capacity. Alternatively, the use of sulfur gas and irrigation with partly neutralized high-residual-carbonate water, with gypsum or sulfuric acid, has also proved effective. A drawback of this technique is that acidification of the pH of calcareous sodic soils generates high CO_2 emissions. An integrated approach using a combination of these adaptation methods is the most effective strategy (78).

3.5. Best Management Practices to Prevent and Minimize Soil Contamination

Environmental contamination is largely an outcome of humans' pursuit of economic growth since the early to mid-nineteenth century. The industrial revolution, coupled with a lack of appropriate legislation during that period, resulted in extensive contamination of the environment due to the disposal of solid and liquid wastes into land and water bodies in most countries worldwide, practices that continue in some areas to this day.

Contaminated sites range in scale from localized point sources (e.g., a single leaking underground storage tank or old landfill site) to large industrial or military megasites. On a regional scale, examples of contamination include large areas of land surrounding smelters or the use of phosphate fertilizers and pesticides, which can have a widespread impact not only on groundwater but also on local and international trade.

Depending on the nature of the contamination—point source or diffuse—contaminated site remediation technologies fall into two main approaches: in situ (81) and ex situ (82). While in situ remediation deals with contamination without removing soil from the ground, ex situ remediation requires the excavation of contaminated soil for treatment or disposal elsewhere. The techniques available for in situ or ex situ remediation can be prohibitively costly, resulting in poor rates of adoption in most countries unless there is a very large increase in the value of the remediated site. The many in situ and ex situ technologies used to remediate contaminated soils include bioremediation, incineration, soil washing, and bioavailability reduction through the immobilization of contaminants. Bioavailability reduction is the best management strategy for diffuse contamination, such as cadmium in farmed soils. While many of these technologies are classed as ex situ, the recent emphasis on minimization of GHG emissions has ignited interest in in situ technologies that do not require transport of contaminated soils to prescribed landfills. However, despite significant investment in the development of remediation technologies, especially in the United States and Europe, contaminated site remediation remains a major challenge due to the complex nature of contaminants and their bioavailability, the presence of mixtures, and the complexity of the local geology and hydrology.

3.6. Best Management Practices to Prevent and Minimize Soil Acidification

Although it is a natural process, soil acidification can be accelerated by human activities such as intensive farming or slowed down by sustainable agricultural management practices. Many solutions have been proposed to overcome soil acidity, such as applying lime, gypsum, or organic materials and growing acid-tolerant crops (38, 83). Liming, the most widespread of these practices, has successfully reduced acidity in various soil types, including oxisol, peatland, kandosol, andisol, cambisol, and ultisol (84, 85). Liming remains the most efficient way to address soil acidity and improve carbon and nitrogen cycles. It can reduce non-CO_2 GHG (N_2O and CH_4) emissions from soils, although it increases CO_2 emissions (86). However, long-term liming to reduce soil acidity and the amendment of soil with magnesium or calcium are not good options, since they are expensive and not environmentally friendly (38). The use of acid-tolerant cultivars can help, but where acidification is severe and likely to extend into the subsoils, an integrated approach involving liming, cultural practices, and plant tolerance is recommended.

3.7. Best Management Practices to Preserve and Enhance Soil Biodiversity

Soil biodiversity is essential for regulating and maintaining the many ecosystem functions and services that are critical for human well-being and global ecosystem sustainability, but it is undermined chiefly by intensive agricultural and forestry management. Therefore, actions, policies, and legislation that promote land management practices to restore or preserve soil biodiversity are needed. Soil management strategies to prevent biodiversity loss in the agriculture and forestry sectors need to consider that soil organisms can respond differently to changes in land use according to the local pedoclimatic conditions and human interventions. In agriculture, a set of SSM practices that reduce soil contamination (see Section 3.5), decrease the use of chemicals (see Sections 3.5 and 3.6), and increase organic farming while maintaining soil health and yielding multiple benefits have been incentivized in Europe (87). In Asia and sub-Saharan Africa, reduction of deforestation, decreases in pesticide and chemical fertilizer use, and agroforestry represent the most effective and frequently used soil management practices for recovering soil biodiversity (88, 89). In Latin America and the Caribbean, best practices include permanent soil cover through intercropping, mulching and agroforestry, use of catch crops,[5] zero-tillage/conservation tillage, and a return to low-input agriculture, with heavy use of organic fertilizers and biostimulants. In North America, producers and researchers alike have developed and implemented management strategies whose aim is to align with the set of principles for reducing tillage (which reduces disturbance of soil microhabitats), implementing cover crops (see above), and increasing rotation diversity (which increases microhabitat diversity) (90). In the forestry sector, management that mimics natural disturbance with reduced thinning intensity and retention of deadwood derived from thinning operations on forest soils (providing more microhabitats for soil fauna and flora) are the most widely used ways to protect soil biodiversity worldwide (91).

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[5] Catch crops are plant species that have short growing seasons, rapid growth, and low soil and nutrient requirements that are planted between main crops and often ploughed back into the soil to increase carbon inputs and reduce nutrient losses.

3.8. Best Management Practices to Prevent Soil Sealing

Land planning is the first tool for reducing the impacts of urbanization on soils by preventing higher-quality soils from sealing; implementing compensation measures such as urban greening and desealing; and mitigating the loss of ecosystem services provided by soils, reducing the degree of imperviousness. Containment of urban expansion is unlikely, especially in developing countries (92). Moreover, although promoting dense urban development can reduce built-up areas and many additional externalities (e.g., carbon emissions for transport), it presents significant trade-offs with important urban ecosystem services, such as loss of green spaces (93), thereby reducing overall urban sustainability (94). Therefore, considering land take in combination with urban ecosystem services and biodiversity, land planning should always be tailored to the specific area or region (50).

Soil desealing can help compensate for what was sealed during urbanization, along with the regeneration and reuse of so-called brownfield sites. Outside Europe, soil desealing has been employed mainly in North America, including in several examples of renaturalization of brownfields (95). However, if this option is pursued in high-income and high-density countries where available land for further urban development is relatively scarce, the cost of the practice could be high because of the likely need for decontamination. Additionally, in light of the urban growth rate, desealing is unlikely to quantitatively compensate for the land consumed.

3.9. Best Management Practices to Prevent and Mitigate Soil Compaction

Soil compaction can be minimized, remediated, or confined (96). Minimizing soil compaction is the most effective approach and is achieved by timing traffic for when soils are drier and less susceptible. With more erratic weather and shifts in the availability of contractors for harvesting crops, timing has become a major challenge and threat (55). In agriculture and forestry, topsoil compaction can be minimized with low-ground-pressure tires, but with heavy machinery the stresses will still transmit to subsoils. The lower impact of lighter machinery has prompted recent technological advances. Groups of six to nine lightweight autonomous vehicles could replace one large harvester, but they would need offloading every 3 min, so the logistical challenge is massive (96). Even though smallholder farms use lighter machinery, compaction still occurs, and the most common remediation approach, subsoiling, can increase yields by 10% (53). Subsoiling disrupts the inherent structure of subsoils, so unless organic matter is incorporated at the same time, the benefits are temporary (55).

Remediation of compacted soils occurs naturally via root growth and weather, to some extent, but it takes time and may not improve compacted subsoils. Plant roots are impeded from reaching subsoil depths, so modern plant breeding could select for root characteristics that penetrate stronger soils (97). Tillage commonly breaks up compacted topsoils, but that comes at the expense of other soil threats (52). Soils with more organic matter and biological activity are more resilient to soil compaction (55).

Confinement of soil compaction is achieved through controlled traffic farming, which uses unified axle widths across machines as well as defined tramlines (55). Controlled traffic farming can increase yields by 38% on large farms and by 16% on smallholder farms (53). Forestry commonly confines compaction and uses brush mats to spread the applied stress (98).

3.10. Best Management Practices to Improve Soil Water Management

Soil water management to avoid either insufficient or excess water increases the amount and stability of crop yield. Irrigation and artificial drainage are the most widespread practices for soil water management and are deployed across more than 400 Mha of cropland. Irrigation relieves water limitation, which is a major source of yield gaps (99). Drainage increases root volume and soil nutrient cycling while enabling timely field operations (100). Irrigation and drainage are not mutually exclusive; sustained irrigation often requires drainage to prevent soil salinization and accretion of shallow water tables. Combined irrigation and drainage systems are also used in regions with seasonal differences in water availability (101). Other soil water management practices are used at a smaller scale or with dual purposes to conserve soil and retain runoff. These include stone lines, planting pits, terraces, and tillage and residue management to increase SOM content (see Section 3.2), which also improves infiltration and soil moisture retention (102).

Systems approaches that integrate soil water management with other conservation agriculture practices can minimize trade-offs among productivity, profitability, and environmental performance. Irrigated cropping systems that combine water delivery management (e.g., furrow, overhead, drip) with residue and tillage management can reduce nitrous oxide emissions while improving water use efficiency and crop yield (103). Drainage systems with control gates that are used to actively manage the water table can increase yield stability and nutrient use efficiency while reducing downstream nutrient losses. Conservation tillage and residue management can reduce erosion while conserving soil water through effects on mulching and weed prevention.

Soil water is a critical factor controlling plant growth, microbial activity, and material transport. A better understanding of how various soil water management practices interact with other soil management practices will lead to new opportunities for sustainable agroecosystem design and management. For a summary of these soil threats and other SSM practices covered in Sections 2 and 3, see **Table 1**.

4. POLICY FRAMEWORKS AND INITIATIVES TO IMPROVE THE STATUS OF THE WORLD'S SOILS

Although there are no policies or initiatives to protect or enhance the status of soils in many regions of the world, a few notable global initiatives aim to do so, as discussed in Section 4.1. There are also a number of national and subnational policies and initiatives, which we describe in Section 4.2.

4.1. International Initiatives

Unlike air, water, and biodiversity, the sustainable management of soils is not recognized within well-established international policy frameworks. Soils are more stationary, less transboundary in nature, and subject to complex land use issues arising from the fact that they are often not a public resource.

Policies and legal instruments can provide a framework to prevent soil degradation. However, soil policies are generally fragmented, addressed with different instruments and in different sectors. Strengthening the cross-compliance of policies is therefore necessary in order to value soils and the ecosystem services that soils provide (4).

At the UN level, the FAO has been developing guidelines and international networks to promote SSM through the Global Soil Partnership, initiated in 2012, which has the objective of becoming a governing body in the future. The Global Soil Partnership Action Framework 2022–2030 (see **https://www.fao.org/global-soil-partnership/about/gsp-action-framework-2022**) leverages the scale and scope of SSM with the goal of improving global soil governance. This action framework provides for the formulation of indicators and targets, evaluation of the performance of soil sustainable management policies in the UN member states, and assessment of global soil health by means of standardized indicators.

During the last 15 years, numerous institutions have addressed aspects of soil management and various citizen initiatives have arisen. Additionally, soils are a crucial component of both the

Table 1 Summary of soil threats and sustainable soil management practices

Soil threat	Causes	Sustainable soil management practices to address soil threats
Soil erosion	Mass movement, caused by wind and water, and tillage, erosion exacerbated by poor land management practices and soils being kept bare	Intensified cropping systems, conservation tillage, management of crop nutrition and water supply, and/or agroforestry These practices contribute to soil cover throughout the year and enhance soil surface organic matter content, aggregate stability, and porosity and permeability. Contour and/or strip cropping, mechanical practices and engineering techniques (e.g., terraces, ponds, channels, waterways), and/or windbreaks can manage or control runoff flow and speed or wind speed
Loss of organic matter	Land use change, vegetation disturbance (including overgrazing), intensive tillage, removal of crop residues/soils left bare, peatland drainage	For mineral soils: soil cover, crop diversification, reduced-intensity tillage, improved nutrient management (including organic amendments), soil and water conservation techniques, improved irrigation, grassland conservation and restoration, grazing management, integrated farming, reduced disturbance in forestry and continuous cover, and improved management of urban green spaces
		For peatland soils: protection of intact peatlands, restoration of degraded peatlands by reversing drainage by blocking drainage channels, and prevention of erosion by physically stabilizing eroded peats through mounding or adding netting as well as revegetation
Poor soil nutrient balance	Soil nutrient mining (through agricultural practices that result in a negative nutrient balance, i.e., where losses are greater than gains), lower nutrient input than crop requirements, soil erosion, poor soil management practices	Increasing primary productivity, conservation agriculture practices including reduced tillage, crop residue retention, improved rotations, integrated soil fertility management, and site-specific nutrient management based on soil testing
Soil salinization and alkalinization	Geogenic processes (dissolution and weathering of rocks) and inappropriate irrigation practices	Use of halophytic (salt-tolerant) crops or microbiota, adequate management of irrigation to avoid further salt accumulation, application of techniques such as mulching to reduce evapotranspiration and thus salt accumulation in the topsoil, organic amendments, salt drainage by adding a leaching fraction on top of water needed by the crop, gypsum (or phosphogypsum) application, sulfur gas, and irrigation with partly neutralized high-residual-carbonate water with gypsum or sulfuric acid
Soil contamination	Geogenic processes and anthropogenic contamination as a result of industrialization, armed conflicts, mining, poor waste management, and intensification of agriculture (particularly the extensive use of pesticides and herbicides)	In situ remediation deals with contamination without removing soil from the ground, and ex situ remediation requires the excavation of contaminated soil for treatment or disposal elsewhere. Techniques include bioremediation, incineration, soil washing, and bioavailability reduction by immobilizing contaminants

(*Continued*)

Table 1 (*Continued*)

Soil threat	Causes	Sustainable soil management practices to address soil threats
Soil acidification	Atmospheric acid deposition, mineralization of organic matter, nutrient uptake by high-yielding crops, root exudates, land use change, and nitrogen enrichment	Application of lime or gypsum, agroforestry, organic materials, and growing acid-tolerant crops
Loss of soil biodiversity	Intensive farming, habitat destruction and fragmentation, harsh climatic conditions associated with the climate crisis, deforestation and harvesting of soil organisms, high-input agriculture, urbanization, contamination, soil sealing, salinization, compaction, and invasive species; fire, salinization, and sodification in dryland regions	Sustainable soil management practices that reduce soil contamination; decrease the use of chemicals; increase organic farming; reduce deforestation; decrease pesticide and chemical fertilizer use; provide for permanent soil cover through intercropping, mulching, and agroforestry; use catch crops; use zero-tillage/conservation tillage and a return to low-input agriculture (with heavy use of organic fertilizers and biostimulants); reduce tillage, use cover crops, and increase rotation diversity; reduce thinning intensity (in forestry); and retain deadwood derived from thinning operations on forest soils
Soil sealing	Urbanization processes that include conversion of agricultural, natural, or seminatural areas to artificial land use, including sparse settlements, urban fringes, industrial estates, and transport infrastructure	Land planning to reduce the impacts of urbanization on soils: prevent higher-quality soils from being sealed, perform urban greening and desealing, mitigate the loss of ecosystem services provided by soils, reduce the degree of imperviousness, implement compensation measures
Soil compaction	Machinery (especially in agriculture) and animal trampling	Minimizing soil compaction by timing traffic for when soils are drier and less susceptible, low-ground-pressure tires on machinery, lighter machinery, tillage to break up compacted soils, modern plant breeding to select for root characteristics that penetrate stronger soils; confining soil compaction is achieved by controlled traffic farming, where axle widths are unified across machinery and defined tramlines and, in forestry, brush mats are used to spread applied stress
Soil water status	Global climate and biogeochemical cycles	Irrigation relieves water limitation, and drainage increases root volume and soil nutrient cycling while enabling timely field operations. Combined irrigation and drainage systems are also used in regions with seasonal differences in water availability. Stone lines, planting pits, terraces, and tillage and residue management increase infiltration and water retention. Other techniques include improved irrigation delivery (furrow, overhead, drip) and drainage systems with control gates

UN Convention to Combat Desertification (UNCCD) and the UN Convention on Biological Diversity.

The Paris Agreement aims to limit global warming to below 2°C, with the goal of achieving 1.5°C. To this end, parties must submit individual climate plans every 5 years, and there are rules for reporting and accounting for emissions from land use, land use change, and forestry. However, specific measures are not mandated, nor are soil and land use explicitly addressed. Nevertheless, the IPCC (104) has emphasized the role of land restoration and soil carbon sequestration in achieving the temperature targets.

For 30 years, the OECD (Organisation for Economic Co-operation and Development) has been working with environmental indicators, including soils, for both forestry and agriculture. Although the OECD focused originally on the indicators most related to soil productivity, the most recent indicators are instead oriented toward GHG emissions and nutrient mismanagement (see **https://www.oecd.org/agriculture/topics/agriculture-and-the-environment**).

During COP12/UNCCD in 2015, all UN members committed to adopting the SDGs as part of Agenda 2030 (105). The 17 SDGs cover, directly or indirectly, several issues relevant for international soil governance (1, 106, 107), but only one (Target 15.3) specifically advocates for a land degradation–neutral world by 2030.

Decision 3/COP.12 of UNCCD (108) defines land degradation neutrality as a state wherein the amount and quality of land resources necessary to support ecosystem functions and services and to enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems. Soil is implicitly considered in this definition, as it is the fundamental component of land resources (109). The Scientific Conceptual Framework for Land Degradation Neutrality (110) specifies the main guidelines for its implementation, although some aspects, such as the operational scale, determination of the baseline state, and off-site consequences of land degradation, remain unresolved (109).

The "4 per 1000" international initiative, Soils for Food Security and Climate, was launched by the French government at the 2015 UN Climate Change Conference to promote organic carbon sequestration in soils as a mechanism to mitigate climate change, while ensuring synergies with soil fertility and adaptation to climate change. This initiative promotes the adoption of agroecological practices and has succeeded in drawing attention to soils and placing them at the center of consideration for agricultural management (111).

4.2. National, Subnational, and Local Initiatives

Many national initiatives aim to protect soils and promote soil health. The FAO maintains a database of soil-related legal instruments and soil governance legislation (SoiLEX) (112). The database lists soil legal instruments in each country and classifies them according to the type of soil threat or intervention they apply to. Although not a perfect indicator of soil protection, since one all-encompassing law to protect soil health might be as effective as (or more effective than) many separate laws, these data are an indicator of how well various components of soil health are reflected in legal instruments. SoiLEX includes a total of 3,823 legal instruments and category combinations (though some legal instruments address more than one category). **Figure 3** shows the legal instruments by category. Legal instruments related to soil conservation are the most numerous globally, followed by those addressing pollution. The least well represented, perhaps partly because of their limited global reach, are laws related to salinization and sodification, acidification, and compaction.

Countries differ in the number of legal instruments related to soils (**Figure 4**). Russia has the most legal instrument/category combinations, many of which pertain to the different regions of this vast country. Canada and Mexico likewise have an array of legal instruments, with many pertaining to different regions. In total, 173 countries have at least some legislation to protect and enhance soil health.

To provide some context to the global analysis presented above, we pick out two countries (Brazil and the United Kingdom) and describe their legal instruments in more detail before

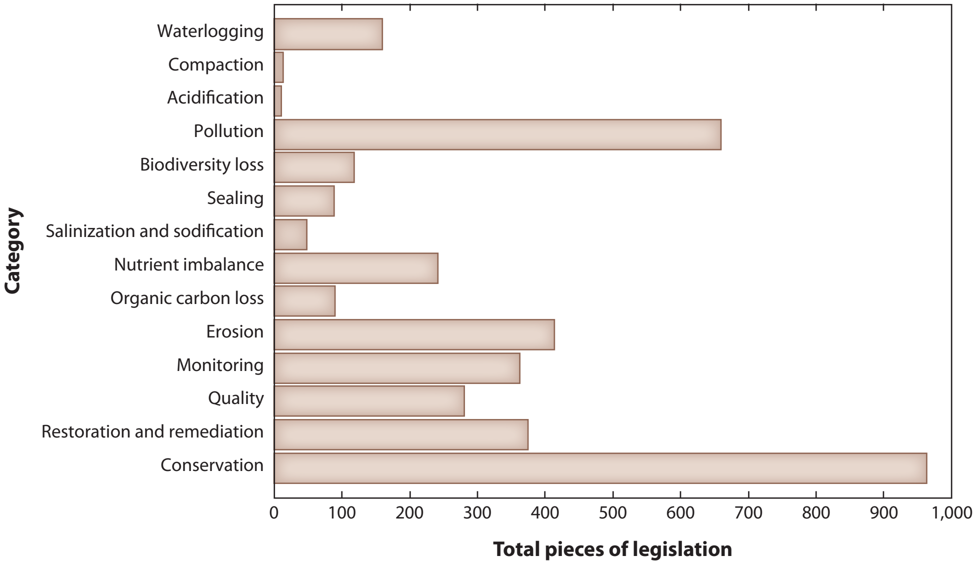
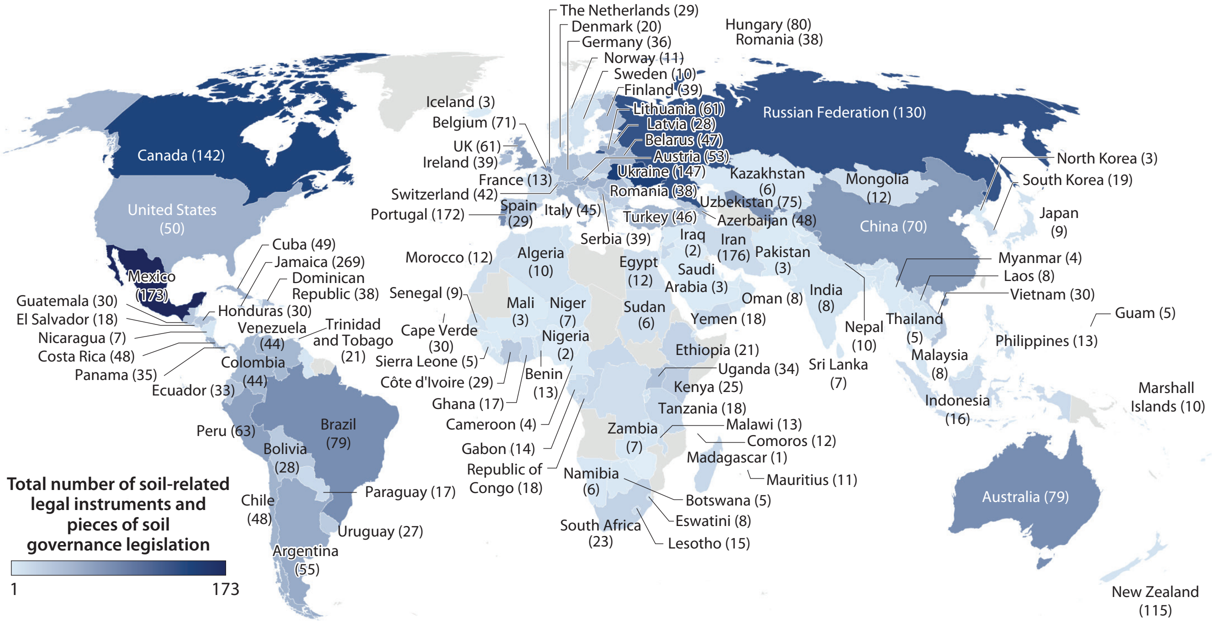


Figure 3

Soil-related legal instruments and soil governance legislation by category, showing totals across all countries. Data are from SoiLEX (112), a global database from the Food and Agriculture Organization of the United Nations that aims to facilitate access to information on existing legal instruments on soil protection and prevention of soil degradation.

discussing notable subnational initiatives. The Cerrado is the second-largest biome in Brazil and the main source of grain, fiber, biofuel, pasture, and silviculture production. Much of the Cerrado has been deforested, causing biodiversity and carbon losses and increasing erosion. National initiatives include the ABC program (launched in 2014), which promotes the adoption of technology through training and technical assistance; integrated crop–livestock–forest systems; and zero-tillage/conservation agriculture. Diversification and intensification of agriculture in the Cerrado, through conservation agriculture, are the most promising ways to increase soil carbon stocks (113). Plans and policies based on zero-tillage/conservation agriculture reduce soil erosion (114). Recently, the Brazilian Fertilizer Plan (2022–2050) (115) was launched to decrease dependency on fertilizer imports by promoting good practices and developing new nutrient sources.

In the United Kingdom, there is overarching legislation that pertains to soils, but there are also separate initiatives in each constituent county. In England, sustainable farming initiative payments encourage actions that improve soil health for arable and horticultural soils, improved grassland soils, and moorland soils (116). Other initiatives, such as the Farming Rules for Water, improve nutrient management (117). There is also major investment in a new national soil monitoring program covering a wide range of chemical, biological, and physical properties and issues covering all dominant land use and soil types. In Wales, funding and a requirement for soil testing are likely to be embedded in the Sustainable Farm Scheme, to be made available in 2025, and Wales includes soil carbon and organic matter as its thirteenth national indicator of well-being (out of 50 indicators covering social, economic, and environmental outcomes). Wales is one of very few countries with soil as a national indicator. The Soil Nutrient Health Scheme of Northern Ireland is one of the most comprehensive regional soil nutrient sampling schemes in the world. It enables farmers to optimize the application of crop nutrients to their soils and provides a baseline for farm carbon stocks. In Scotland, soil health and protection are covered by various acts, regulations, and



Central America and Caribbean

- Antigua and Barbuda (3)
- The Bahamas (5)
- Belize (2)
- Grenada (9)
- Guyana (7)
- Haiti (9)
- Puerto Rico (2)
- Saint Kitts and Nevis (4)
- Saint Lucia (10)
- Saint Vincent and the Grenadines (12)

Europe

- Albania (17)
- Bosnia and Herzegovina (11)
- Bulgaria (21)
- Croatia (26)
- Cyprus (5)
- Czechia (12)
- Estonia (22)
- Georgia (29)
- Greece (19)
- Hungary (49)
- Luxembourg (18)
- Malta (20)
- Moldova (20)
- North Macedonia (9)
- Poland (28)
- Slovakia (10)
- Slovenia (37)

- European Union (41)

Africa

- Burkina Faso (4)
- Burundi (8)
- Djibouti (6)
- Democratic Republic of the Congo (13)
- Equatorial Guinea (5)
- Guinea (3)
- Liberia (8)
- Rwanda (9)
- Seychelles (8)
- Sierra Leone (5)
- The Gambia (2)
- Togo (8)
- Tunisia (8)
- Zambia (7)
- Zimbabwe (1)

Middle East

- Afghanistan (1)
- Bahrain (2)
- Israel (2)
- Jordan (17)
- Kuwait (1)
- Lebanon (28)
- Qatar (2)
- Syria (3)
- United Arab Emirates (3)

Oceania

- Fiji (3)
- Kiribati (3)
- Federated States of Micronesia (3)
- Nauru (3)
- Palau (2)
- Samoa (5)
- Solomon Islands (6)
- Tuvalu (6)
- Vanuatu (3)

Asia

- Armenia (28)
- Bangladesh (3)
- Bhutan (2)
- Cambodia (5)
- East Timor (3)
- Kyrgyzstan (7)
- Maldives (3)
- Tajikistan (4)

Figure 4

Global map showing the total number of soil-related legal instruments and pieces of soil governance legislation in each country included in the SoiLEX database (112). In areas of the map where labels would be overlapping and illegible, countries appear below the map in alphabetical order by region.

policy guidance (see **https://soils.environment.gov.scot/soils-in-scotland/soil-protection**) including a soil monitoring action plan.

Subnational and local soil conservation initiatives are executed through both governmental and nongovernmental organizations, which have a wide range of administrative structures, funding sources, and missions. Administrative structures include locally elected and appointed officials, employees, and volunteers. Funding sources include local and national governments, private donations, and well-organized consortia of private for-profit and nonprofit organizations. Missions include research (both citizen and scientist based), conservation practice implementation, and policy development and guidance. Some initiatives focus specifically on soils, while others address soils through a broader focus on natural resources. Below, we describe several diverse and salient examples of local or subnational efforts to promote soil conservation. All of these programs recognize the importance of soil for food security and the need for national or regional policies to be carried out through local representatives.

In response to the Dust Bowl in the 1930s, the United States created a comprehensive local network of approximately 3,000 soil conservation districts. Today, the mission of these districts has expanded to promote the conservation of soil, water, and other natural resources (see **https://www.nacdnet.org**). The districts, led by locally elected officials representing the national government, provide private landowners with technical and financial assistance with conservation planning and implementation. Examples include help with reduced tillage, cover crops, and improved fertilizer management.

In 2022, China created a law to protect, restore, and promote sustainable agricultural production specifically for black soils, which are found in four geographic regions. Similar to the US case, the Chinese national law enables local townships to execute the organization and implementation of the conservation work.

The Basque region of Spain developed the Basque Soil Protection Strategy (118), which includes four action areas: understanding and monitoring soil health, developing policies to ensure protection of soil health, fostering SSM, and increasing awareness and training for SSM practices. In Catalonia, Spain, the Agricultural Land Law (119) protects soils that are important for food production. For example, solar farms cannot be installed on soils that are listed in agrological capability class I or II. Nevertheless, the region requires more complete soil mapping to ensure adherence to the law.

The French Network of Scientific and Technical Expertise on Soils (see **https://rnest.fr**) brings together policymakers and stakeholders from academia, companies, farmer organizations, and others to strengthen technical expertise and coordination among various initiatives to guide public policies and respond to stakeholders' concerns about soil management. The network is supported by 11 organizations representing key national soil research, development, and innovation actors and ministries.

There is a growing number of consortia funded by corporations with an interest in soil conservation. Missions generally include applied research and raising awareness among farmers about soil conservation practices. Examples include Agriculture du Vivant in France (see **https://agricultureduvivant.org**) and the Soil Health Institute in the United States (see **https://soilhealthinstitute.org**).

Within the United Kingdom, subnational efforts in England and Scotland aim to promote the conservation of soils for economic, social, and environmental needs. The United Kingdom's 25 Year Environment Plan (120) includes a goal to improve soil health. The Scottish Soil Framework (121) recognizes soils as a nonrenewable resource and aims to protect and enhance soil functions.

5. DISCUSSION

Despite the increasing awareness of soils and the many initiatives to address soil degradation, the status of soils has not always improved where such initiatives have been implemented. Examples of success exist; for example, some European and North American countries have applied agroecological practices along with strict monitoring programs that have effectively reduced soil and groundwater pollution, increased SOM, and enhanced soil quality parameters. In other cases, the recognition of soil as a carbon pool with environmental benefits has led to the implementation of policies that reward farmers for applying practices that maintain or increase SOM. For instance, the FAO's RECSOIL program (67) is currently being tested and has been successful in Costa Rica, Mexico, Colombia, Brazil, and Tunisia, among other countries.

One large-scale, transnational soil restoration program, the Great Green Wall in Africa, was announced in 2007 by the African Union and funded by the European Union, the World Bank, and the UN. Although it did not reach its original goals, it had some success in stopping desertification as soon as it evolved into a more decentralized and participatory program, where specific actions took into account local knowledge and socioeconomic frames (122).

Another large-scale project is the Grain for Green Program, which began in the 1990s in China. The program converted 16,000 km^2 of the highly eroded Chinese Loess Plateau into forests or grasslands to minimize soil water loss and improve livelihoods. It resulted in a visible greening trend and reduced soil erosion and water loss while improving carbon fixation, ecosystem services, and agricultural production. However, vegetation expansion affected the hydrological balance, causing water shortage and drier soil layers, to the point that further revegetation is controversial. Industrial transfer was positive, but energy consumption per unit output was approximately twice the national level. Therefore, sustainable economic growth is still a serious issue in the Loess Plateau (123).

SSM can fail when applied without sufficient soil knowledge. For instance, while organic agriculture is generally considered a sustainable and environmentally friendly approach to food production, significant reductions in chemical fertilizers and pesticides have reduced production and farmers' incomes, leading to economic and social crises in some regions [e.g., Sri Lanka (124) and Eastern Europe (125)]. Addressing these challenges requires capacity building, research, stronger cross-sectoral collaboration, social awareness, and the development of appropriate policies and support systems.

In general, successes have been reported mainly in places with considerable soil information databases and consistent environmental monitoring networks, where the administration can afford adequate monitoring, reporting, and verification protocols. In this respect, soil information is essential in order to develop soil management programs that can combat soil threats such as those derived from climate change (126).

Wars are a major threat to soil quality, with long-term environmental, agricultural, and health consequences (127). Major soil disturbance (trenches, bombturbation, compaction), pollution (use of explosives, munitions, and chemical warfare agents releasing heavy metals and contaminants), and antipersonnel mines directly prevent the use of land for agriculture (128). Indirect effects derive from population displacement, causing both land abandonment and the establishment of refugee camps, with adverse consequences for agricultural land use (129).

Healthy soils contribute to a wide range of ecosystem services and virtually all of the UN SDGs (1) (**Figure 5**). Since soil health is compromised by all of the soil threats discussed in Section 2, BMP need to be implemented to ensure that ecosystem services are supported and the SDGs are delivered. Doing so will require strengthened policies to support farmers and land managers in implementing BMP. Policies need to target improved knowledge, data, and education available to land managers, in addition to offering financial support for practices that could compromise farm income. As described in Section 4, although many regions of the world have no policies or initiatives to protect or enhance soil status, a few notable global initiatives aim to do so, along with several notable national and subnational initiatives. These initiatives have helped remove implementation barriers and reflect action areas including sustainable financing, capacity building, and public awareness and education. Repetition and scaling up are required at all levels. Including soil degradation and SSM as focal areas in international funding mechanisms, coordinating capacity building regionally, and establishing national SSM units are all good examples of opportunities to strengthen SSM at the global, regional, and national level, respectively. Above all, a

Figure 5

Functions provided by soils (*inner ring*), ecosystem services and Nature's Contributions to People (NCPs) provided by soils underpinned by these functions (*gray middle ring*), and impacts on the United Nations Sustainable Development Goals (SDGs) through NCPs supported by soils (*outer ring*). Teal numbered circles in the middle ring show the corresponding soil functions that contribute to the NCPs. Gray numbered circles in the outer ring show the NCPs contributing to the SDGs. Figure adapted from Smith et al. (1).

process-oriented approach that encourages interaction and communication may be the best way to convince soil users of its importance.

There are many examples of the importance of traditional knowledge and its potential contribution to the sustainable use and management of soils and ecosystems. One is the addition of pyrogenic carbon (charcoal, black carbon, or biochar) to residues of food preparation, cooking fires, and so forth to improve the fertility of soils that formed the Amazonian dark earths (*terra preta*), some of which date from 450 BCE and 950 CE (130, 131). Modern biochar has been proposed as a way of improving soil fertility, and its use shares many characteristics with this forgotten centuries-old practice, whose loss is perhaps as culturally significant as its practical value. Many traditional soil management practices worldwide (132) are likely to vanish during the twenty-first century, given the intensification of production systems toward monocrops and loss of traditional populations.

In 2015, FAO & ITPS (4) produced the first global assessment of the status of the world's soil resources, and they are expected to deliver an update in 2025, providing a comprehensive assessment of how the world's soils have changed over the past 10 years. This report will become the major international summary of the state of the world's soils. It will begin with a summary of the major global advances since 2015 in our understanding of threats to soil functions and how SSM can address these threats. The second part will comprise summaries of the status of the threats to soil functions in each of the seven regions of the Global Soil Partnership, together with the state of SSM in each region.

SUMMARY POINTS

1. The majority of the world's soil resources are in only fair, poor, or very poor condition, with conditions getting worse in more cases than they are improving.
2. A total of 33% of soils are moderately to highly degraded as a result of erosion, compaction, pollution, acidification, salinization, and other components of soil degradation.
3. The main threats to soil health are erosion, loss of organic matter, poor nutrient balance, salinization and alkalinization, contamination, acidification, loss of biodiversity, sealing, compaction, and poor water status.
4. Best management practices to limit or mitigate threats to soil health are available, and many of them mitigate multiple soil threats.
5. Initiatives at field scale seem to work better than those applied in large regions; one-size-fits-all approaches are less effective.
6. In many countries around the world, policies or initiatives to protect or enhance the status of soils have recently begun to increase.
7. Healthy soils contribute to a wide range of ecosystem services and virtually all of the United Nations Sustainable Development Goals.

FUTURE ISSUES

1. While there is good national and global information for some soil indicators, such as soil organic matter and nutrient status, data for others, such as soil biodiversity, are far less complete.
2. Comprehensive soil health monitoring, covering biological, chemical, and physical indicators of soil health, would provide an evidence base both for assessing soil health status and for planning best management strategies to protect and improve soil health.

3. Further research should focus on developing suitable soil health indicators for each region and type of soil that are easy and inexpensive to measure and correlate well with specific soil functions; defining targets and thresholds for these indicators; and designing suitable monitoring, verification, and reporting frameworks for soil health.
4. New technologies, such as advanced modeling, robotics, and artificial intelligence, may have a role to play in assessing soil health in the near future.

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AUTHOR CONTRIBUTIONS

P.S. led the writing of the review, with significant contributions from all authors. All authors were involved in reviewing and editing the article. All authors have read and approved the final version of the article.

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