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Soils and sustainable development goals of the United Nations: An International Union of Soil Sciences perspective

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ABSTRACT

Being critical to achieving Sustainable Development Goals (SDGs) of the United Nations, strengthening understanding of the properties and processes of soil at national and regional scales is imperative. The necessity to realize SDGs by 2030 also inspires a greater sense of responsibility and care for soils. Sustainable management of soil health is important to achieving several SDGs. Pertinent SDGs intricately connected with soil health include SDG 1 (End Poverty), 2 (Zero Hunger), 3 (Good Health and Wellbeing), 5 (Gender Equality), 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 9 (Industry Innovation and Infrastructure), 11 (Sustainable Cities and Communities), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land). Some of these SDGs rely considerably on plant production and others depend on soil processes. Pertinent among soil processes are water movement, heat transfer, sorption and physical filtration, ion exchange, and biochemical and biophysical transformations. In terms of specific accomplishments, 130 countries have aligned with the Zero Hunger Challenge, the globally available fresh water has decreased to 71% of needs, Technosols (soils whose formation is influenced by anthropogenic based materials) are used in urban ecosystems, food wastes are composted, specific targets of Land Degradation Neutrality have been signed by several countries, and soil C sequestration targets are widely implemented through initiatives such as the 4 Per Thousand (4P1000) initiative, Platform on Climate Action in Americas (PLACA), Adapting African Agriculture (AAA), Living Soils of the

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Americas (LiSAM), etc. In addition, policy and regulatory frameworks being widely promoted by several U.N. agencies (e.g., U.N. SDGs,limiting global warming to 1.5°C or 2 °C) can be supported by innovations in soil science including forensic soil science, remote sensing and other innovations.
Soil health is becoming a central element of the research and innovation program of the EU, aiming to reach a 75% of healthy soils by 2030. In addition, the importance of soil health to human health and environmental issues is being widely promoted through educational books on soil science and secondary schools, as well as the revision of curricula. With continuous progress in movement into the digital world, transfer and communication of knowledge of the soil sciences can improve for the end users, policymakers, and the general public but additional efforts are needed. Soil science knowledge and research forms a significant contribution to specific aspects of food and nutritional security, human wellbeing, nature conservancy, and global peace and harmony. Achieving critical SDGs by 2030 can be facilitated by soil restoration and sustainable management.

Contents

1. Introduction and motivation

Soil science is critical to achieving the Sustainable Development Goals (SDGs) of the United Nations (U.N, 2020a; U.N, 2015a). However, soils knowledge cannot be applied to modern challenges with a scarcity of well-trained specialists with a deep knowledge of soils, how they function, and the ability to communicate effectively. A major concern that has been expressed by some soil scientists is the lack of a holistic disciplinary foundation to support many who are working as soil scientists or otherwise doing soil science work (Brevik et al., 2020a; Collins, 2008; Diochon et al., 2016; Field et al., 2017; Havlin et al., 2010), with direct relevance to realizing the SDGs.

Effective communication on the SDGs with society requires a basic grounding in soil science to enable the general public to understand the importance of soils in our lives, throughout the world, and to understand how soils are formed and sustained, how they vary across the landscape, and how they relate to fundamental aspects of the world's economy – from agriculture, forestry, gardening and town and country planning through ecology and conservation. Aside from a basic grounding in soil science, modern means of communication should also be explored to reach stakeholders and young citizens in the modern era (e.g. Bouma, 2018a, 2018b). Learning about soils can inspire a greater sense of responsibility and care for soils as part of our fragile natural environment. It also extends to learning about soils at school, through general science, geography, modern studies and biology, and ultimately to studying soil science at university, as a main subject, but also increasingly as part of a geography, geology, agriculture, botany or biology and human health degree (Brevik et al., 2020a; Diochon et al., 2016).

Soil health is essential for human health – this may seem obvious and yet its importance is still too often underestimated. In Europe, however, Soil Health and Food is one of five so-called Missions of the large "Horizon Europe" Research and Innovation program of the European Union (2021–2027). Other Missions focus on, in short, cancer, water, climate, and cities. This presents a major challenge to the soil science profession. The report of the Mission (Veerman et al., 2020) emphasizes that healthy soils are a source of the provision of numerous ecosystem services (ESs) such as food production, nutrient supply, detoxification, water and nutrient retention, maintaining biodiversity, and carbon (C) sequestration. These ESs, in turn, contribute to various SDGs (e.g. Bouma, 2014). Veerman et al. (2020) have therefore defined Soil Health as: *"the capacity of soils to contribute to ecosystem services in line with the UN-SDGs and the EU Green Deal,"* emphasizing the need for interdisciplinary research approaches, thereby establishing the major role that soils play in realizing ecosystem services.

Being the largest terrestrial sink of C, sustainable management of soil is important to adaptation and mitigation of climate through adoption of climate-resilient agriculture (Lal, 2016), sequestration of C by afforestation of degraded and denuded lands (Lal et al., 2018), and the creation of sustainable food systems based on agroecological approaches linked with indigenous knowledge. All of these functions are directly and indirectly related to ESs, SDGs and human wellbeing.

There are a myriad of ways soils can either improve or degrade human health and wellbeing depending on the types of exposures and interactions humans have with soil. Despite this, few people seem to be aware of the multiple connections between soil and human health; communicating these connections is of critical importance (Brevik et al., 2019b). Soil contamination, pesticides, and the use of artificial fertilizers all impact soil health, which in turn impacts the quality and quantity of the foods produced. Despite this, the links between soil health and nutritional quality are still relatively poorly understood.

There is also an emerging paradigm that the soil microbiome might be important for the human gut microbiome, being mainly responsible for the immune system and allergic disorders (van Bruggen et al., 2019).

Regarding the role soils play within human immune systems, research has shown that playing in soil increases children's immune responses, improving responses to diseases such as asthma and eczema. However, it is still unclear if the increase of these diseases is caused by most of today's children growing in very sterile and protected environments, where access to the soil, woods, pastures and other green spaces are limited.

Biodiversity is important for the maintenance of soil quality. Biodiversity has been shown, for example, to be important in controlling populations of pathogens. Healthy, well-covered, carbon-rich soils can reduce disease outbreaks, provide pest control, and exposure to soil microbes can reduce allergies. Soil microbes have provided many of the current antibiotics and can enhance crop plant resilience. Finally, healthy soils promote good clean air quality, are less prone to wind and water erosion, and provide clean and safe water through filtration, decontamination by microbes and removal of pollutants. Soil biodiversity is highly recognized now as an important feature of healthy soil and imbalances have been shown to give advantage to harmful over beneficial organisms (Wall et al., 2015).

Despite lessons from history, the thin layer of precious soil which covers most of our planet's land surface has been largely ignored. It's only in recent years that the importance of soil health and the millions of species which live within this fragile layer, and its relationship with food security and climate change, are starting to become understood (D'Hondt et al., 2021; Yang et al., 2021). And yet, soil is much more than this. It is fundamental to human, animal and plant health and well-being.

A brief review of how soil science relates to the SDGs covered in this paper will demonstrate the importance of a holistic, interdisciplinary foundation in soil science to human wellbeing and nature conservancy. Although "soils are not explicitly mentioned" in the SDGs, soil is addressed in and builds the basis of numerous SDGs even though involvement of soil scientists in articulating the SDGs has so far been limited (Bouma et al., 2019). Sustainable soil management practices are key factors in achieving SDGs (Ussiri and Lal, 2018), SDGs 2, 6, 7, 13, and 15 are especially interconnected with soil parameters and functions, while soils may also play a substantial role in others e.g. 3, 12, 14 (Horn et al., 2018; Keesstra et al., 2016) and SDG 1. SDG 12 (Sustainable consumption and production, Gasper et al., 2019) is mentioned less often in connection with soil, although soil is central to this goal. Importance of soil is specifically mentioned in Target 12.2 (Sustainable management and use of natural resources), Target 12.3 (Global Food loss) and Target 12.5 (Substantially reduce waste generation).

Soil processes and their judicious management is important to realizing several SDGs. For example, SDG 1 is "End Poverty", 2 is "Zero Hunger," 3 is "Good Health and Wellbeing," 4 is "Quality Education," 5 is "Gender Equality," 6 is "Clean Water and Sanitation," 7 is "Affordable and Clean Energy," 9 is "Industry Innovation and Infrastructure," 11 is "Sustainable Cities and Communities," 12 is "Responsible Consumption and Production," 13 is "Climate Action," 15 is "Life on Land," and 16 is"Justice for All." Many of these SDGs rely, at least partially, on plant production using soil (SDGs 2, 3, 7, 11, 12, 13, 15). All of the SDGs that rely on plant production, plus others that utilize various soil processes such as water movement, heat transfer, sorption and physical filtration (SDGs 6 and 9), rely on soil physical and chemical properties, information studied in classes such as pedology, soil chemistry, soil mineralogy, and soil physics and supplemented by a variety of supporting fields (i.e., chemistry, geography/geology, mathematics, physics). Progress made thus far in realizing some of these goals by initiating and implementing soil-based programs is outlined in Table 1. However, this is just the beginning, and a lot more needs to be done to advance SDGs by 2030.

Table 1
Examples of using soil science in realizing Sustainable Development Goals.

SDG #	Focus	Principles of Soil Science to Realize SDGs: Examples
1	End Poverty	Micro-enterprise and micro-finance programs; conditional Cash Transfer Programs
2	Zero Hunger	130 countries have aligned with the Zero Hunger Challenge (ZHC) 23 U.N. agencies fund programs on ZHC
3	Good Health and Wellbeing	Books on the soil-human health nexus; improved understanding of transfer of nutrients from soil to plants to humans
4	Quality Education	Books on soil education; curricula changes at the school-level regarding sensitization about soils; teacher-supportive curricula; school kitchen gardens, etc.
5	Gender Equality	Enhanced enrollment of women in soil science education and professional jobs
6	Clean Water and Sanitation	Global population of using clean water increased from 61% in 2000 to 71% in 2017; eco-sanitation using tera preta principles costing ~US $50
9	Industry, Innovation, and Infra-Structure	Enhancing societal connections to soil and where our food comes from; organizations working with community groups, schools, etc.; best practice advice in how soils are handled, stored, and reused at construction projects
11	Sustainable Cities and Communities	Composting waste and recycling; strengthening local food production systems through urban agriculture and home gardens; use of Technosols in urban ecosystems; permaculture as agroecological farming in Australia; green infrastructure
12	Responsible Consumption and Production	Composting food waste; awareness-raising projects such as "My Food – My Future" on sustainable nutrition; reducing land consumption
13	Climate Action	Global initiatives (e.g., 4p1000, AAA, PLACA, Living Soils in the Americas); negative emission technologies (NETs); payments for ESs
15	Life on Land	Implementation of the concept of Land Degradation Neutrality by 2030; c-sequestration in land (soil, trees, wetlands)
16	Peace, Justice, and Strong Institutions	Policy and regulatory frameworks being promoted by the U.N.; forensic soil science; identifying locations of buried objects; characterization of illegal environmental deposits; criminal justice system

Indeed, soil is intricately interconnected with SDGs of the Agenda 2030 of the United Nations. Therefore, the objective of this article is to: (i) deliberate and highlight the importance of soil in realizing the SDGs (ii) show how restoration and sustainable management of world soil resources can contribute to realization of the SDGs by 2030, and (iii) discuss what is needed in terms of innovative interdisciplinary research and communication, directly involving a wide range of stakeholders.

2. SDG #1 end poverty

Poverty refers to the status of per capita resource availability at a level that cannot provide for basic needs. While the value changes with time, for the decade of 2020, The World Bank (2020) indicates that the International Poverty Line (IPL) is U.S. $1.90 per day. While poverty is a global phenomenon that has plagued humanity since the dawn of civilization, regions prone to endemic poverty since the 20th century are Sub-Saharan Africa (SSA), South Asia (SA), the Caribbean, the Andean region, etc. The United Nations (U.N, 2020b) indicated that prevalence of poverty (PoP) in 2018 was 41.1% in SSA, 12.4% in SA, 4.1% in Latin America and the Caribbean (LAC), 2.7% in the Middle East and North Africa (MENA), 2.3% in East Asia and the Pacific, and 1.5% in Central Asia and Europe. It is in this context that the Agenda 2030 recognized the need for ending poverty in all its forms everywhere. Yet, the persistence of endemic poverty is a cause for concern.

Regions faced with endemic poverty are also those where a majority of the population is dependent on agriculture and is dominated by resource-poor and small land holders. Thus, sustainable soil management and improved agriculture are key factors to eliminate poverty. Improved agriculture in SSA and elsewhere can eradicate poverty and advance food and nutritional security by narrowing the yield gap. However, it is important to understand the site-specific conditions (both biophysical and socio-economic) where and for whom improved agriculture can raise farm/family income (Gassner et al., 2019). The majority of small land holders in SSA are women and improving conditions for them is critical to eliminating poverty and advancing SDG 1. Gender equality is addressed in SDG 5. Water management, to alleviate drought and adapt to climate change, is also important to the elimination of poverty (Chen, 2017).

3. SDG # 2: zero hunger

While SDG# 2 aspires to achieve Zero Hunger by 2030, a prevalence of undernutrition (PoU) affects 690 million (M) in 2019 (FAO et al., 2020), which is 60 M more than in 2014. The COVID-19 pandemic, by adding 132 M and increasing the PoU to 900 M before 2021 (FAO et al., 2020; HLPE et al., 2020), has jeopardized SDG # 2 of achieving Zero Hunger by 2030. Of the 821.6 M PoU in 2018 (FAO et al., 2019; WHO, 2019), 513.9M were in Asia; 256.1M in Africa, and 42.5M in Latin America and the Caribbean (LAC). Whereas the PoU decreased to 679 M in 2019, the trend remained the same with 381 M in Asia, 250 M in Africa and 48 M in LAC. While the absolute largest PoU is in Asia, the fraction of population affected, and the rate of increase are largest in Africa (19.1%) followed by Asia (8.3%) and LAC (7.4%). The PoU is exacerbated by the COVID-19 pandemic, not only in fragile societies (e.g., South Asia, Africa, LAC) but also in rich countries such as France, where 8M needed food aid during 2020 even prior to the COVID crisis.

Poverty, the major cause of global hunger, affects 11% of the world's population, which survives on only $1.90/day or less. Hunger-prone regions also experience wars and conflicts viz. sub-Saharan Africa (SSA), Yemen, and Syria. Global warming, manifested by flood/drought syndrome and heat waves, disrupted the food supply of 5.5M in South Sudan and 2.3M in Zambia (WFP, 2019). The PoU is exacerbated by gender inequality, poor education, malnutrition, etc. Therefore, canceling the debts of developing countries, ending conflicts, and creating employment may enhance access to safe and nutritious food, clearly demonstrating that “zero hunger” is not only a matter of crop production.

Climate change is the greatest threat to global health in the 21st Century (WHO, 2020). Sustainable soil and agricultural management, in addition to promoting adaptation and mitigation of climate change, is also critical to realizing SDG #2 by 2030. The latter, a necessity rather than a political slogan, is critical to addressing humanity's common enemy, the hunger.

Launched at Rio + 20 Conference on Sustainable Development in 2012 by the former Secretary-General of the United Nations Ban Ki-moon (Swaminathan, 2017), the Zero Hunger Challenge (ZHC) has inspired actions at country level and contributed to ensuring that food and nutrition security and sustainable agriculture have remained high on the global development agenda (U.N, 2015b). Three years later, this challenge received a favorable response as more than 130 countries have aligned themselves with the ZHC, national policies and programs for zero hunger were in place in more than 40 countries. The 23 UN agencies, funds, and programs of the High-Level Task Force on Global Food Security have aligned their collective work plans with the elements and vision of the Zero Hunger Challenge. The clear evidence of this progress was that number of hungry people in the world has dropped to 795 million – 216 million fewer than in 1990–1992 – or around one person out of every nine, according to the latest edition of the annual UN hunger report of the state of food insecurity in the world (FAO, 2015). However, since 2015 the number of people affected by hunger globally has been slowly on the rise and this will become significant as the food security and nutritional status of the most vulnerable population groups is likely to deteriorate further due to the health and socio-economic impacts of the COVID-19 pandemic (FAO et al., 2019).

4. SDG 3: good health and well-being

Good health and well-being are interconnected with soil because healthy soils produce healthy crops that in turn nourish humans and animals, allowing for their health and productivity. There is evidence that healthy soils underpin nutritious and healthy food. Soils contribute to global health through nutrient storage and supply, which in turn supports the production of food and fiber. However, global intensification of agriculture has led to negative effects on the regulatory ESs of soil, air, and water quality (Smith et al., 2013). Fertile soils need to be preserved and restored where lost, which includes protecting and preserving the broader soil ecosystem (Cotrufo et al., 2013). However, the ever-increasing anthropogenic pressure on world soils is exacerbating nutrient depletion, reducing biodiversity, increasing risks of malnutrition and undernourishment, and adversely affecting human health and wellbeing.

Soil has both negative and positive effects on human health (Brevik et al., 2020c). Potential negative health effects from human exposure to soils include toxicity through heavy metals, radioactive elements, and organic chemicals, diseases through exposure to soil organisms, and respiratory problems caused by the inhalation of dust (Brevik et al., 2020c; Steffan et al., 2018). Deficiencies in nutrients and excesses in heavy metals in soil and plants are also directly linked to human health. Selenium deficiency (e.g., Keshan disease in China) and excess as in food and groundwater (arsenicosis) are examples of soil-induced diseases in humans. Micronutrient deficiency [iron (Fe), zinc (Zn) and selenium (Se)] are serious threats to human and animal health. In 2011, 3.7 billion (B) people were Fe-deficient and 2B of these were anemic (WHO, 2011), including 46% of women of child-bearing age in South Asia (SA) (IFPRI, 2014). Deficiency of Zn is the fifth leading cause of death and disease in the developing world (Das and Green, 2016). Nearly half of the soils on which food crops are grown are deficient in plant-available Zn, leading to reductions in crop production and the nutritional quality of the harvested grains (Shukla and Behera, 2012).

Positively, soils contribute to human health through the supply of medications including antibiotics, anticancer drugs, and others (Mbila, 2013), filtration of water (Helmke and Losco, 2013), enhancement of the immune system (Brevik et al., 2020c), and the provision of shelter, clothing, and fuel (Brevik et al., 2019a). The quality of meat products consumed by humans depends on several soil factors, and human health is therefore influenced through the soil-plant-herbivore nexus (Singh et al., 2017). Geophagy, the deliberate ingestion of soil, may have both positive (Young et al., 2011) and negative (Sing and Sing, 2010) effects on human health. There are still many areas that need additional investigation. As soil is a very complex mixture of physical, chemical, and biological processes, it is very difficult to predict its behavior. We also have sparse information on how most chemicals react within the physically, chemically, and biologically active soil ecosystem, and what those reactions mean for human health (Burgess, 2013).

At present there is good understanding of nutritional transfer of nutrients from soil to plants (to animals in some cases) to people, of exposures to some pathogens, and to some chemicals that are found in soils. However, the bioavailability of nutrients and especially the dynamic changes in chemical environment and microbial interactions in the rhizosphere are not fully understood. We need more research in areas like interactions between pollutants in the complex soil environment and a much better understanding of the soil ecosystem and pathogen vectors, survival, etc. We also need to be better at communicating the importance of soil to human health with the public.

5. SDG 4: quality education

SDG 4 is: "ensure inclusive and equitable quality education and promote lifelong learning opportunities for all." This goal particularly seeks to ensure that children in all the world's households, including the poorest, have access to a quality education. The COVID-19 pandemic has created significant challenges for SDG 4, as school closures kept 90% of the world's students out of school and reversed progress that had been made towards achieving SDG 4. At least 500 million students do not currently have access to remote learning to address the challenges posed by face-to-face education during the COVID-19 pandemic, and 35% of primary schools do not have the basic handwashing facilities required for their students to remain safe (U.N, 2020c). Therefore, our current environment poses significant threats to achieving SDG 4, which hopefully will be overcome in the near future with the many efforts ongoing across the world.

Quality soil science education that includes training in all the foundational knowledge and skill sets essential to the discipline is key to solving this. Soil science can contribute considerably to increase the quality of education due to its holistic and interdisciplinary nature. Education that produces soil experts, those who *know* soils, is further empowered when those in other disciplines *know of* soil and its integrative role in the challenges they are addressing (Field et al., 2020). Beyond soil science expert education, educating and communicating about soils at the basic and non-formal levels has a great potential to enrich and widen the outreach and quality of education, for it encompasses the possibility of an integrated approach to environmental issues.

An important goal to be achieved in quality education using a soils approach is to increase the ability of people to perceive and realize the existence and uniqueness of soils, by what we call sensitization, a previous step to learning and acquiring formal knowledge. Sensitization does not need guidance and pushing, it is an inherent characteristic of humans and the basis of cognitive development. Still, sensitization about soils may need to be awakened among people that are not directly in contact with soils and their productive and environmental functions, as nowadays, the majority of the population lives in urban areas.

Understanding gender equity issues (SDG 5) includes the realm of the social sciences. Classes from all these areas are part of a well-rounded soil science curriculum (Brevik et al., 2020b), but in practice are not necessarily taught in all soil science preparatory programs (Brevik et al., 2020b; Diochon et al., 2016).

There are local efforts in some countries to develop a teacher supportive curriculum with authentic student assessment that encourage collaborative learning in groups (Kosaki et al., 2020), such as with school kitchen gardens and the internationally recognized Tea Bag Index (TBI) experiment (Keuskamp et al., 2013; http://www.teatime4science.org/).These learning opportunities in part succeed through negotiation and are dependent on gender diversity and equity, which may be used to assess if soil learning activities are directed by and contributing to SDG indicator 4.7. This should also build the foundation for a set of transferable skills to other areas of the world for study or work. They involve families and communities, thus encouraging lifetime learning and awareness raising across generations. These activities develop basic skills in numeracy, arithmetic (math) and temporal and spatial skills which partly contribute to SDG indicator 4.6. Collaborative learning at more senior levels addressing soil and its role in providing food security, women's empowerment and environmental sustainability (SDGs 2, 5 & 15) are fertile ground for students to explore and demonstrate work-ready skills in leadership, collaboration, social engagement and entrepreneurship contributing to SDG indicator 4.4. It also promotes multi-disciplinary and transversal thinking, making connections between the role of soil to cognate areas, as well as disciplinary humility within an ethical framework (Field et al., 2020) that enables robust and effective collaborative conversation and debate (Field, 2020). A well-trained soil scientist with a holistic educational background is prepared to address challenges in all of these areas and to interact with professionals from other disciplines, aiding in the successful achievement of the stated goals.

6. SDG 5: gender equality

SDG #5 addresses the important issue of gender equality. Gender equity remains a concern in the sciences across the world, including soil sciences (Larivière et al., 2013). Women remain a minority in soil science and related fields, and their representation at conferences as keynote speakers, on editorial boards, as reviewers, and on grant funding panels is even worse. Women have made important contributions to science throughout history but have consistently been underrepresented at all levels (Royal Society of Chemistry, 2018; FAO et al., 2020). The main issues related to gender equality in soil science have been lower percentages of women working as soil scientists than in the general population, fewer chances to serve on committees or as invited speakers at scientific meetings, unconscious bias, tensions with work-life balance, poor funding and pay, lack of career progression and a lack of networking opportunities. The question of how and at which level initiatives should be encouraged to promote global gender equality, particularly in developing nations, needs to be addressed.

Research in soil science indicates that achieving gender equality will require addressing what to do on two interrelated central issues that link to other SDGs: education and access to land ownership. To improve equity in the sciences, including soil science, we need to educate in a way that changes the gender stereotypes that link science to stereotypes about masculinity. Women and girls constitute half of the world's population and consequently half of all human capacities (U.N., 2020), which means that their participation is essential for the enrichment of scientific, economic and social activity to achieve the SDGs. It also means that failure to do so puts agricultural production at risk as the fundamental economic engine, and therefore impacts upon food security.

A rethinking of gender equity (SDG 5) and education (SDG 4) is needed to create a new paradigm that allows us:

a) to create an inclusive perspective that encourages respect, collaboration and solidarity between the genders. An education based on the full understanding that "equality does not mean that women and men will become the same but that women's and men's rights, responsibilities and opportunities will not depend on whether they are born male or female." (U.N. Women, 2001).

b) An education that recognizes that soil is a natural resource, but also a social, economic, cultural, political and patrimonial good. The soil enables humans to live on it, and through their work to obtain food, water and a legitimate sustenance that allows them to overcome poverty, but also enables one to construct an identity, cultural and economic independence.

7. SDG 6: clean water and sanitation

Soils play a major role in the movement, storage, and transformation of water and influence the quality and availability of water supply. Thus, the advance of soil science influences the prospect of achieving SDG 6 – clean water and sanitation. Water is essential not only to survival and health, but also to poverty reduction, food security, peace and human rights, ecosystems and education. Nevertheless, countries face growing challenges linked to water scarcity, water pollution, degraded water-related ecosystems and cooperation over transboundary water basins. In addition, funding gaps and weak government systems hold many countries back from making needed progress. Unless current rates of progress increase substantially, Goal 6 targets will not be met by 2030 (U.N, 2015c) .

While present agriculture accounts for about 70% of global water withdrawals, increased future water demand definitely would occupy the limited availability of water resources for other uses. The proportion of the global population using safely managed drinking water services increased from 61% in 2000 to 71% in 2017. Despite progress, 2.2 billion people lack safely managed drinking water and 4.2 billion people lack safely managed sanitation (U.N, 2020a) . Thus, the improvement of water use efficiency (WUE) is essential for agriculture. The majority of agricultural water use is consumed by irrigation, and irrigation water efficiency has been improved significantly with model irrigation techniques. In addition, soil management practices the manipulation of the soil surface by tillage and surface residual management or mulching are important supplements (Hatfield et al., 2001). From the water-energy-food nexus perspective, the actions in any one particular area often can have effects in one or both of the other areas (FAO, 2014).

Declining water quality and increasing pollution of surface water and groundwater hamper the prospect of achieving SDG 6. In comparison to surface water pollution, pollutants often travel some distance through soils. Soil performs an important function in pollution control via buffering and filtering. Once a groundwater supply is contaminated, there are usually no easy ways to improve the situation. However, unsustainable agricultural practices usually cause lower soil organic matter (SOM) and facilitate the transfer of pollutants into groundwater (Guo et al., 2010). Contamination of groundwater by agricultural chemicals and wastes has become the most prevalent water quality issue in almost all developed countries and, increasingly, in many developing countries (U.N.E.P, 2016). For example, China is the world's largest consumer of nitrogen fertilizer, and up to half of the nitrogen applied is lost by volatilization and another 5 to 10% by leaching (Lassaletta et al., 2016). The nitrates finally get into surface water and groundwater. In 2015, China established an action plan for achieving zero growth in chemical fertilizer use for major crops by 2020. Relevant management options would directly reduce the extent of future contamination. Besides, soil influences water provision and sanitation by detoxification, water and nutrient retention. There are universal principles for systematically and safely detoxifying human excreta, without contaminating, wasting, or even using water (Factura et al., 2014). Ecological sanitation focusing on sustainability through reuse and recycling offers pragmatic solutions such as compost-based eco-sanitation, in which composted excreta is re-used as nitrogen- and phosphorus-rich fertilizer (Glaser et al., 2001).

The developed world may think it has cracked the problem, but trouble is gurgling away underground. 'Flush and forget' sanitation systems constitute one of the more bizarre hangovers from the Victorian age. In older toilets, up to 25 l of drinking water go down the pan per flush, although 'low-flow' toilet designs are coming into their own and, in 1995, the US federal government set a 7-l-per-flush limit. Aside from wasted water, the feces-laden 'black water' from flush toilets is not always treated. Many older sewage systems mix toilet wastewater with storm water in combined sewage outflows, which can overflow after heavy rain (Ingvaldsen et al., 2015). Innovative on-site waste disposal systems for septic tank effluent have been developed for different soil types, considering natural soil water regimes and soil filtration capacities (Bouma, 1979).

Sewage sludge, the solid residue after wastewater treatment in sewage works, can be also problematic. Although it can contain significant traces of pharmaceuticals and heavy metals even after treatment, it is widely used in the West as a soil conditioner and fertilizer on cropland, with uncertain effects on human health. In the megacities and scattered villages of the developing world, the challenge is even more daunting. Thousands of children die every day from a lack of basic sanitation or clean water. Open defecation contaminates soils with the eggs and larvae of soil-borne intestinal worms, or helminths, as well as other pathogens. More than one billion people are infected with these helminths, which cause, among other problems, weakness and malnutrition.

The discovery of a practice originating in Brazilian Amazonia more than 1000 years ago could, paradoxically, kick-start a modern revolution in composting sanitation. The pre-Columbian Native Americans created 'black' soils known as "terra preta." Found in patches throughout Amazonia, terra preta is composed of charcoal (biochar), composted excreta and other organic residues (Glaser et al., 2001; Glaser and Birk, 2012; Kern et al., 2019) . Terra preta also contains huge amounts of stable and nutrient-rich SOM content (Glaser et al., 2000; Glaser and Birk, 2012; Lehmann et al., 2003).

Eco-sanitation systems using the terra preta principle can help to solve two problems inherent to developing countries: poor soils and a lack of sanitation. The terra preta sanitation technology offers the efficient creation of well-structured, humus-rich compost, which is important for food security, resistance to soil erosion, water retention in soil and the growth of local agricultural economies. And it is cost-effective. A basic terra preta sanitation toilet costs about US $50, inputs are inexpensive, and it is not hooked to sewage systems.

8. SDG 9: industry, innovation, and infrastructure

Inclusive and sustainable industrialization, together with innovation and infrastructure, can unleash dynamic and competitive economic forces that generate employment and income. Soil carbon (C) is recognized as the largest store of terrestrial C (Lal, 2004), and soils have the potential to sequester more C through strategies such as woodland planting and no-till farming. Resilient soils, with good and stable carbon contents, have the potential to be part of the overall solution to the C crisis. Good and stable soil structure which enhances infiltration can slow the rate at which surface runoff is generated and hold soil particles together, reducing sediment loads in runoff (Liu et al., 2020). This can have multiple benefits – reduced sediment build-up in channels and dams, reduced need to manage sediment deposition on transport infrastructure, increased ability of infrastructure to withstand extreme events and reduced incidents of wind erosion, limiting the risk of smothering of crops and vegetation (Tibke, 1988).

Enhancing our connection to the land and where our food comes from by promoting local food production based on appropriate and sustainable soil and land husbandry will also reduce the reliance of communities on food imports. Promoting access to land for food production at a local scale brings with it enhanced health and wellbeing benefits for individuals and communities, and there are many examples of organizations who work with community groups, schools, etc. which create new growing spaces or enhance existing ones to realize these benefits (e.g. www.propagate.org.uk).

Working with soils brings the functions they provide into sustainable solutions to global challenges. Leaky dams have been used in the UK to promote the spread of flood waters higher up in the catchment in habitats that can withstand intermittent flooding, slowing peak flows and protecting downstream areas. These are simple and inexpensive to install, reduce the need for complex and financially and carbon expensive engineered solutions (e.g. see https://edenriverstrust.org.uk/your-eden/explore-edens-rivers/leaky-dams/) and the reduced peak flows and sediment loads also support the resilience of downstream infrastructure.

Consideration is needed regarding how soils are handled, stored, and reused as part of construction projects, following best practice advice (e.g., DEFRA, 2009; SEPA, EnviroCentre, 2011), and how measures can be included to change land management practices to increase carbon sequestration. A balance will need to be found between taking land out of agricultural production, which can be used as one approach (Bell et al., 2020), and changing agricultural practices (Onwonga, 2019).

Enhanced knowledge and understanding of soils, soil process and function will generate better engagement. Lobry de Bruyn et al. (2017) suggests that the solution to stemming continued soil degradation lies with five groups and their capacity to connect with each other and to the soil knowledge they require: educators, policymakers, researchers, outreach agents, and practitioners (working with or relying on soil).

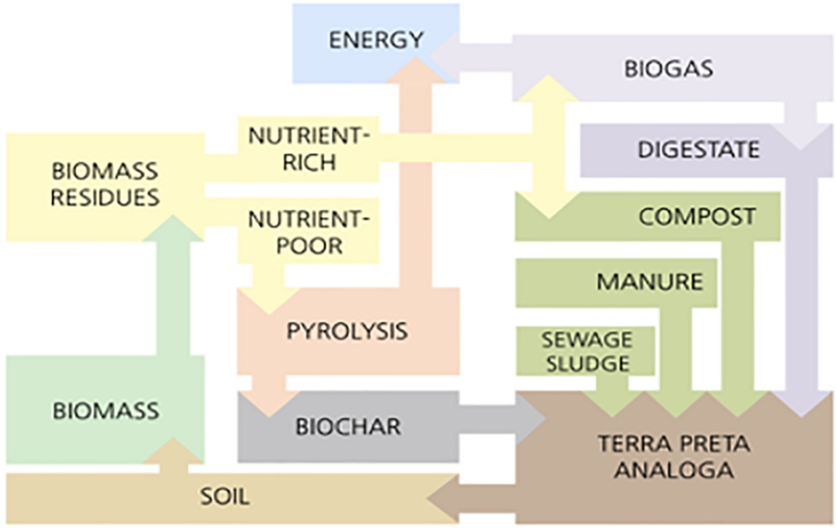

Fig. 1. Urban gardening following the terra preta concept.

9. SDG 11: sustainable cities and communities

SDG 11 deals with making cities and human settlements inclusive, safe, resilient and sustainable. Targets 11.6 and 11.7 particularly address soil issues such as waste management and the provision of universal access to safe, inclusive and accessible green and public spaces. Target 11.B is also directly related to soil issues since it addresses climate change mitigation and adaptation, and soils will play an important role herein since they provide numerous ecosystem services for the benefit of urban life.

In 2008, the global urban population outnumbered the rural population. This milestone marked the advent of a new 'urban millennium,' and, by 2050, it is expected that two-thirds of the world population will be living in urban areas. About 75% of global C emission happen in cities and about 80% of material and energy resources are consumed there (U.N.E.P, 2012). Urban systems do not only harm the environment within its own borders, but the ecological footprint affects vast areas through the mining of raw materials and deposition of waste and sewage. From the viewpoint of material and energy flow, combined with the approach of geochemistry, urban systems together form a new worldwide active envelope called the astysphere, which interacts with the agrosphere and the anthroposphere (Norra, 2014; Norra, 2009; Norra and Stuben, 2003).

Urban systems cover between 0.3% to 3% of the terrestrial surface worldwide (Angel et al., 2005; Salvatore et al., 2015; Schneider et al., 2009; Zhou et al., 2015), Although this is a relatively low share of the total global land area, urban inhabitants' lives depend on it. In developed countries such as Germany, this portion is even higher. In Germany 66 ha were developed each day in 2015 and 13.7% of the land area was covered by settlements and traffic infrastructure (Destatis, 2018). In Europe, Iceland has the lowest share of sealed area with 0.07% and Malta the highest with 16% (EEA, 2019). This development affects the local soils with respect to sealing, densification, excavation and pollution. The original soils become highly impacted, partly eliminated or mixed with technogenic materials (IUSS Working Group WRB, 2014).

From a soils' perspective, water, sanitation, waste management, disaster risk reduction such as erosion and inundation, and promoting sustainable land-use planning and management, among other non-soil-related aspects, are relevant issues to sustainable urban development. Potential future sustainable uses of soil within cities and megacities are i) urban gardening, ii) permaculture, iii) vertical gardening, and iv) terra preta, which are briefly discussed in the following. Furthermore, urban development produces a typical urban soil, the v) Technosol. In the face of manifold environmental and health crises such as COVID-19, the awareness of the positive effects of gardening and agriculture in urban contexts has consistently increased (Lal, 2020a) . The idea that urban gardening represents something that cities must foster has become indeed a universal assumption in political planning debates about the sustainable city.

Permaculture as an abbreviation of "permanent agriculture" originated in Australia at the end of the 1970s (Ulbrich and Pahl-Wostl, 2019) . Most commonly, permaculture is seen in relation to agroecological farming (Ulbrich and Pahl-Wostl, 2019) , and the design of regenerative, closed-loop systems, similar to terra preta (Glaser, 2007) . The *terra preta* technology offers the efficient creation of well-structured, humus-rich compost, which is important for food security, resistance to soil erosion, water retention in soil and the growth of local agricultural economies. Terra preta is not only a humus-rich sustainably fertile soil, but also a concept to close regional nutrient cycles (Fig. 1). In the 20th century, flat roofs became the new gardens of overcrowded cities and possible spaces for air purification and relaxation for the citizens. With different means, this was the line of thought followed in the 1970's to seek a sustainable response in which a high degree of commitment to the environment was achieved.

Urban waste production, management and potential recycling are important issues for the sustainability of cities also in relation to soils, in a moment where the amounts of urban wastes are increasing in parallel to the rise of urban population (Kaza et al., 2018). The organic fraction of urban wastes can be conveniently treated and recycled through composting, a biological process in which mesophilic and thermophilic microorganisms decompose organic wastes, leading to a stabilized product known as compost. Composted organic urban waste is usually recycled as soil amendment in agricultural areas, counteracting the decline of organic matter in agricultural soils and improving their physical, chemical and biological properties (Hargreaves et al., 2008). But cities also offer opportunities for reuse of urban waste compost, which have been less explored to date, although they will undoubtedly gain importance in the future. In this sense, composts can be employed as organic amendments in urban agriculture (Ulm et al., 2019), which is rapidly developing in many cities under different modalities: home gardens, community gardens, allotments, school gardens, or rooftop gardens (Sattler et al., 2020). Urban waste compost can also be used as a component of substrates for green infrastructures, such as green roofs or vertical gardens (Paradelo et al., 2019) or in the restoration of degraded urban soils.

Regarding Ecosystem services (ESs), urban soils are not only providing ESs by themselves, but also by the ecosystem components they facilitate, e.g.: trees (Fig. 2) and green areas that improve the health of citizens. Thus, soils in urban systems contribute not only to the goals of SDG11, but also to the goals of SDG 3: Ensure healthy lives and promote well-being for all at all ages, as the health of city dwellers depends on the availability and access to green spaces. Within this context, urban soils have to be much more considered, protected and supported within the urban planning process. Without urban soils SDG #11 and, in this context, SDG #3 for urban inhabitants will not be realized.

The importance of soils as ESs providers that are essential for the development of sustainable cities is getting increased recognition worldwide from the scientific community. More and more attention is being paid to the study of urban soils morphology, formation and properties, in comparison to what happened in previous decades. Also, knowledge of urban soils starts to be considered as an essential aspect for urban agriculture, gardening and greenery management. However, there is much work yet to do before soils can be widely accepted as an integral element of sustainable cities. In the absence of national or regional plans for urban soil studies in most countries, important differences exist in the status of urban soil knowledge, both among countries and within countries. But more importantly, communication of soil scientists with the main stakeholders involved in the management of urban areas (city planners, economists, politics, engineers…) needs to be improved.

10. SDG 12: responsible consumption and production

Sustainable management of soil is also critical to realizing SDG 12. With the onset of the 21st century, the unsustainable use of natural resources, measured by the material footprint, has accelerated globally. Improvements in resource efficiency - that should take into account the whole life cycle - in some countries were outweighed by increases in material intensity in others (U.N, 2020a). The improvement of crop production in terms of water management, agricultural yields, phosphorus recycling rates, and nitrogen use efficiency may reduce environmental effects of food systems (Springmann et al., 2018). Sustainable soil management that maintains or enhances soil organic matter (SOM) may mitigate climate change and increase soil quality and food security (Rumpel et al., 2020). Especially beneficial for SOM are reduced (non-inversion) tillage, the incorporation of crop residues, organic amendments including organic wastes and a crop rotation with extensive soil cover (Lehtinen et al., 2017; Sandén et al., 2018; Spiegel et al., 2018). Most of the above-mentioned sustainable soil management strategies are part of the FAOs Voluntary Guidelines for Sustainable Soil Management (FAO, 2017). Learning from the small-scale farming systems where most of the calories consumed today are produced could further increase sustainable use of soils and scientific knowledge of sustainable food systems (Måren, 2019). Moreover, land consumption and sealing is a substantial threat to soils (Glæsner et al., 2014; Günal et al., 2015; Montanarella and Panagos, 2020) and urgently needs to be minimized.

Food losses along the supply chain are reported to have significant environmental impacts, mainly originating from agricultural production (Eberle and Fels, 2016; Scherhaufer et al., 2018). About one third of food is lost globally from agricultural production to household consumption (Gustavsson et al., 2011), food waste in the European Union amounts to about 88 Mt. (Scherhaufer et al., 2018). An additional complication to the assessment of domestic consumption comes from transboundary environmental impacts that are mainly kept out of the assessments (Amos and Lydgate, 2020). The current COVID-19 pandemic is expected to lead to less environmental pollution and a better food production within global environmental limits because it may increase focus on local food chains and the circular economy (Lal et al., 2020; Springmann et al., 2018). The waste of animal products (meat, dairy products) causes severe environmental impacts, because their production often needs, for example, more agricultural land and water, and this in turn results in higher GHG (including methane and nitrous oxide) emissions compared to plant production (Eberle and Fels, 2016). This also strengthens the need for dietary changes with limited meat consumption and more plant-based human diets. Theurl et al. (2020) show that diets are the main determining factor for GHG emissions from food systems, vegan diets resulting in lowest emissions. Halving meat consumption as well as global food waste would also prevent future biodiversity losses (Bryan and Archibald, 2020).

Aldaco et al. (2020) report that during the pandemic household food waste and losses have increased by 12% in Spain, but this does not counteract the losses before the crisis if outside consumption is taken into consideration. In Austria, SDG 12 is supported by awareness-raising projects, e.g. the project "My Food - My Future", where specially trained farmers pass on knowledge about sustainable nutrition and careful food choices to pupils (Bundeskanzleramt, 2020). Overall, land consumption with 12 ha per day is too high for the small country and jeopardizes valuable agricultural land, especially for food production.

11. SDG 13: climate action

SDG #13 deals with taking urgent action to combat climate change and its impact. The increase in atmospheric carbon dioxide

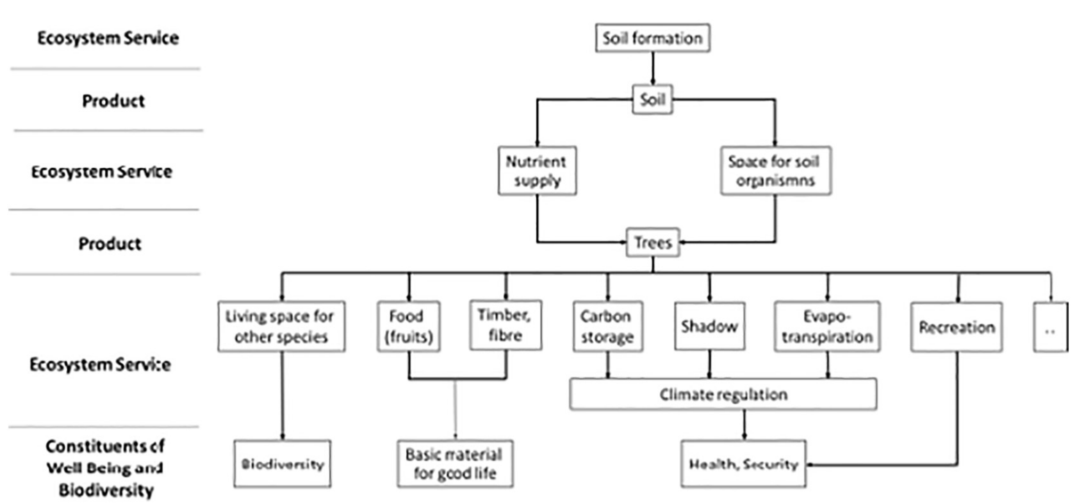

Fig. 2. Interconnections of soil ecosystem services with trees in urban systems.

concentration from 280 ppm in the pre-industrial era to 410 ppm in 2019, along with the enrichment of other GHGs, has already caused a global mean temperature increase of 1 °C (Lal, 2020b) . Climate change has a major impact on soil and vice versa. Therefore, without healthier soils and sustainable land and soil management, we cannot tackle the climate crisis and produce enough food while adapting to a changing climate. The answer might lie in preserving and restoring key ecosystems and letting nature capture carbon from the atmosphere.

Historically, soils in managed ecosystems have lost about 90–133 Pg C through land use change, some of which has remained in the atmosphere (Eglin et al., 2010; Lal, 2020b). Mechanization of agriculture after the 1950s has accelerated SOM loss in croplands, whereas development of C-sequestering practices since the 1990s may have limited SOC loss from arable lands. Most projections suggest that soil C changes driven by future climate change will range from small losses to moderate gains, but these global trends show considerable regional variation (Eglin et al., 2010) . The response of soil C in the future will be determined by a delicate balance between the impacts of increased temperature and decreased soil moisture on decomposition rates, and the balance between changes in C losses from decomposition and C gains through increased productivity. In terms of using soils to mitigate climate change, soil C sequestration globally has a large, cost-competitive mitigation potential. Soil C sequestration can be useful to meet short-term to medium-term targets, and confers a number of co-benefits on soils (Eglin et al., 2010) .

Sustainable management of soil can lead to a high resilience to extreme climate events, as least in the short term (Glaser et al., 2013; Jentsch et al., 2011; Schmitt et al., 2010, Schmitt et al., 2008; Schmitt and Glaser, 2011a, b) . However, the biggest climate concern linked to soil is the CO_2 and CH_4 stored in permafrost in boreal regions, mainly in Siberia. As the global temperature increases, the permafrost melts, leading to emission of GHGs into the atmosphere.

The Intergovernmental Panel on Climate Change (Arneth et al., 2019) confirms that GHG emissions from all sectors including soils and food need to be reduced in order to achieve the target of keeping global warming to well below 2 °C. Despite the uncertainties, restoring ecosystems and improving soil quality could be a cost-efficient measure in terms of climate action with a triple impact. First, growing plants remove carbon dioxide from the atmosphere. (UNFCCC, 2017) estimated that restoring currently degraded soils could remove up to 63 Pg C, which would offset a small but important share of global GHG emissions. Second, healthy soils keep the C underground. Third, many natural and semi-natural areas act as powerful defenses against the impacts of climate change.

There are also various methods for increasing soil's capacity to capture CO_2 from air, such as no till (NT), cover cropping, organic farming, agroforestry, use of biochar, and soil inorganic C (SIC). However, recent meta-analysis showed that only agroforestry; (Feliciano et al., 2018; Lal, 2004; Shi et al., 2018) and biochar (Kuzyakov et al., 2014; Liu et al., 2015; Lorenz and Lal, 2014) are suitable to substantially sequester C in the long-term.

Biochar, a solid porous material obtained from the carbonization of biomass under low or no oxygen conditions, has been proposed as a climate change mitigation tool because it is expected to sequester carbon for centuries and to reduce GHG emissions from soils (Brassard et al., 2016; Kuzyakov et al., 2014; Schimmelpfennig and Glaser, 2012) . Biochar production and application to the field can be used as a tool to mitigate climate change. Biochar is one of the most affordable negative emission technologies (NET) at hand for future large-scale deployment of CO_2 removal (CDR), which is typically found essential to stabilizing global temperature rise at relatively low levels. It is also a soil amendment capable of improving yield and soil quality and of reducing soil greenhouse gas (GHG) emissions (Tisserant and Cherubini, 2019) . Biochar production using only forest or crop residues can achieve up to 10% of the required CDR for 1 °C pathways and about 25% for 2 °C pathways; the consideration of dedicated crops as biochar feedstocks increases the CDR potential up to 15–35% and 35–50%, respectively (Tisserant and Cherubini, 2019) . A quantitative review of life-cycle assessment (LCA) studies of biochar systems shows that the total climate change assessment of biochar ranges between a net emission of 0.04 $MgCO_2$ eq and a net reduction of 1.67 $MgCO_2$ eq per tonnes feedstock (Tisserant and Cherubini, 2019) . Overall, biochar in soils presents relatively low risks in terms of negative environmental impacts and can improve soil quality. Decisions regarding feedstock mix and pyrolysis conditions can be optimized to maximize climate benefits and to reduce trade-offs under different soil conditions.

SIC as both $CaCO_3$ in arid soils and as bicarbonate in groundwater has also been proposed as a climate change mitigation tool (Lal et al., 1999; Monger et al., 2015). Studies concluding that SIC might serve as a C sink have been conducted in Russia (Mikhailova and Post, 2006), China (Wang et al., 2014), California (Wu et al., 2008), Nevada (Wohlfahrt et al., 2008), Arizona (Cueva et al., 2019), and New Mexico (Wang et al., 2016). SIC is the product of CO_2-driven chemical weathering of calcium and magnesium silicate minerals (Berner, 2004). Enhanced silicate mineral weathering has the potential to sequester from 2 to 4 Pg CO_2 yr^{-1} (Fuss et al., 2018). Further enhancement might be capable using soil microorganisms (De Muynck et al., 2010; DeJong et al., 2011).

Soil C sink capacity, between 2020 and 2100, with the global adoption of best management practices that create a positive soil/ecosystem C budget, is estimated at 178 Pg C for soil, 155 Pg C for biomass, and 333 Pg C for the terrestrial biosphere with a total CO2 drawdown potential of 157 ppm (Lal et al., 2018) . Important among techniques of SOC sequestration are adoption of a system-based conservation agriculture, agroforestry, biochar, and integration of crops with trees and livestock. There is growing interest among policymakers and the private sector regarding the importance of soil C sequestration for adaptation and mitigation of climate change, harnessing of numerous co-benefits, and strengthening of ecosystem services (Lal, 2020b).

12. SDG 15: life on land

SDG 15, "Life on Land", states that a flourishing life on land is the foundation for our life and we all are part of the planet's ecosystem. However, through excessive exploitation and mismanagement of soil resources, such as deforestation, loss of natural habitats and land degradation, we have caused severe damage to land and soil. For example, land degradation through human activities is undermining the wellbeing of at least 3.2 billion people, pushing the planet towards a sixth mass extinction and costing more than 10% of total Gross Domestic Product (GDP) (IPBES, 2018). Sustainability of terrestrial ESs (SDG 15) depends on the provision of ESs where soil properties and functions play a key role to deliver these. In particular, land degradation neutrality (SDG 15.3) is desired by 2030 to combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world (Tóth et al., 2018).

Soil degradation is exacerbated by compaction, soil subsidence, SOM decline, diffuse pollution, and biodiversity decline. Among all these threats, decline of SOM is the most important because it affects all aspects of soil functioning, ranging from soil fertility to soil structure, from water retention and infiltration capacity to the regulation of nutrients, and from prerequisites for a rich soil ecosystem to a carbon pool of global importance (Paustian et al., 2016).

To halt and reverse the current degradation trends, soils must be managed in a judicious and sustainable manner. Proven climate-smart technologies, innovations and management practices (CS-TIMPs) are essential to adapt and mitigate the adverse climate change effects, build resilience in farming systems, reduce GHG emissions and advance food security. These technologies consist of an array of practices: for example, conservation agriculture (CA), precision agriculture (PA), integrated nutrient management (INM), residue retention, soil biological management, soil and water conservation (e.g., terracing and mulching), agroforestry, controlled grazing at optimal stocking rates and use of organic amendments (e.g., manure), cover crops, biochar, improved plant varieties, and crop rotations (Were and Singh, 2020).

CA aims at accumulating SOC and creating a healthy soil ecosystem by NT the soil prior to planting and establishing crops on the residues left on the ground after harvesting, while INM maximizes the use of organic resources and improved germplasm, minimizes nutrient losses, allows timely and judicious use of inorganic fertilizers based on need and economic viability, and maintains and enhances beneficial soil organisms and biological processes (Oladele and Braimoh, 2014). Integration of green manure and leguminous cover crops in rotation is also a promising technology for C sequestration in agricultural soils (Were and Singh, 2020), leading to increased soil aggregate stability, reduced erosion, improved soil quality and soil biodiversity.

Some of the technologies, such as CA, PA, INM and use of biochar have proved beneficial for combating soil degradation and improving soil health. They have also showed potential of C sequestration, biodiversity benefits and economic viability. However, adoption of these technologies at national and international scale is still confined to regional and small segments of farmers. Therefore. more applied research and extension innovations are needed to extend these technologies to farmers in larger national and global areas. Thus, promoting sustainable use of terrestrial ecosystems, reversing land degradation and halting biodiversity loss are the keys to achieve soil degradation neutrality and for our own survival.

13. SDG 16: peace, justice and strong institutions

The stated goal of SDG #16 is to "promote peaceful inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels." This goal can be seen as a central enabling tool for all of the SDGs. Soil science underpins many of the individual targets within this goal. Fertile and productive soil plays an important part in establishing food security, in particular in the developing nations food security, and consequently a secure and healthy agricultural sector plays a vital role in preventing conflict. It also plays a key role in influencing migration, and ultimately in building peace and stability. In many countries disasters or political instability have resulted in protracted crises and food shortages leading to food insecurity and famine.

Rural populations tend to be the communities which are most affected in conflict situations, as attacks on farming communities undermine livelihoods and can force people from their homes. Peace and food security tend to be mutually reinforcing. Interventions to ensure food security and to support the agriculture sector should consider the many fundamental causes of conflict. International organizations such as the FAO are working with partners in countries to develop policy and regulatory frameworks, innovative institutional arrangements, and functional rural organizations that help small-scale producers overcome social, political and economic barriers. This contributes to improving the impact of livelihoods, fostering inclusive economic growth, and adopting governance to new challenges (FAO, 2018). Through actions on the ground to reinstate soil fertility and to secure local food production, such organizations play a key role in helping deliver this vital SDG, entwined with so many other goals.

Soil science knowledge and research contributing to aspects of soil and food security, it also underpins documented and accredited systems in forensic soil science supporting the establishment of effective, fair and humane criminal justice systems and access to justice. It's presence within the criminal justice system helps strengthen its integrity. With the advance in techniques within the field of forensic soil science for both intelligence and evidence, in particular from the UK (Dawson and Hillier, 2010; Donnelly et al., 2021); USA (Murray, 2004; Murray and Tedrow, 1992); Australia (Fitzpatrick and Donnelly, 2021; Kobus and Robertson, 2019); Italy (Di Maggio and Barone, 2017); Russia (Gradusova and Nesterina, 2009); China and South America (Prandel et al., 2020; Testoni et al., 2019), for example, with the discipline of forensic soil science assisting in establishing safe convictions while also assisting in delivering another reliable tool to act as a deterrent against committing a crime.

Soil scientists have identified the location of buried objects, such as chemical drums, storage tanks, vehicles, waste disposal trenches, bodies, drugs, precious metals and weapons, as well as human bodies (Dawson et al., 2020; Donnelly et al., 2019; Pringle et al., 2012; Ruffell and McKinley, 2008). Soil science can also be useful in the characterization of illegal environmental deposits such as toxic waste and environmental contaminants (Ruffell et al., 2018) and can help track where materials were transported (Ruffell and Dawson, 2009). In addition, illegal wildlife trade and wildlife crimes such as dog fighting and badger baiting have been solved through soil and geological materials adhering to items such as dog collars and tools (Morgan et al., 2006). Based on chemical concentrations in the soil and groundwater, a forensic soil scientist can calculate original chemical concentrations to which workers were exposed to in the past (Murray and Tedrow, 1992) and can help resolve issue liability in relation to contamination and human health, and the issue of mining contamination has been assisted throughout the forensic geosciences (Pirrie and Shail, 2018).

With the goal, by 2030, of significantly reducing illicit financial and arms flows, strengthening the recovery and return of stolen assets, and combating organized crime; forensic soil science provides tools which could disrupt illicit financial flows and supports recovery of stolen assets, e.g. with provenance tools such as DNA profiling (Demanèche et al., 2017; Habtom et al., 2017) and mineral profiling (Pirrie and Shail, 2018). Research and data collection in several areas connected to organized crime, including firearms, drugs and other illicit markets such as in trace metals and minerals, wildlife crime and trafficking in persons, and benefits from tools related to earth sciences where trace evidence can be recovered from questioned items involved in the criminality can be identified.

These tools, related to soil science, have also benefited the criminal justice system in reducing corruption and bribery, as often the same networks are involved in the different types of criminality. The international soil science community, as part of the International Union of Geological Sciences-Initiative on Forensic Geology (IUGS-IFG), have assisted law enforcement internationally in the investigation, detection, and in promoting international cooperation, in addition to the recovery of proceeds of corruption both domestically and internationally. A recent initiative of the IUGS IFG on mining and mineral fraud is applying geoscience to the problem of illegal trade, especially in mining products, often interconnected with criminal networks.

The IUGS-IFG also delivers to the target to develop effective, accountable, and transparent institutions through the sharing of information and adaptability of good practices (e.g. by producing a Guide (Donnelly et al., 2021)). A recognition of the need to uphold high ethical standards (Dawson et al., 2021) and to have transparency of the institutional functions and services has been acknowledged. As a sector we encourage and facilitate the participation of a wide range of civil society organizations, contributing to an open, responsive, and accountable decision-making process on crime- and drug-related matters at an international level aiming to meet the target of inclusive, participatory, and representative decision making.

The target to strengthen relevant national institutions, including through international cooperation, for building capacity at all levels, in particular in developing countries, to prevent violence and combat terrorism and crime is being reached through focused international network groups in forensic soil science, e.g. with current development initiatives in India, UAE, and South America, in particular Brazil. In Europe, the European Network Forensic Science Institutes-Animal Plant Soil Trace working group have created a best practices manual to help standardize practices and procedures across Europe (Bourguignon et al., 2019). The IUGS-IFG has also produced a Guide

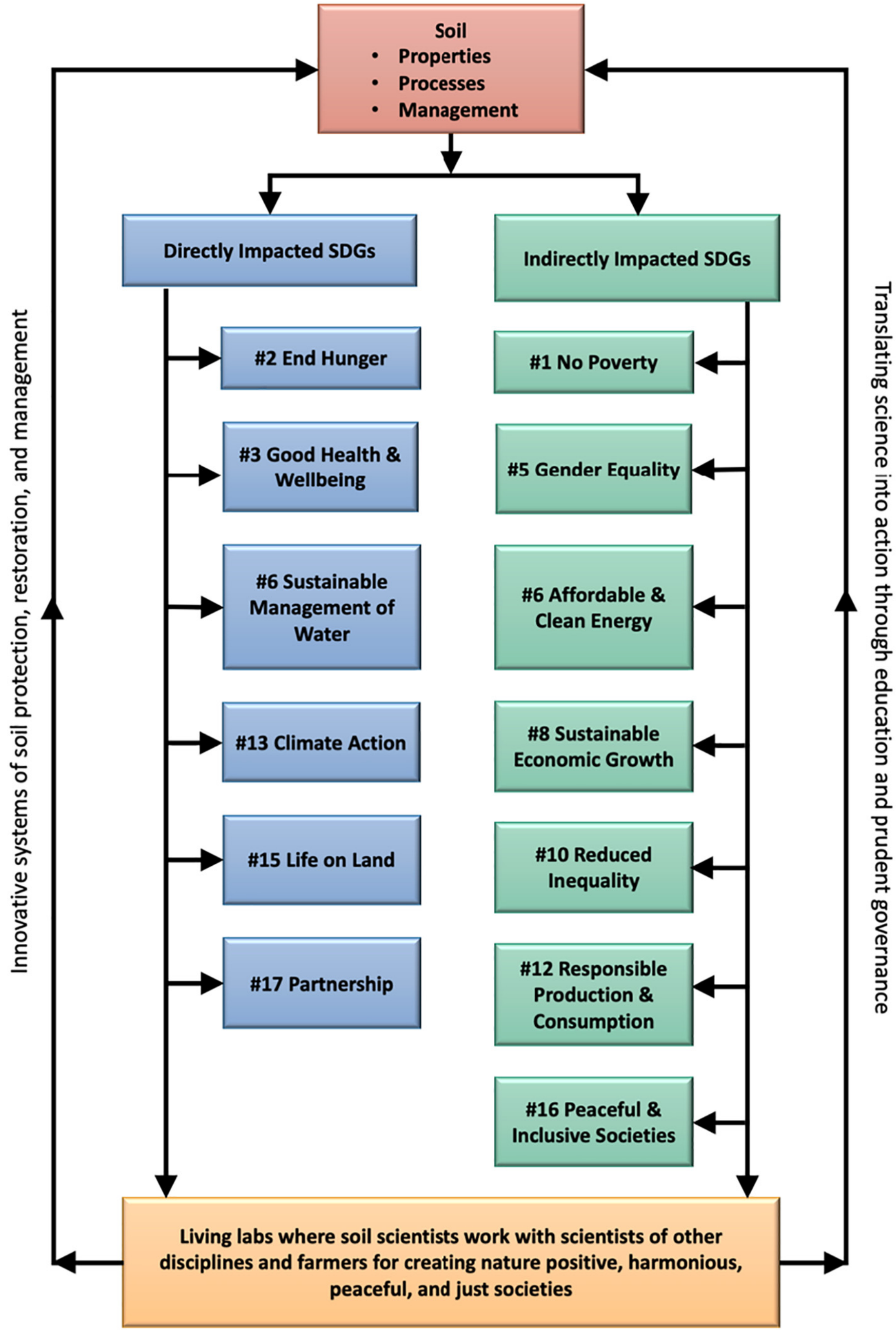

Fig. 3. Managing soils for keeping Sustainable Development Goals od the Agenda 2030 on track.

(Donnelly et al., in press) and encourage international events to increase awareness of such techniques and approaches globally through building international networks, being inclusive and helping sustainable development, and providing access to justice for all.

14. Roadmap to the future

Over the past few years there has been a noticeable and welcome upsurge in soil research, in commitment of a widening group of stakeholders and in interest of the policy arena. The latter is particularly evident when considering the soil health concept that has been widely embraced (Lehmann et al., 2020). The analysis presented in this paper shows that the importance of soils extends way beyond the traditional focus on production of crops as clear impacts on other societal goals, associated with the SDGs, are evident. This only strengthens awareness of the societal importance of soils. But links between soil health and human health and wellbeing are still not widely recognized. For example, exposing children to 'dirt' improves their immune system. Gardening or engaging in a variety of forms of community agriculture improves our mental well-being and happiness, including helping patients slow or overcome the progression of Alzheimer's. There is a real opportunity to focus further funding and research in this area, as well as a need for policy makers, city planners and health professionals to identify opportunities to re-connect communities to the soil, through, for example, the establishment of community gardens, allotments and food growing initiatives within schools, hospitals, community centers, prisons and within workplaces. New focus and effort must be given to reconnecting all of us with the soil, the mother of life.

Considering European conditions, Veerman et al. (2020) cite figures showing that 50–70% of European soils are unhealthy due to various forms of soil degradation, as discussed in this paper: erosion, pollution, compaction, carbon depletion, biodiversity loss and sealing. But after decades of research remedies to solve these problems have often been generated but are not (yet?) applied. As mentioned above, a new interactive communication effort is needed to be based on specific and well documented examples of sustainable land use systems in agriculture, forestry and cities that meet SDGs. This implies a need for soil scientists to cooperate by actively reaching out in a multi-actor and engaging manner to other scientific disciplines, like agronomy, hydrology, climatology, ecology, human health, sociology and economics. In that context, use of widely used soil-water-atmosphere-plant simulation models are a pragmatic vehicle for interdisciplinarity (Bonfante et al., 2020; Bouma, 2018b).

The analysis in this paper shows that trying to satisfy SDGs presents a major challenge finding a delicate balance between a large number of goals focused on land use. When considering agriculture, this implies that not only healthy food is produced in a profitable manner (SDGs 1,2,3,12), but that also water quality (SDG 6), energy use (SDG 7), greenhouse-gas emissions, carbon capture (SDG 13) and biodiversity preservation (SDG15) should be achieved. To establish this, new monitoring and measurement methods have to be developed, applying proximal and remote sensing techniques and automatic monitoring equipment. And all of this in a societal context, defined by SDGs 4,5, 9,16, including cities, presenting different and unique challenges (SDG 11). To face this future challenge, Veerman et al. (2020) suggest to focus research in future on "Living Labs" where scientists of different disciplines work together with land users in a "joint-learning" or "co-creation" mode, trying to meet the SDGs and, in the process, prove the major role that soils play in achieving the SDGs. Successful Living Labs can be used as "lighthouses" communicating positive results to colleague land users, the policy arena and citizens at large. This approach acknowledges the fact that every farmer is different, if only because he/she has to deal with different types of soil in a typical socio-economic context. The SDG challenge presents "wicked" problems without single solutions but, rather, options from which a choice has to be made. Every land user will make choices that fit their particular management philosophy and allowing them to do so with suitable rules and regulations, can be a major contribution to acceptance in everyday practice of innovative land use practices, aimed at achieving the SDGs. The soil science research community must, therefore, look at how well their knowledge and outputs are accessible, understandable and applicable to all. This will improve by bringing those likely to benefit from the research into programs at an earlier point, reflecting on seeking an understanding of what information land managers want and looking beyond peer reviewed journals to media which are more accessible to practitioners, outreach agents and policy makers. The Living Lab concept, coupled with innovative communication efforts, has proven to be effective in achieving these intentions. As we move further into a digital world it will become more important to maximize the range of avenues available to share knowledge and to listen. In a post-COVID world it will also be critical to build these innovations alongside face-to-face communication to make the world safer and more secure.

15. Conclusions

Sustainable management of soil is critical to advancing SDGs. Several SDGs are directly impacted by soil properties and processes and their sustainable management. Important among these are SDDG #2,3,6,13,15 and 17 (Fig. 3). Additionally, several SDGs are indirectly affected by soil quality and its management (e.g.,1,5,6,8,10 and 16). Many of the SDGs are not on the track for accomplishment by 2030 (e.g., #2,13,15) because soil and their management are not given the emphasis that they deserve. Whereas the scientific knowledge and information about proven technology exist, there is a strong need for translating science into action through prudent governance and political will power. Yet, additional on-farm and participatory research based on the concept of living labs where scientists work with farmers and land managers in adopting and adapting innovative options is needed to bridge the yield gap and accomplish SDGs by 2030. In addition to policy interventions, there is also a strong need for involvement of the private sector in promoting the innovative technology. Thus, partnership between researchers, private sector, policy makers and land managers is needed to promote adoption of innovation technology. There also exists a strong need to periodically revise and upgrade the curricula of primary school to college and incorporate soil science and natural resources at all levels of education. Respectability of the farming profession must also be improved by empowering farmers and implementing policies which are pro-farmer and pro-nature. Farmers must be compensated through payments for ecosystem services. There is still time to put SDGs on the track for accomplishments of the targets by 2030.

Declaration of Competing Interest

None.

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